# AGRICULTURAL DRAINAGE CRITERIA

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# 17 AGRICULTURAL DRAINAGE CRITERIA

## 17.1 Introduction

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

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 water logging 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 criteria will be presented in Chapter 25, but are also briefly discussed in this chapter.

A correct assessment of the agricultural drainage criteria requires:

- knowledge of the various possible types of drainage systems;
- an appropriate index for the state of water logging;
- 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-climatic regions of the world.

## 17.2 Types and Applications of Agricultural Drainage Systems

### 17.2.1 Definitions

"Agricultural drainage systems" are systems that make it easier for water to flow from the land, so that agriculture can benefit from the subsequently reduced water 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 water logging occurs on the soil surface, whereas a subsurface drainage system is applied when the water logging occurs in the soil. Although subsurface drainage systems are sometimes installed to reduce surface water logging and vice versa, this practice is not recommended. Under certain conditions, however, combined surface/subsurface drainage systems are quite feasible (Chapter 21).

Agricultural drainage systems do not necessarily lead to increased peak discharges. Although this may occur, especially with surface drainage, the reduced water logging can lead to an increase in the temporary storage of water on or in the soil during periods of peak rainfall, so that peak discharges are indeed reduced. 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, submerged 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 water logging 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 water logging. 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 water logging 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. A single interceptor drain cannot intercept the upward seepage of groundwater: 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 water table, 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.

The bedded and graded systems may or may not have ridges and furrows.

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 relations between the various regular surface field drainage systems, the reduction in the degree of water logging, 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 tube wells) 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 (sub-soiling), provided that the underground has sufficient natural drainage. In other instances, a combination of sub-soiling 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".

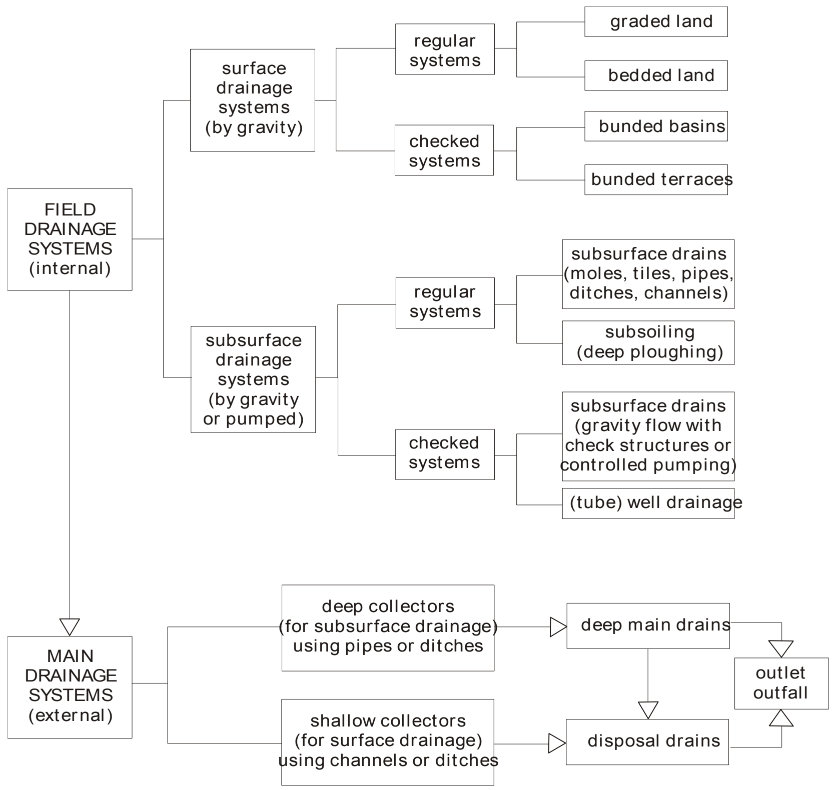



Figure 17.1 Classification of types of agricultural drainage systems

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 water logging occurs on the soil surface.

Subsurface drainage systems are used when the drainage problem is mainly that of shallow water tables. When both surface and subsurface water logging 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 tube wells 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 drainage systems 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 water logging;
- 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.

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; 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: 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.

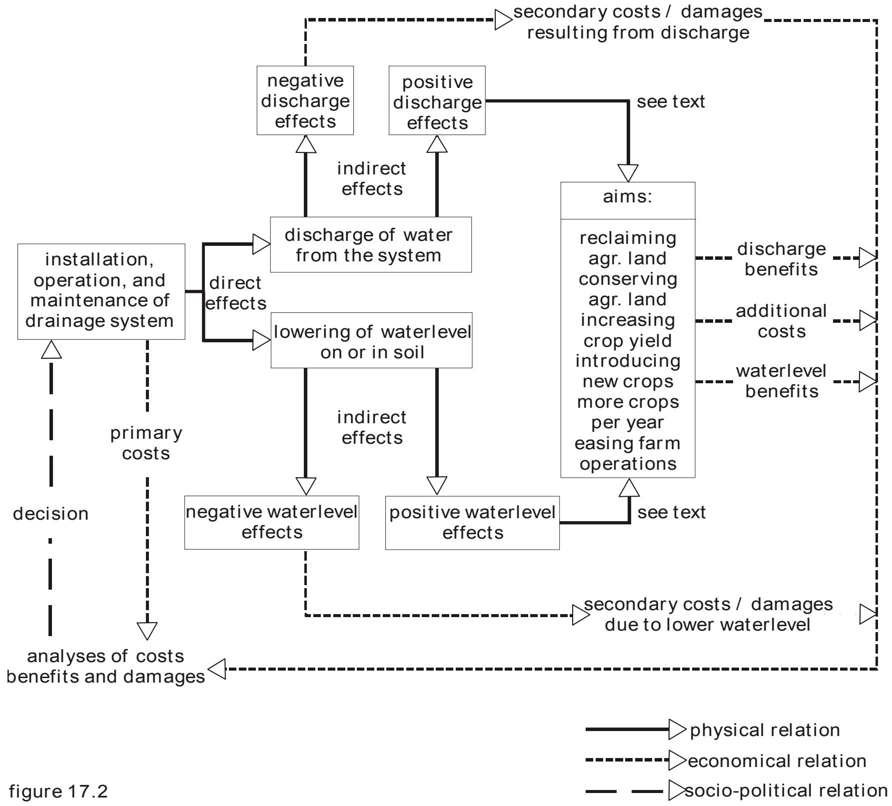



Figure 17.2 Diagram of the effects of drainage on agriculture and the economic evaluation

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 evapo-transpiration 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 optimisation, yielding "agricultural targets" (see the insert in Figure 17.3). Optimising is done with criterion factors, which are factors that are affected by the drainage system and at the same time influence the object factors.

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

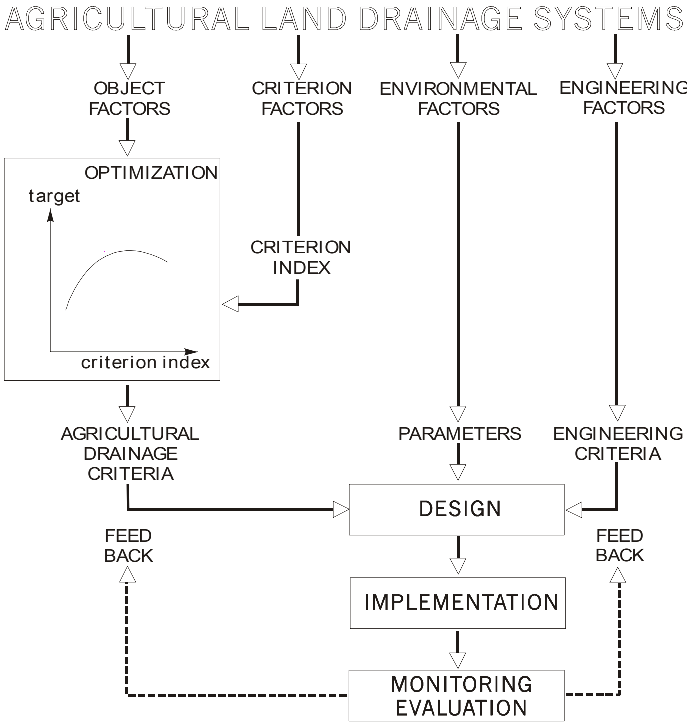



Figure 17.3 The role of agricultural, environmental, and engineering factors in the optimisation, design, and evaluation of drainage systems

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 water table during the cropping season;
- The average depth of the water table during the off-season;
- The exceedance frequency of the water table over a critically high level;
- Seasonal average salinity of the root zone;
- 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 optimisation 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 optimising 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.

Optimising 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 analysed 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 water table and a depth-to-water table 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. Nijland and El Guindy (1984) and Oosterbaan et al. (1990) give examples of such an analysis are given by

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 un-drained 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 Water table Indices for Drainage Design

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

The depth of the water table 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 water table in the soil fluctuates with time, as illustrated in Figure 17.4, the behaviour of the water table 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 water table has to be made.

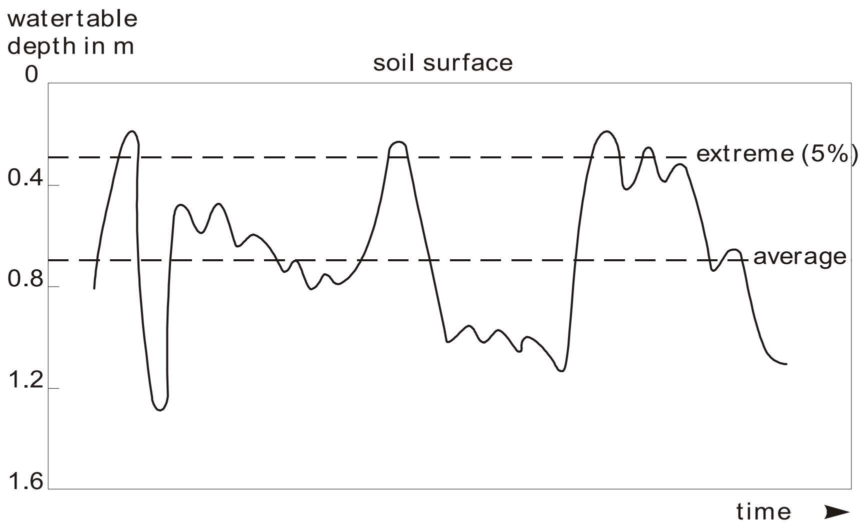



Figure 17.4 A fluctuating water table with an indication of the average depth and an infrequent shallow depth of the water table

Figure 17.5 shows a typical frequency distribution of the daily average depth of the water table. 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.

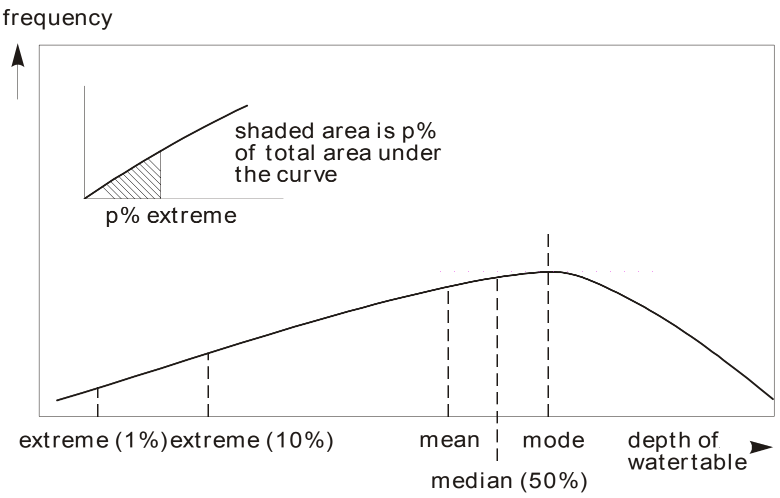



Figure 17.5 A frequency distribution of the daily average water table depths with some of its characteristic values

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 water table index, or whether short-term extreme values, even though they occur infrequently, need to be considered.

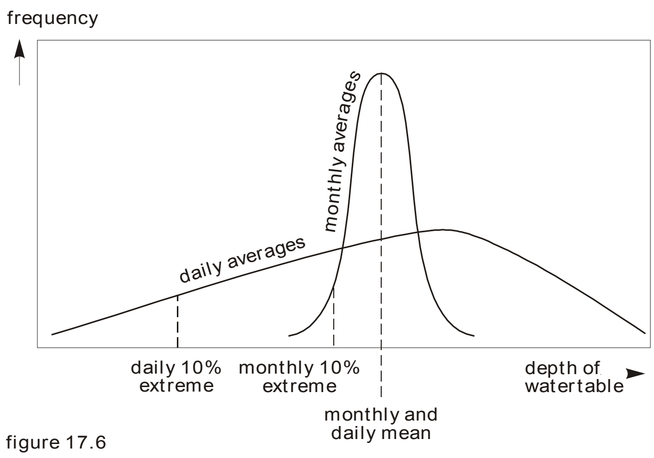



Figure 17.6 Frequency distributions of daily average and monthly average depths of the water table

Figure 17.7 shows the production of sugarcane as a function of the average depth of the water table during the growing season from December to June (indicated by circles), and the number of days during which the water table 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

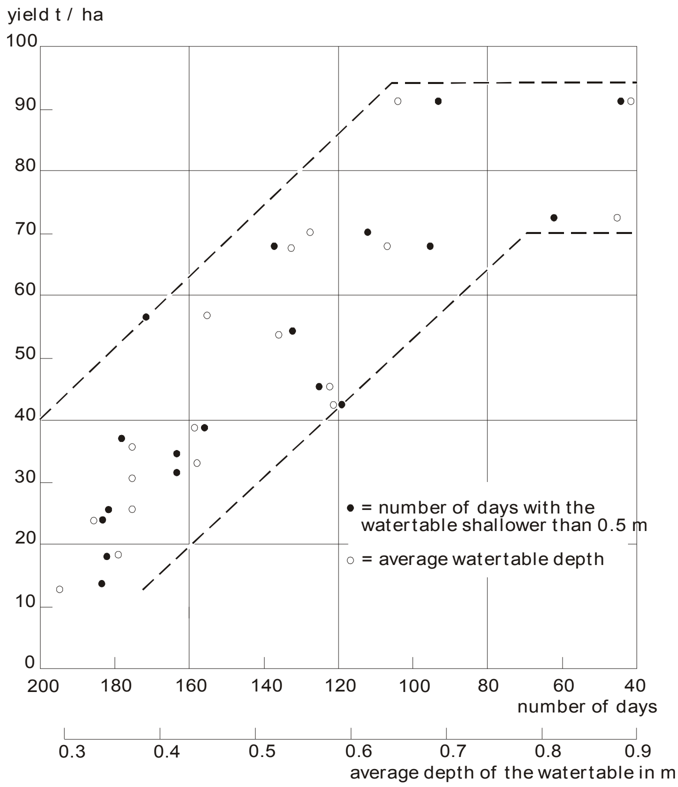



Figure 17.7 A plot of yield data of sugar cane versus average depth of the water table and number of days with a water table shallower than 0.5 m during the growing season from December to June in N. Queensland, Australia (Rudd and Chardon 1977)

additional explanation of variations in yield. In this example, it is better to use the long-term 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 water table 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 water table indices have been used:

1) The depth of the water table at harvest date (Oosterbaan 1982);
2) The average depth of the water table during a season with rainfall excess (Figures 17.7 and 17.8);
3) The average depth of the water table during the irrigation season (Figure 17.9; Nijland et al. 1984; Safwat Abdel-Dayem and Ritzema 1990);
4) The frequency or number of days during the growing season with a water table shallower than a certain reference level (Figure 17.7; Doty et al. 1975);
5) The Sum of the Exceedances ($SE_x$) of daily water tables 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 water table 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 water table regime. Nevertheless, literature does not provide much information on the value of this index and it will therefore not be further discussed.

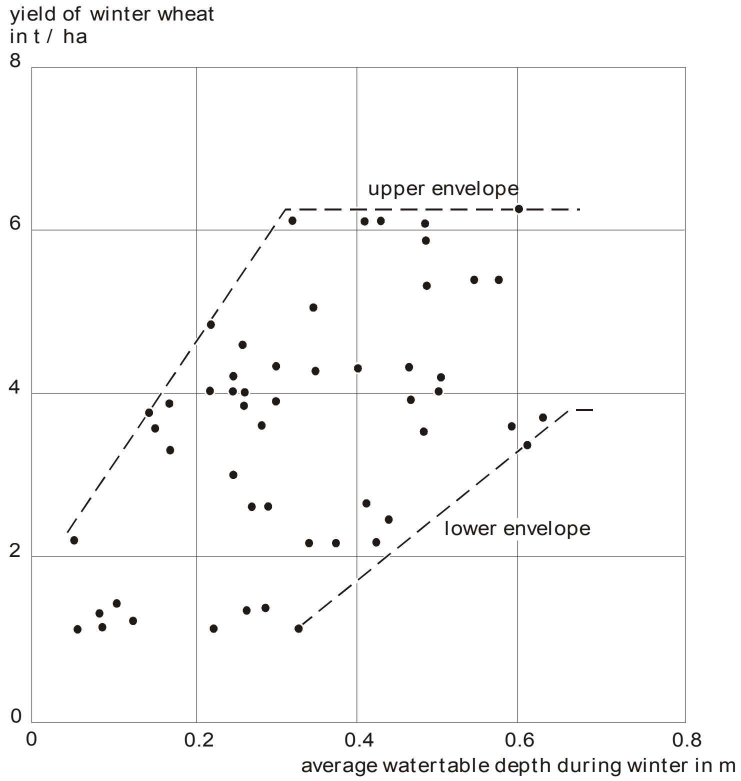



Figure 17.8 A plot of the yield of winter wheat versus average depth of the water table in winter in a heavy clay soil; 5 years of observation (unpublished data, FDEU, Min. Agr., U.K.)

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 water table 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, water logging in spring may create unfavourable chemical or physical soil conditions. In summer, there is usually no drainage problem in England because the evapo-transpiration is then much higher than in winter, and the water tables are therefore deep (> 1 m).

From the data of Figure 17.8, we can conclude that, if drainage could maintain the water table 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 water table 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 water table (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 water table depths. Further, the data show that the relationship between crop production and depth of the water table is subject to considerable scatter, which is logical because crop production is not determined exclusively by the depth of the water table 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 water table 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 water table depths of over 0.90 m (the safe depth). This indicates that the yield increase of a drainage project would be less than

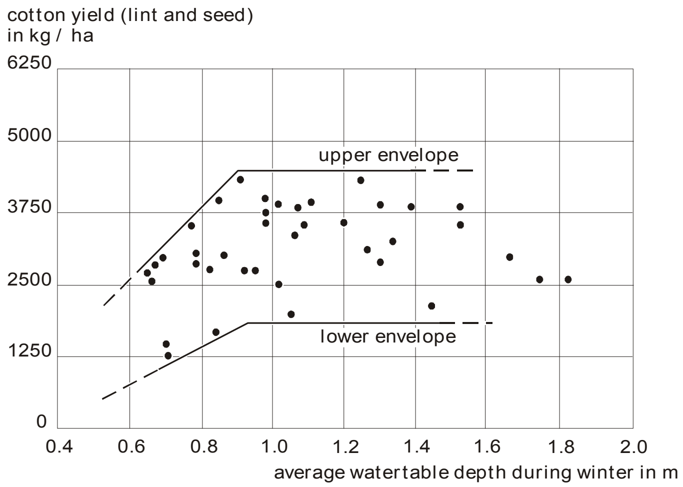



Figure 17.9 A plot of cotton yield (lint + seed) versus average depth of the water table in the Nile Delta, Egypt (Nijland et al. 1984)

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 water table 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 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 water table appear to be damaging.

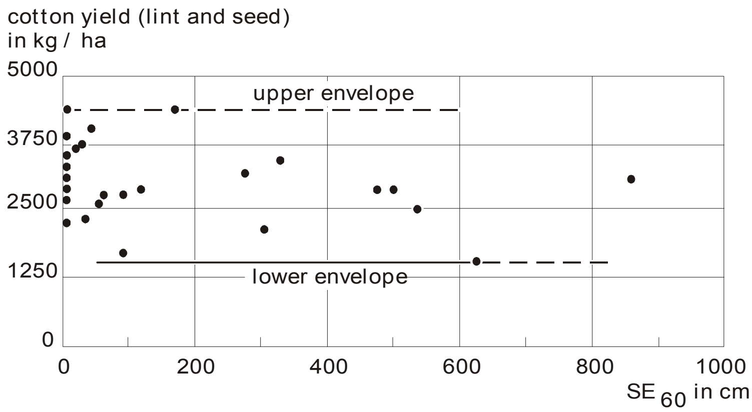



Figure 17.10 A plot of cotton yield (lint + seed) versus $SE_{60}$ in farmers' fields in the Nile Delta (Advisory Panel 1982)

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 draw down from the soil surface to a depth of 50 cm is about 75 hours or about 3 days. With a shorter draw down time (i.e. with a faster draw down rate), the number of workable days does not increase, and its maximum value is about 20 days a month. The drains placed at 75 cm depth show a less favourable workability response than the deeper drains.

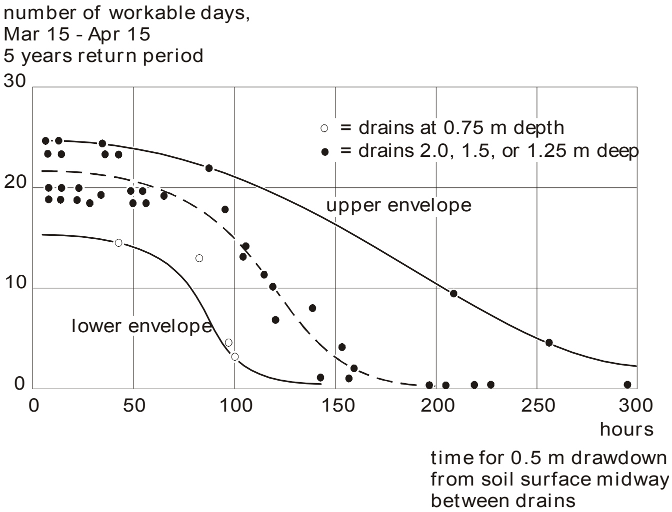



Figure 17.11 A plot of draw down time of the water table versus number of workable days for different drainage systems in North Carolina, U.S.A. (Skaggs 1980)

We can therefore conclude that the long-term average depth of the water table influences not only the crop production but also the workability of the land.

The draw down rate of the water table as a criterion index should be used with great care, because it does not specify how frequently the water table 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. depth and spacing of 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

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

where:

$q_d$ = drain discharge (mm/d)
$R_d$ = net recharge rate (mm/d)
$\mu$ = drainable pore space (-)
$\Delta h$ = change in water table depth (m)
$\Delta t$ = period (d)

The term $R_d$ includes percolation, capillary rise, and groundwater inflow and outflow. In a steady-state situation, the net recharge rate ($R_d$) equals the drain discharge ($q_d$) and the water table is at the same level at the beginning and the end of the period ($\Delta t$) under consideration.

In unsteady-state, recharge and discharge are not equal. When $R_d > q_d$, the water table 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 water table 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 water table 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 water table 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 water table can also give a significant explanation of such object factors as the workability of the land and the subsidence of peat soil (Chapter 4, Section 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 water table 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 water table 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 water logging by drainage creates a potential for the 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 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 water table to a great depth (5 to 10 m), create a large buffer capacity. For these systems, the seasonal or yearly average depth of the water table 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 can 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. water logging 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 water logging 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.

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

### 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 water table. 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 water table.

With a well-designed and properly-operated irrigation system, the water table need not be kept at extra deep levels to control soil salinity. If, on the other hand, the irrigation system is poorly designed and operated, even maintaining very deep water tables 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 water table in the range of 1.0 to 1.2 m are amply sufficient for effective salinity control, whereas maintaining deeper water tables may even negatively affect the irrigation efficiency. Also Rao et al. (1990) have shown that the time-averaged depth of the water table 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 water table for salinity control to the upward capillary flow in the soil resulting from a constant depth of the water table 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 water table 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 water table 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 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 low field irrigation efficiency.

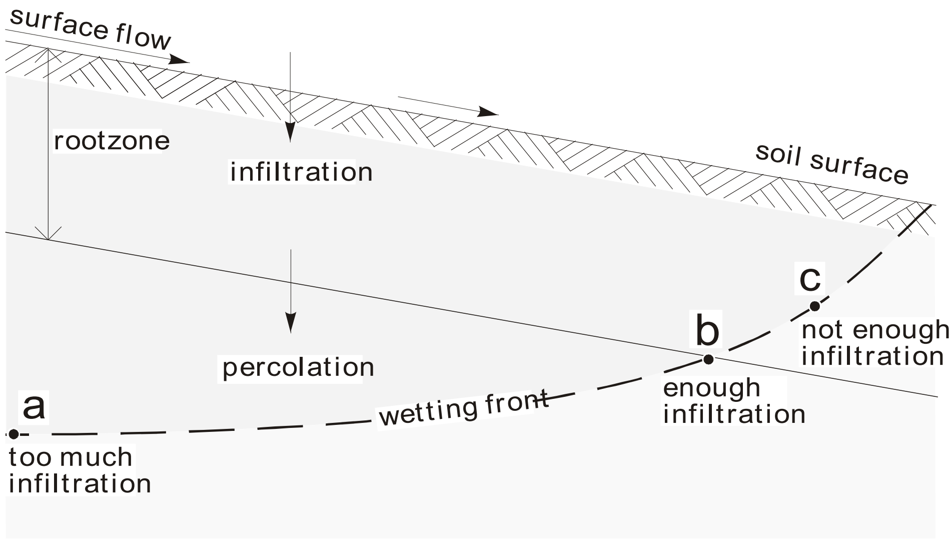



Figure 17.12 Illustration of the systematic irregularity in the spatial distribution of the deep percolation in an irrigated field

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.

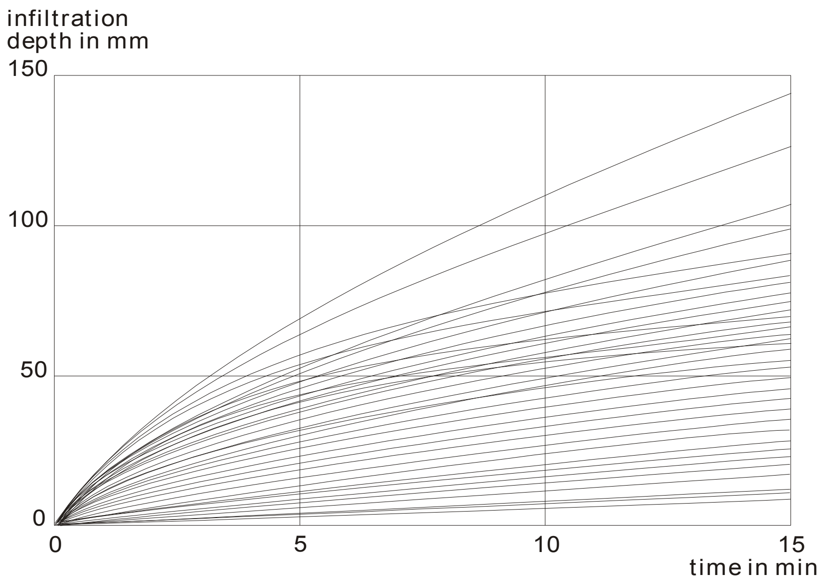
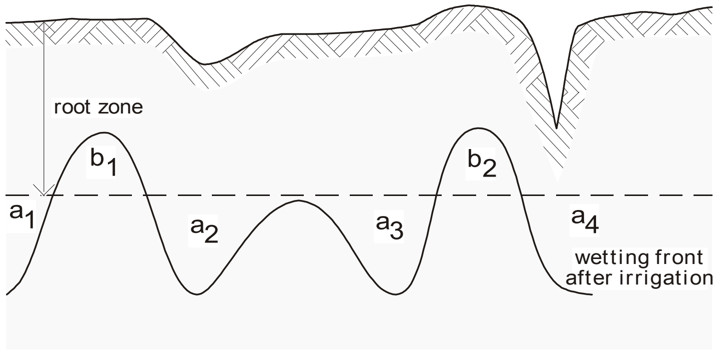



Figure 17.13 Accumulated infiltration versus time measured with 63 infiltrometers set at 1.0 m spacing on a 7 by 9 m grid in a sandy loam soil (Jaynes et al. 1988)




$a_1$ 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

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.

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 water table 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 water table 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 water table 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 water table 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 water table 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 water table 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 water table has reached a specified critical height ($h_o$) above drain level, the drainage system should be able to effect a specified draw down of the water table 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 are related. Otherwise, one runs the risk of applying the criteria to situations that occur far too often or that never occur.

## 17.4 Effects of Field Drainage Systems on Agriculture

### 17.4.1 Field Drainage Systems and Crop Production

To obtain a quantitative insight into the effects of drainage on agriculture, one can do experiments with varying drainage designs and measure the corresponding crop production. This straightforward procedure is illustrated in Figure 17.15. The engineering factors mentioned in the figure depend on the type of drainage system involved (Section 17.3.2). Some of the engineering factors are specified in Table 17.2.

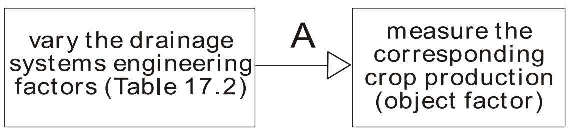



Figure 17.15 Illustration of a straightforward method of analysis of drainage effects on agriculture

Table 17.2 Examples of engineering factors by type of drainage system

| Type of drainage system | Engineering factor |
|---|---|
| Subsurface drainage system | Depth, spacing, and dimensions of ditches or pipe drains |
| Tubewell drainage system | Depth, spacing, and dimensions of wells, pump capacity |
| Surface drainage system | Length and slope of the fields, dimensions of furrows and bedding |
| Main drainage system | Depth, width, cross-section, and slope of drains, spacing of the network |

The effect of the engineering factors can be studied step by step (e.g. by using a range of drain spacings as shown in Figure 17.16), or by simply considering the "with and without" case (e.g. by comparing the crop production in drained and un-drained land as shown in Table 17.3).

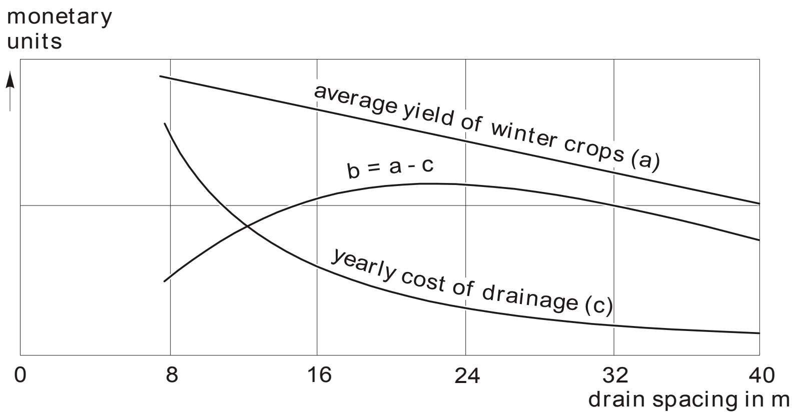



Figure 17.16 Example of Relation A of Figure 17.15 showing net benefit (b) of winter crops as a function of drain spacing in a 60% clay soil in Sweden (Eriksson 1979)

Table 17.3 Annual maize production (t/ha) with and without field drainage systems and different doses of N-fertilizer (Schwab et al. 1966)

| Type of drainage system | N fertilizer (kg/ha) | | |
|---|---|---|---|
| | 0 | 100 | 200 |
| Subsurface field drainage system | 3.7 | 5.9 | 7.0 |
| Surface field drainage system | 3.5 | 5.1 | 6.2 |
| Without field drainage system | 2.5 | 3.0 | 4.0 |

Many data of the with/without comparison have been published by Trafford (1972), Baily (1979), and Irwin (1981). The first author reviewed data from literature and also quotes cases of unsuccessful drainage systems. Found et al. (1976) studied the economic impact of several drainage systems in Ontario, Canada. Some of their conclusions are:

- The benefit/cost (B/C) ratios of drains varied from 0.1 to 20, which indicates that some of the systems are uneconomical and other systems are highly beneficial;
- Influential factors on the B/C ratio were:
  - The productivity of the environment: poor soils and adverse climatic conditions decreased B/C ratios;
  - Local initiative to take advantage of the drainage facilities: some farmers did not make the necessary additional investments;
  - Quality of engineering: some drains were too elaborate and costly for their purpose;
- Despite its significance, little analysis of the full effects of drainage systems has been undertaken.

When the relationship between engineering factors and crop production (Relation A in Figure 17.15) is established in a certain area, it has no validity for application elsewhere, because it depends on the area's pedological, climatic, hydrological, topographic, agronomic, and socio-economic conditions. A more universal applicability of experiences can be promoted by introducing additional factors into Relation A. In Figure 17.17, for example, the water table regime is used as an additional intermediate factor, so that Relation A is divided into Relations B and C.

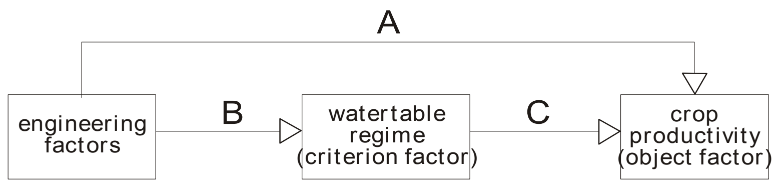



Figure 17.17 Relation A of Figure 17.15 is divided into Relations B and C by means of the water table regime

Relation B represents a direct effect of a drainage system (Section 17.3.1, Figure 17.2). It is entirely a hydraulic function and lends itself to the development of generalized drainage formulas (Chapter 8). These formulas have more than local value because they include parameters to represent natural conditions like recharge and hydraulic conductivity. A difficulty is still to survey and correctly assess these parameters, because of their wide variation in time and space (Chapters 12 and 16).

Relation C represents an indirect effect of a drainage system and has already been discussed in Section 17.3.3. This relationship is very site- specific and is therefore not universally applicable. A more universal applicability can be obtained by dividing Relation C into other relationships with the help of the proper additional factors (Section 17.4.3). This, however, leads to complicated interactions and therefore constrains practical application. Hence, the establishment of empirical relationships of the C-type remains a necessity in any region where a drainage project is proposed.

Implementing and operating a drainage system can have far-reaching effects, not only on the crop production but also on the total cropping system of an area. This is illustrated in Figure 17.18, which shows profound changes in the cropping pattern in England and Wales after drainage systems had been introduced.

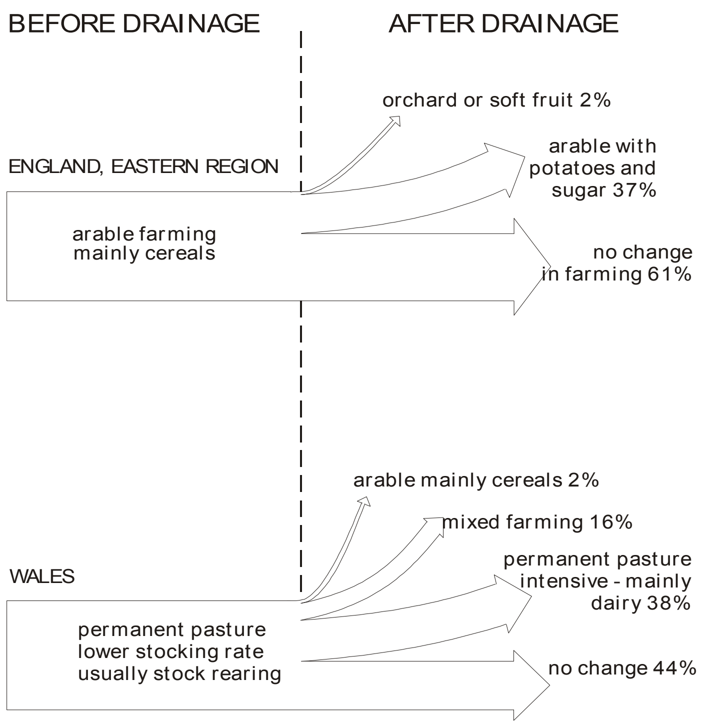



Figure 17.18 Changes in cropping pattern as a result of drainage (FDEU 1972)

## 17.4.2 Water table and Crop Production

The use of the water table as an index for crop production was explained in Section 17.3.3. In this section, some additional data are given on Relation C (Section 17.4.1) between crop production and the water table regime.

Figure 17.19 shows the relationship between the yield of wheat in farmers' fields in the Nile Delta and the average depth of the water table during the growing season for wheat (i.e. winter). The figure reveals that in most fields the average depth was more than 0.5 m, and no clear relationship with the yield can be detected. This indicates that the fields did not suffer from serious drainage problems and that the critical depth (i.e. the minimum permissible depth) of the water table is 0.5 m or less. There are insufficient data on a water table depth of less than 0.5 m to determine the value of the critical depth accurately, but it can be concluded that the lowest crop yields observed are not due to a shallow water table but to other, unfavourable, agricultural conditions.

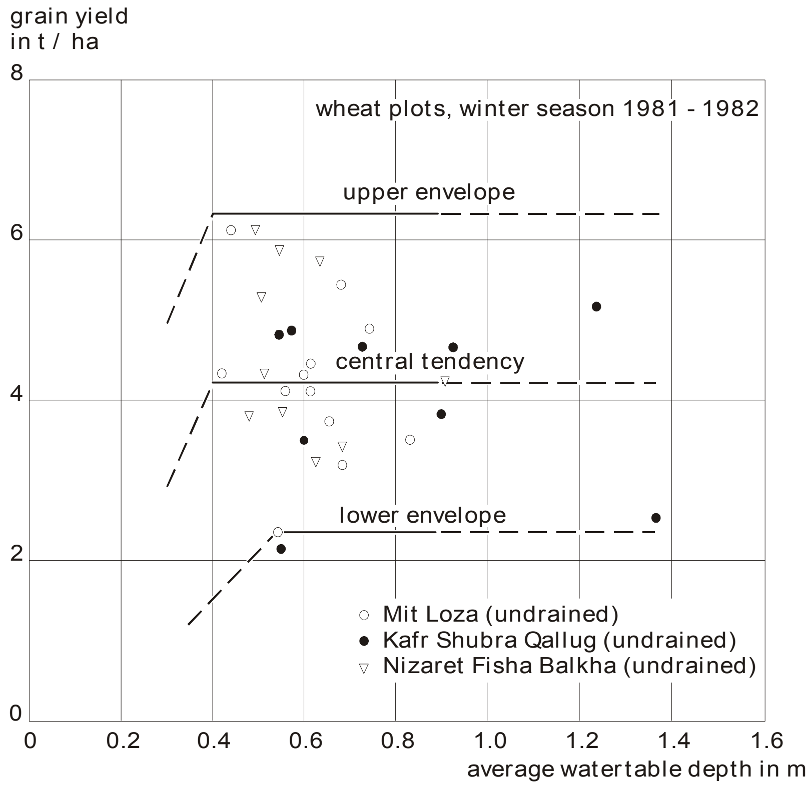



Figure 17.19 A plot of data on the yield of wheat in farmers' fields and the average seasonal depth of the water table in the Nile Delta, Egypt (Advisory Panel 1982)

Figure 17.20 shows similar yield data for wheat (a winter crop) and for maize and cotton (summer crops) in the drained Mashtul Pilot Area in the Nile Delta. It appears that the area is adequately drained, because no clear relationship can be detected between the average depth of the water table and the yields, and all seasonal average depths of the water table were deeper than 0.5 m. Some fields in the pilot area were even excessively drained (i.e. the water table is much deeper than required). As in Figure 17.19, the critical value of the water table for the crops investigated in Figure 17.20 cannot be determined accurately because of the lack of data on very shallow water tables. Anyway, it is likely that depths of 0.6 to 0.7 m are safe for all three crops.

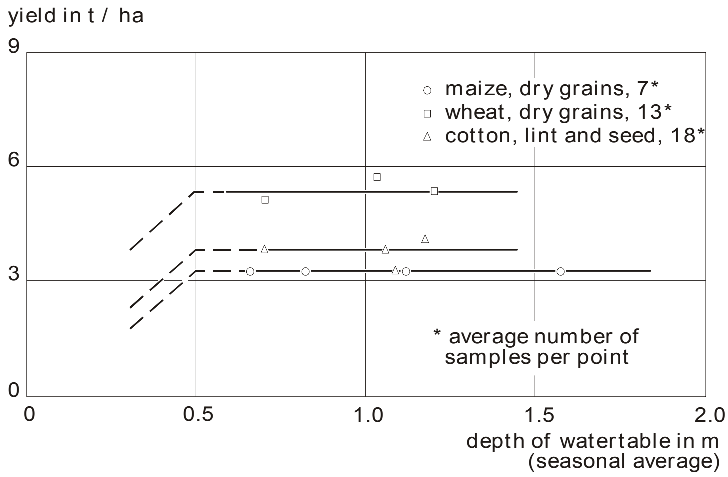



Figure 17.20 The yield of some irrigated crops versus seasonal average depth of the water table. Data from the Mashtul Pilot Area in the Nile Delta, Egypt (Safwat Abdel-Dayem and Ritzema 1990)

Figure 17.21 shows the relationship between banana yield, plantation age, and average depth of the water table in Surinam. For all ages, a depth of 0.8 m is a safe depth. The banana production is severely reduced at depths of 0.7 m or less. The lowest yields were obtained on plantations that were seven years old.

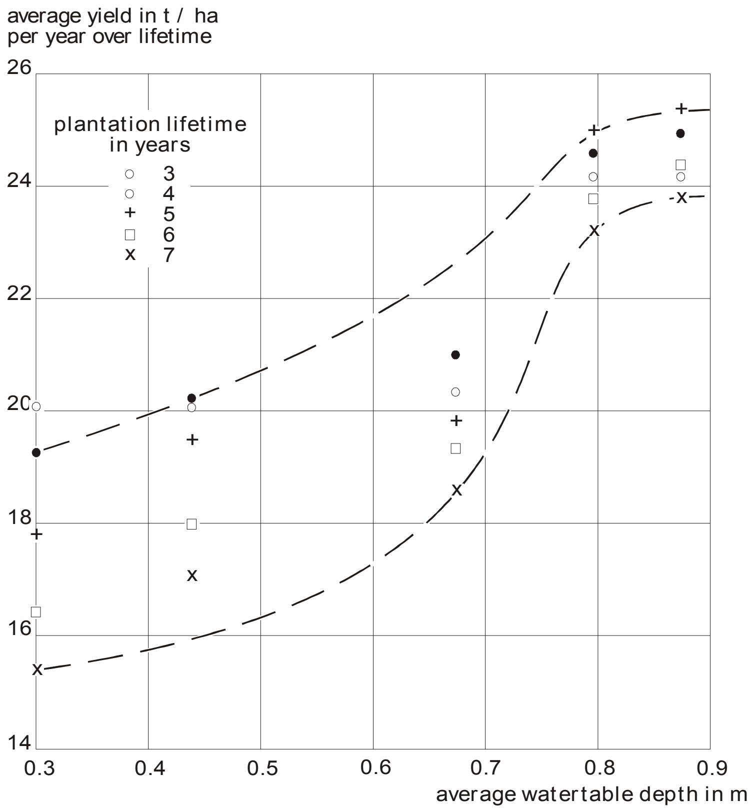



Figure 17.21 Relation between banana yield, plantation age, and average depth of the water table in Surinam (Lenselink 1972)

Table 17.4 shows the relative yields of potatoes, onions, maize, and carrots in dependence of the depth of the water table in a muck soil. A depth of 0.6 m is safe for all four crops, although potatoes and carrots perform slightly better when the depth is 0.8 m or more. The yield of onions even decreases at depths of more than 0.8 m. This effect is probably related to the quality of the muck soil.

Table 17.4 Relative yields (in %) of crops with different depths of the water table in a muck soil (Harris et al. 1962)

| Crop | Number of years | Depth of water table (m) | | | |
|---|---|---|---|---|---|
| | | 0.4 | 0.6 | 0.8 | 1.0 |
| Potatoes | 12 | 46 | 94 | 97 | 100 |
| Onion | 11 | 63 | 109 | 113 | 100 |
| Sweet corn | 4 | 61 | 100 | 92 | 100 |
| Carrots | 4 | 59 | 93 | 96 | 100 |
| Average | | 63 | 98 | 100 | 100 |

Figure 17.22 gives the expected production of a high-yielding dwarf rice variety in relation to the average depth of the standing water layer on the soil. It appears that a depth between 0 and 0.1 m guarantees maximum possible yields. Depths of more than 0.15 m lead to severe yield reductions. Nevertheless, there are many sturdy rice varieties that can withstand much higher depths.

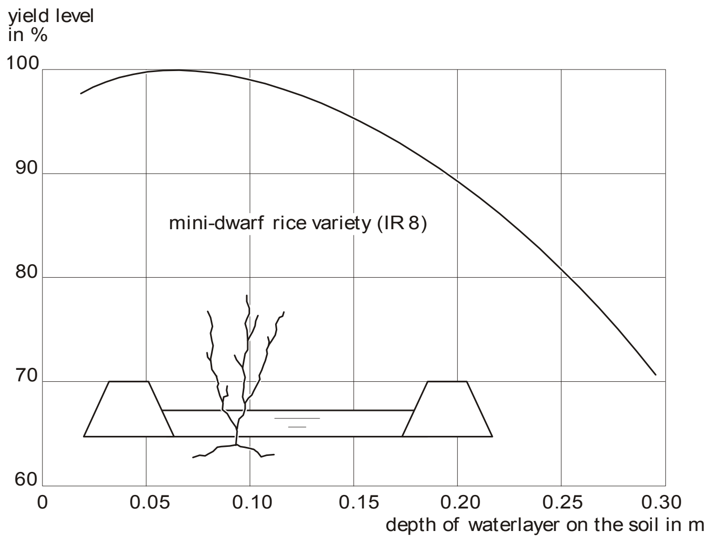



Figure 17.22 Production of a dwarf rice variety as a function of the depth of the standing water layer on the soil surface (personal communication from K.J. Lenselink and J. de Wolf, ILRI, Wageningen, The Netherlands)

Figure 17.23 shows that, in farmers' rice fields in the Nile Delta, the average seasonal depth of the standing water layer on the fields ranges between 0 and 0.1 m, and that within this range the yield is independent of the depth: there are no drainage problems.

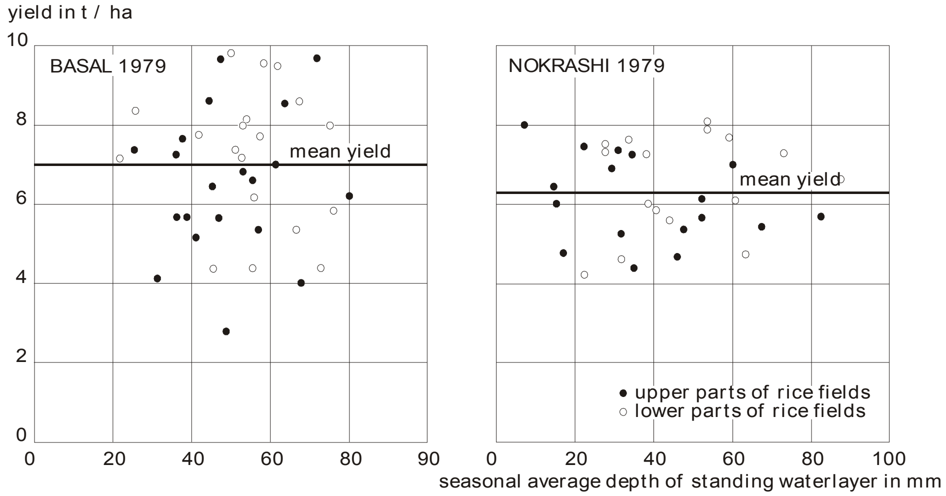



Figure 17.23 A plot of rice yields in farmers' fields versus seasonal average depth of the standing water layer on the soil surface in the Nile Delta, Egypt (Nijland and El Guindy 1986)

## 17.4.3 Water table and Soil Conditions

To enable a wider application of the relationship between the depth of the water table and the agricultural effects, we can separate Relation C, discussed in the previous paragraphs, into Relations D and E, using the soil-related growth factors of the plants as intermediate factors (Figure 17.24). These factors can be distinguished in soil physical, chemical, biological, and hydrological factors, which are highly interactive (Figure 17.25).

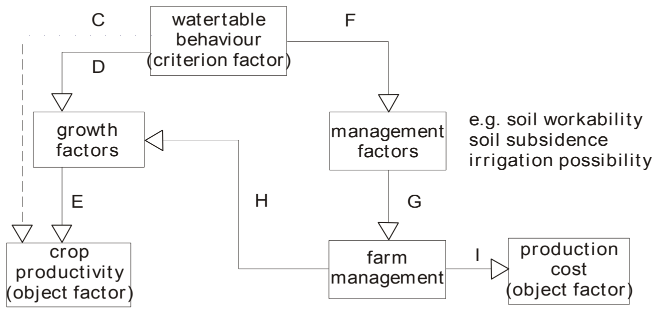



Figure 17.24 A further breakdown of Relation C of Figure 17.15 into Relations D, E, F, G, H, and J, using soil related growth and management factors

Figure 17.24 shows a separation using the soil-related farm-management factors as intermediates (Relations F and G). The management factors have an influence on the farm management (depending on the farmer's response), which again exerts an influence on the growth factors (Relation H), but also on the cost and effort put into crop production (Relation I). All this may result in a profound change in the cropping system after the introduction of drainage systems, as was illustrated in Figure 17.18.

A disadvantage of the drainage-response model of Figures 17.24 and 17.25 is its complexity, the usual lack of data, and the difficulty of collecting the necessary information to make it functional. In drainage design, therefore, one usually has to depend on empirically obtained relationships of the C-type. Nevertheless, an insight into the soil-related growth and management factors is important, and for this reason some examples will be discussed below.

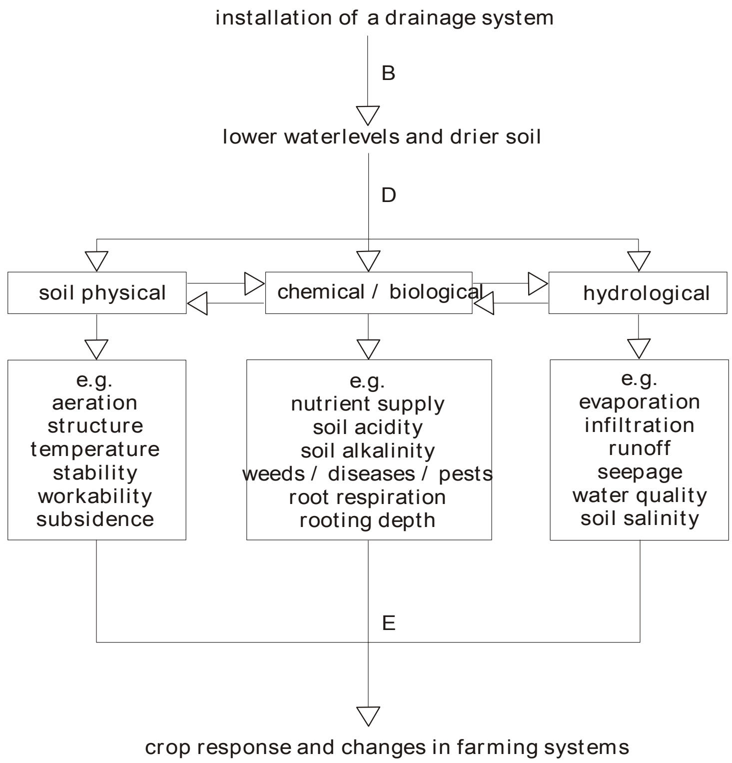



Figure 17.25 Soil physical, chemical/biological, and hydrological interactions in Relations D and F of Figure 17.24

**Soil Structure**

A good soil structure favours the simultaneous aeration and storage of soil water, reduces impedance to root growth, and provides stable traction for farm implements. A drainage system affects the soil structure through its influence on the water table (Relation E; Figures 17.24 and 17.25). Figure 17.26 shows the influence of groundwater depth on pore volume % for two pore-size classes (< 30 micron and > 30 micron). As can be seen, the percentage of large pores increases with increasing depth of the water table. As a result, when the depth of the water table increases from 0.4 m to 1.0 m, the hydraulic conductivity of the soil layer between 0.5 and 0.9 m depth increases from 0.35 m/d to 2.5 m/d (Van Hoorn 1958). It appears that maintaining the water table at a depth greater than 0.4 m exerts a beneficial influence on soil structure and structurally-determined soil properties.

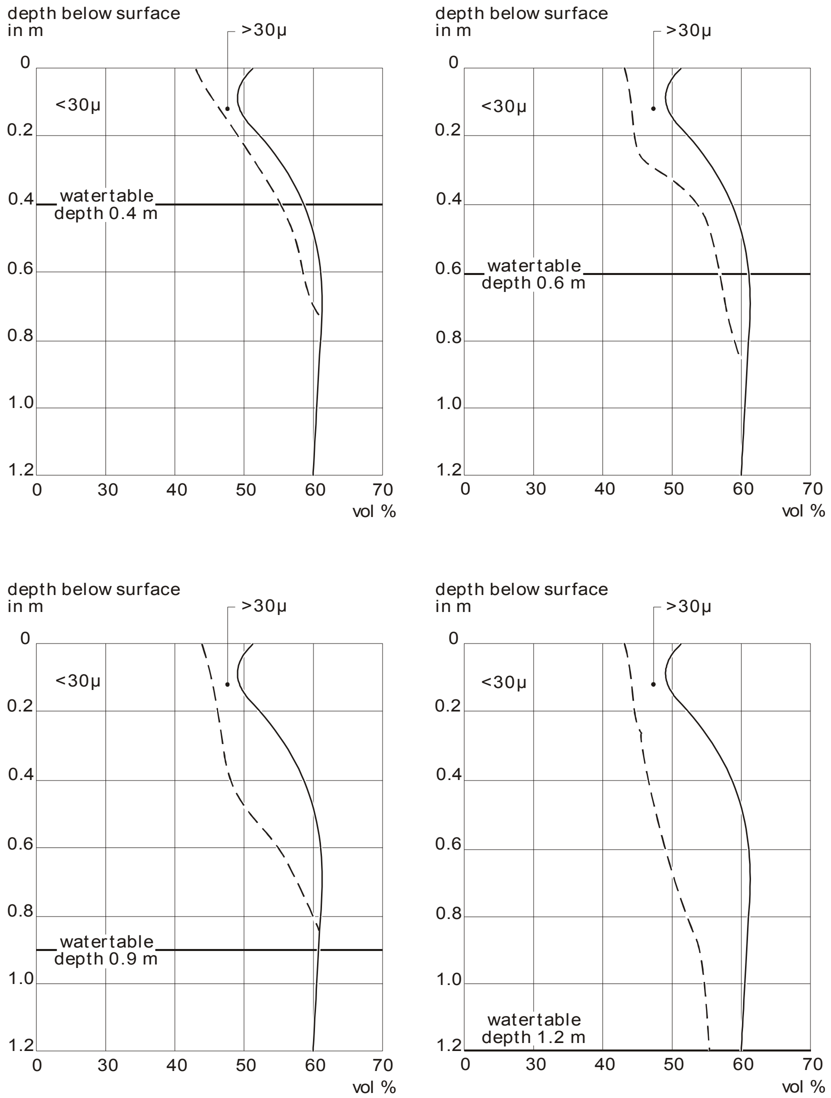



Figure 17.26 Influence of groundwater depth on water and air content, and pore-size distribution (van Hoorn 1958)

**Soil Temperature**

The reduced water content and the increased air content brought about by a drainage system result in a lowering of the specific heat of the soil, because water requires five times more heat to raise its temperature than dry soil. Consequently, waterlogged soil with about 50% moisture requires 3 times more heat to warm up than dry soil. In addition, the cooling effect of the greater evaporation from a wet soil delays a temperature rise. In temperate climates, both these effects cause a delay of growth in spring. In general, it can be stated that the temperature of the soil surface is favourably changed by a drainage system, which will promote early planting in spring in areas with cold winters, which in turn leads to a yield increase. This chain of reactions gives a good example of the interactions existing between Relations F, G, H, and I in Figures 17.24 and 17.25. Wesseling (1974) and Feddes (1971) have reviewed the influence of drainage systems on temperature and of temperature on plant growth.

Sometimes, wet soils have a favourable effect. In hot climates, for example, a wet soil prevents an excessive rise in soil temperature during the day, so that a lower, more favourable soil temperature is maintained. In climates with an occasional night frost during the growing season, wet soils are able to release more heat than dry soil and thus maintain a higher night temperature. In fields with a water table deeper than 1.0 m, Harris et al. (1962) reported a 50% stand reduction of maize, potatoes, and peppermint due to a frost in June, whereas no damage was observed in fields with a water table at 0.4 m depth. This example shows that excessive drainage criteria should be avoided.

**Soil Workability and Bearing Capacity**
With an adequate drainage system, the average water content of the topsoil, even in humid areas, will seldom rise above field capacity. This is important, because there is a narrow range of soil-water contents for tillage operations, which for most soils is below field capacity. Working the soil at higher water contents gives rise to mechanical difficulties and destroys the soil structure, especially in clayey soils. Such a deteriorated soil can be very hard when dry, and as a result of compaction (plough-sole, tractor-sole, or traffic layer) and crust formation, both the infiltration and hydraulic conductivity are low.

In grazed grasslands, the bearing capacity of the soil and its resistance to puddling (trampling) by the hoofs of cattle can be favourably influenced by a drainage system (Berryman 1975).

In Chapter 11, the equilibrium relationship between soil-water content and water table depth was discussed, including hysteresis. It is not always easy to find such a relationship under field conditions. An example of the scatter in the relationship between the soil-water content and the depth of the water table is shown in Figure 17.27. Still, the figure shows the expected trend that the average water content of the soil at 0.15 m depth is considerably less with deeper water tables than with shallow ones. On the other hand, a deep water table and an intensive subsurface drainage system are no absolute guarantees of a soil-water content below field capacity, especially not on rainy days.

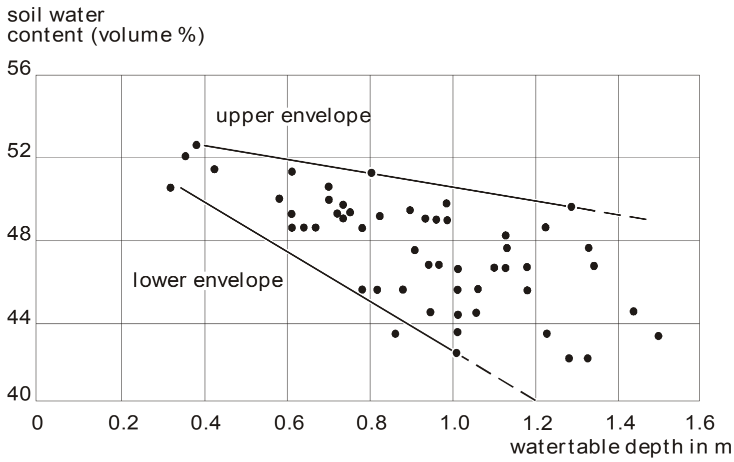



Figure 17.27 Relation between soil water content at 0.15 m depth and water table depth in a silt loam soil in S. Carolina, U.S.A., from January through May 1970 (Young and Ligon 1972)

For a silt loam soil in The Netherlands, Figure 17.28 presents an example of the relationship between the percentage of workable days in April, the drainage intensity (q/h ratio), and the average depth of the water table. The figure shows that the average depth of the water table exerts a great influence on the number of workable days (Relation F in Figure 17.24). The influence of the q/h ratio is much smaller. In fact, the calculations were made only up to water table depths of 1.3 m, so that the maximum number of workable days cannot be determined.

Other examples have been presented by Nolte et al. (1982).

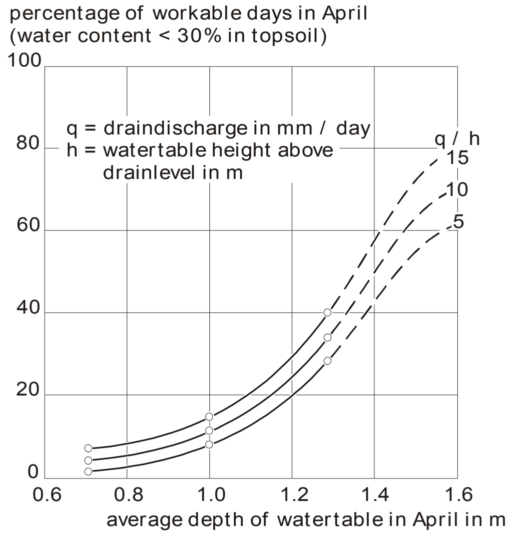



Figure 17.28 Drainage and workability of a silt loam soil under Dutch climatic conditions. Data obtained with a simulation model covering a period of 35 years (adapted from Wind and Buitendijk 1979)

**Soil Subsidence**

Newly reclaimed wetland clay soils will subside when drainage is introduced. These soils, which are originally supersaturated with water, subside because of the loss of water (Chapter 13). Any soil will subside if the water table is pumped down to several tens of metres (Todd 1980). Such pumping is not generally done for drainage, however, but for water supplies, and is therefore not further discussed here.

Drained peat soils subside for two reasons. The first is physical, because the soils shrink with the loss of water. The second is chemical, because the organic matter oxidizes and decomposes. Figure 17.29 illustrates the shrinkage of peat soils in The Netherlands as a function of seasonal average depth of the water table. When the shrinkage is used as an object factor, this average depth can also be used as a drainage criterion.

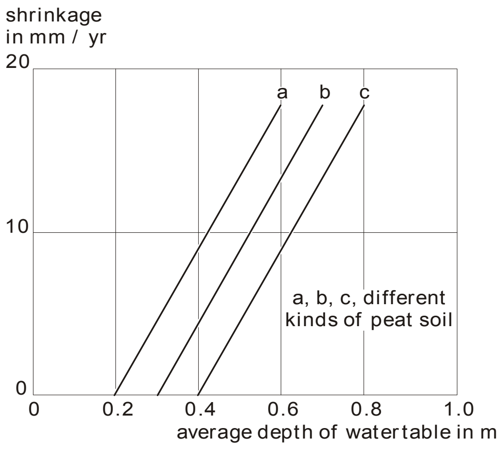



Figure 17.29 Subsidence of peat soils in The Netherlands as a function of average water table depth (Schothorst 1978)

Irrigated gypsiferous soils can also subside. When irrigation water is applied to them, the gypsum in the soil dissolves and is removed by natural or artificial drainage (van Alphen and de los Rios 1971).

**Nutrient Supply from the Soil**

Various processes activated by bacteria, fungi, and other micro- and macro- organisms in the soil depend on the aeration and the drainage status of the soil. Minessy et al. (1971) have shown that the uptake of mineral nutrients (N, P, K, Ca, Mg) by orange and mandarin trees in Egypt increases with increasing depth of the water table. Yamada (1965) reported that the continuous flooding of rice fields causes a chemical reduction of the soil and an accumulation of toxic products like hydrogen sulphide ($H_2S$). An occasional drainage of water from the fields results in a favourable oxidation of the harmful substances.

Nitrogen (N) fixation and nitrification by micro-organisms are other examples of aerobic processes that are influenced by the soil moisture content and exert an important influence on plant growth. Van Hoorn (1958) found that, when the average depth of the water table is 0.6 m, the soil releases only 60 kg N per ha per year, but, when this depth is 1.2 m, it releases 120 kg per N ha per year. Thus, when the depth of the water table is 0.6 m, and an amount of 60 kg N per ha is applied in the form of a nitrogen fertilizer, the yields will be comparable in both cases. Apparently, certain agricultural practices can compensate for the effects of poor drainage conditions, as was already mentioned in Section 17.3.3 (Figure 17.8).

In confirmation, Figure 17.30 shows the combined influence of N-fertilization and average depth of the water table on grassland in peat soil in The Netherlands. With shallow water tables, a high N-dose has a considerable effect on the yield, but when the water table is at 0.5 m or more, the effect vanishes. Also in Table 17.3 (Section 17.4.1) it is seen that an N-dose in un-drained fields leads to similar yields as in drained fields without fertilizer application. However, contrary to the tendency shown in Figure 17.30, the data of Table 17.3 show that the effect of fertilizing is large in the well-drained fields. The effect of fertilizer on crop production in relation to the drainage status of the soil is apparently dependent on local conditions. This also holds for the quality of the produce.

Shalhevet and Zwerman (1962), conducting experiments with a maize crop, proved that the N-fertilizer could best be given in the form of nitrates when the water table is shallow and as ammonia when the water table is deep. Nitrate is more mobile than ammonia, however, and may therefore be easily leached by the drainage water and cause excessive nitrification of the water in the main drains (Bolton et al. 1970).

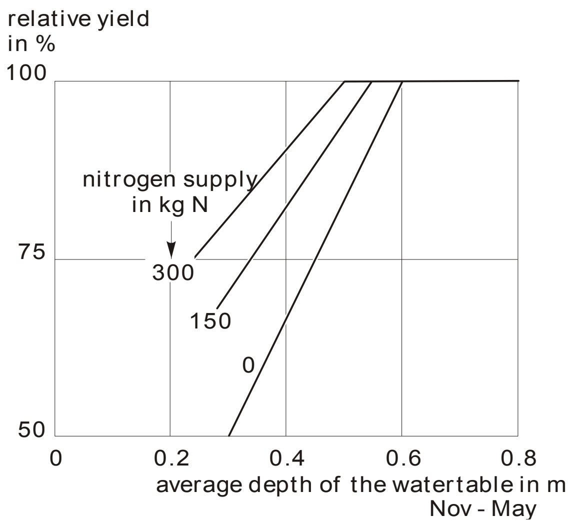



Figure 17.30 Nitrogen supply, average depth of water table, and yield of grassland in The Netherlands (Feddes and van Wijk 1977)

**Soil Sodicity**

Sodic soils containing $CaCO_3$ can be reclaimed by incorporating acidifying materials in the soil, either through organic matter or a reclamation crop. (Many grasses serve this purpose.) The acids dissolve the precipitated $CaCO_3$. Subsequently, the excess $Na^+$ needs to be leached. If necessary, gypsum or sulphur compounds can also be added. The $Ca^{2+}$ in the gypsum displaces $Na^+$ from the exchange complex, and the sulphur reacts with oxygen from the air and water in the soil to form sulphuric acid. If the natural drainage is insufficient for the necessary leaching, an artificial drainage system may have to be installed.

**Soil Acidity**
Soil acidity is related either to organic-matter production and natural leaching of the soil, or to the presence of acidifying minerals in the soil.

If the acidity is due to the first cause, ferralitic soils may be formed. These soils are not the primary concern of the drainage engineer, because they are associated with excessive natural drainage.

If the acidity is related to the second cause, we are dealing with "potential acid sulphate soils" or "cat clays" (Chapter 3). If they are drained, either by natural causes or by artificial drainage, the resultant oxidation and hydrolysis of the acidifying minerals produces sulphuric acid and iron oxides. The pH of these "actual acid sulphate soils" is below 4 and, after a long time of leaching, their properties become similar to those of the ferralitic soils discussed above ("para-acid sulphate soils"). There are examples of relatively successful reclamations of these soils by farmers, done with time and patience, but large-scale interferences often lead to disaster.

**Soil Salinity**
Saline soils form chiefly under conditions of permanent or recurrent water logging (Chapter 3). Crop production on saline waterlogged soils is seldom rewarding. Artificial drainage may solve the salinity problems, as was discussed in Section 17.3.6 and Chapter 15.

### 17.4.4 Summary
The development of agricultural drainage criteria is an inter-disciplinary science. Before drainage criteria are developed in any drainage project, the following aspects have to be considered:
- Pedology and agriculture (chemical/physical/biological soil conditions; crop production; farm operations; irrigation);
- Hydrology and geology (surface and subsurface water balances; river and aquifer conditions);
- Hydraulics (flow of water under the influence of hydraulic gradients and resistances or conductivities);
- Technology (presence or absence of labour and machinery;, quality of materials and maintenance);
- Socio-economy (farmers' organizations; farmers' attitudes; rural laws; distribution of benefits and costs; compensations);
- Environment (natural resources; ecology; side-effects).

Hence, establishing agricultural, technical, and environmental criteria for land drainage systems needs a careful approach and should not be done merely from handbooks. Because of the large variation in local conditions, the introduction of land drainage systems ought to be done by combining theoretical insight with local experience. Otherwise, the drainage project may be either too costly or non-beneficial, if not damaging.

## 17.5 Examples of Agricultural Drainage Criteria

### 17.5.1 Rain-Fed Lands in a Temperate Humid Zone

How drainage criteria are used for the design of drainage systems in rain-fed lands in temperate humid zones will be exemplified with design particulars for field and collector drainage systems in The Netherlands.

**Example 17.1 Field Drainage Systems in The Netherlands**
The water balance of field drainage systems in many parts of The Netherlands can be written in the simple form, neglecting groundwater flow components

$$Dr = q_d \Delta t = P - E - \Delta W \qquad (17.2)$$

where:

| | | |
|---|---|---|
| Dr | = | drainage (mm) |
| $q_d$ | = | drainage rate (mm/d) |
| $\Delta t$ | = | period (d) |
| P | = | precipitation (mm) |
| E | = | evapo-transpiration (mm) |
| $\Delta W$ | = | water storage (mm) |

Figure 17.31 presents the monthly balances of rainfall (P) and evapo-transpiration (E) in The Netherlands. It shows that, in summer, the evapo-transpiration exceeds rainfall, so that, according to Equation 17.2, no drainage is required ($q_d = 0$), except in areas with a strong upward seepage of groundwater. In winter, the rainfall exceeds the evapo-transpiration and the change in storage equals about 180 mm, which, for 4 months, gives an average drainage rate $q_d$ = 1.5 mm/d. Crop- response functions have indicated that, in winter, an average depth of the water table of 0.9 m below the soil surface is amply sufficient. This represents a long-term, steady state agricultural criterion for subsurface drainage systems. Assuming a drain depth of 1.0 m, we find the average hydraulic head to be h = 1.0 - 0.9 = 0.1 m. Defining the drainage intensity ratio as $q_d/h$ ($d^{-1}$), we find $q_d/h = 0.0015/0.1 = 0.015$ $d^{-1}$.

In The Netherlands, when the depth of the water table midway between the drains is 0.5 m, subsurface field drainage criteria are expressed as a normative discharge ($q_d$ = 7 mm/d). This normative discharge and reference level of the water table are exceeded only once a year on average, so we are dealing with a short-term, unsteady-state criterion. The drainage intensity factor becomes $q_d/h = 0.007/(1.0 - 0.5) = 0.014$ $day^{-1}$, which is only slightly less than the ratio q/h = 0.015 found for the steady-state situation.

The $q_d/h$ ratio for the steady state is very sensitive to changes in drain depth; for example, if we take a drain depth of 1.1 m instead of 1.0 m, the $q_d/h$ ratio becomes 0.0075 instead of 0.015. In addition, because the agricultural effects of drainage are usually more responsive to average long-term water levels than to short-term extreme water levels, the $q_d/h$ ratio should not be employed as a drainage criterion outside The Netherlands or without extensive empirical evidence.

For situations in which the incoming or outgoing groundwater flows cannot be ignored, van Someren (1958) used the observed water table depths to derive normative discharges and reference levels of the water table for a subsurface field drainage system (Table 17.5). The underlying principle is that shallow water tables indicate net groundwater inflow and upward seepage, and deep water tables indicate net groundwater outflow and natural drainage. The table shows that the drainage rates, $q_d$, diminish when the observed water tables are deeper (i.e. as the upward seepage reduces and the natural drainage increases). Since this is not generally true in other parts of the world, Table 17.5 is not directly applicable outside The Netherlands.

With the established agricultural criteria for subsurface drainage, either for long-term steady state or short-term unsteady-state conditions, one can proceed to design the subsurface field drainage systems. The steady-state criteria permit the use of steady-state drainage equations. Since the short-term criteria of Table 17.5 have already taken the storage into account (they are specified in terms of normative drain discharge exceeded on an average of only once a year, which equals the corresponding recharge, less storage), here too steady-state drainage equations can be used.

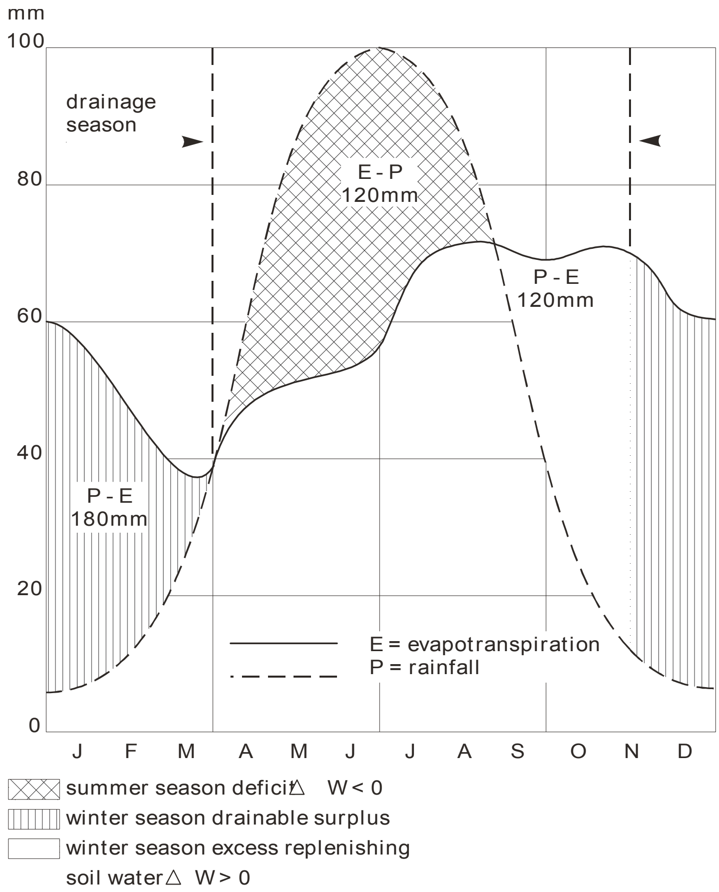



Figure 17.31 Monthly values of rainfall, evapo-transpiration, storage, and drainage surplus in The Netherlands (The legend in the figure needs correction: E=dotted line, P=full line)

Table 17.5 Normative extreme discharge ($q_d$) and corresponding water table depth (j) for subsurface field drainage systems in The Netherlands, by type of land use. The q/h ratios ($d^{-1}$) (where the height h = 1.1 - j, for a drain depth of 1.1 m) are indicated between brackets (van Someren 1958)

| Reference level observed to be exceeded by the water table only once a year (m below soil surface) | Normative discharge (q, mm/d) | | |
|---|---|---|---|
| | Grassland j = 0.3 m | Arable land j = 0.5 m | Orchards j = 0.7 m |
| 0 | 7 (0.009) | 7 (0.012) | 7 (0.018) |
| 0.1 | 7 (0.009) | 7 (0.012) | 7 (0.018) |
| 0.2 | 3 (0.004) | 5 (0.008) | 6 (0.015) |
| 0.3 | 0 | 3 (0.005) | 5 (0.013) |
| 0.4 | - | 0 | 4 (0.010) |
| 0.5 | - | - | 3 (0.008) |
| 0.6 | - | - | 2 (0.005) |
| 0.7 | - | - | 1 (0.003) |
| ≥ 0.8 | - | - | 0 |

**Example 17.2 Collector Drains in The Netherlands**
In The Netherlands, we recognize two criteria for water levels in open collector drains (Figure 17.32): a high water-level criterion (HW) and a normal water-level criterion (NW). The HW criterion specifies that the water level in the collector may exceed a level of 0.5 m below the soil surface only 1 day a year. The NW criterion specifies that the water level in the collector may exceed the outfall level of the laterals (i.e. 1.1 m below soil surface) no more than 15 days a year. For collectors serving small areas, the second criterion is the most critical and will therefore be adopted for the design, whereas for collectors serving large areas, the first criterion is the appropriate one.

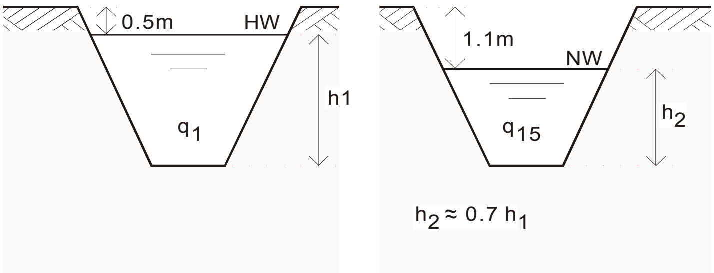



Figure 17.32 High water level (HW) and normal water-level (NW) criteria used in The Netherlands for the design of collectors

According to Blaauw (1961), the collector discharge ($q_{15}$) that is exceeded 15 days a year is about half the discharge ($q_1$) that is exceeded only 1 day a year ($q_{15} = 0.5q_1$). In general, he found for the discharge that is exceeded in x days a year

$$q_x = q_1(1 - 0.44 \log x) \ \text{mm/d}$$

The extreme discharge, $q_1$, is found from the empirical relationship

$$q_1 = 8.64 \ B \ (0.53 - 0.05 \log A) \ \text{mm/d}$$

where A is the area (ha) served by the collector, and B is a factor depending on the area's hydrological conditions. The value of B is usually between 2 and 3, depending on the soil type, kind of cropping system, and intensity of the field drainage system, but when upward seepage or natural drainage occurs, the factor B may go up to 4 or down to 1, respectively.

With the water-level criteria and the corresponding discharges thus determined, we can proceed with the design of the capacity and dimensions of the collector system, using Manning's steady-state formula (Chapter 19), because the dynamic storage of water in the collector system is small compared with recharge and discharge (Section 17.3.4).

## 17.5.2 Irrigated Lands in Arid and Semi-Arid Regions

How subsurface drainage criteria are used in arid zones and how the corresponding water balances are applied will be illustrated with cases from Egypt and Peru.

**Example 17.3 Egypt**
For Egypt's Nile Delta, the agricultural drainage criterion reads: "The seasonal average depth of the water table midway between the drains should be 1.0 m." (Safwat Abdel-Dayem and Ritzema 1990). Although there are indications that this depth could be somewhat less (Figures 17.19 and 17.20), the value 1.0 m was adopted for safety reasons. On the other hand, it would be inefficient to lower the average water table to more than 1.2 m, because this would increase the deep percolation losses and reduce the irrigation efficiency (Oosterbaan and Abu Senna 1990).

Starting from the overall water balance given in Chapter 16 (Equation 16.8), we may ignore rainfall, surface evaporation, and surface runoff, and add a drainage term to obtain

$$q_d = q_{si} - E + q_{gi} - q_{go} \qquad (17.3)$$

where

| | | |
|---|---|---|
| $q_d$ | = | drainage rate (mm/d) |
| $q_{si}$ | = | surface irrigation (mm/d) |
| $E$ | = | evapotranspiration rate (mm/d) |
| $q_{gi}$ | = | groundwater inflow (mm/d) |
| $q_{go}$ | = | groundwater outflow (mm/d) |

The continuous irrigation throughout the year and the steady-state long-term agricultural criterion for subsurface drainage in Egypt permits us to neglect also the change in storage.

In many parts of the Nile Delta, it has been observed that there is natural drainage of groundwater to an underlying deep aquifer (so that $q_{go} > q_{gi}$). Hence, we can expect the value of $q_d$ to be relatively small.

Safwat Abdel-Dayem and Ritzema (1990) reported on measurements of drain discharge and found an average rate of $q_d$ = 0.6 mm/d. This discharge includes the discharge from subsurface-drained rice fields, which is in fact not desired (Qorani et al. 1990). When the drain discharge rates were determined per crop, these rates were found distributed as shown in Table 17.6. From that table, we can conclude that, if the drainage from the rice fields could be restricted, a design discharge rate of q = 0.4 mm/d (corresponding to the average discharge rate of the maize fields) would be amply sufficient for the design. The value of $q_d$ can be so low because it is only supplementary to the natural drainage.

Table 17.6 Average drain discharge in Egypt's Nile Delta per season and per crop (Safwat Abdel-Dayem and Ritzema 1990)

| Season | Winter | | Summer | | |
|---|---|---|---|---|---|
| Crop | Berseem | Wheat | Cotton | Maize | Rice |
| Drain discharge (mm/d) | 0.2 | 0.1 | 0.1 | 0.4 | 1.3 |

With the steady-state agricultural criterion for a subsurface field drainage system (i.e. the seasonal average depth of the water table midway between the drains equals 1.0 m) and the corresponding design discharge rate (i.e. $q_d$ = 0.4 mm/d), we can proceed with the design, using steady-state equations.

In a pilot area in the Nile Delta, it was found that the rate of natural drainage to the underground ($q_{go} - q_{gi}$) amounted to 0.5 mm/d (Oosterbaan and Abu Senna 1990). The total water flow through the profile for this area would amount to 0.9 mm/d, the artificial drainage contributing 0.4 mm/d and the natural drainage 0.5 mm/d.

The irrigation rate causing this drainage flow amply satisfies the leaching requirement, as is shown in Figure 17.33. Before the drainage system was installed, the area had a slight salinity problem, because a small percentage of salinity data were higher than the critical value $EC_e$ = 5 dS/m and the corresponding yields were lower than average. After the drainage system had been installed, all soil salinity data showed an $EC_e$ below 2 dS/m, a very safe value, and the corresponding crop yields are independent of soil salinity. No additional amount of leaching water therefore need be included in the design discharge. We can also note from Figure 17.33 that the average crop yield (5 t/ha) after drainage is higher than the average yield of the data with $EC_e$ < 5 dS/m before. Apparently, by reducing the soil salinity and lowering the water table, drainage has contributed to the general yield improvement. In addition, improved agricultural practices upon the introduction of drainage have had a further positive effect on crop yields.

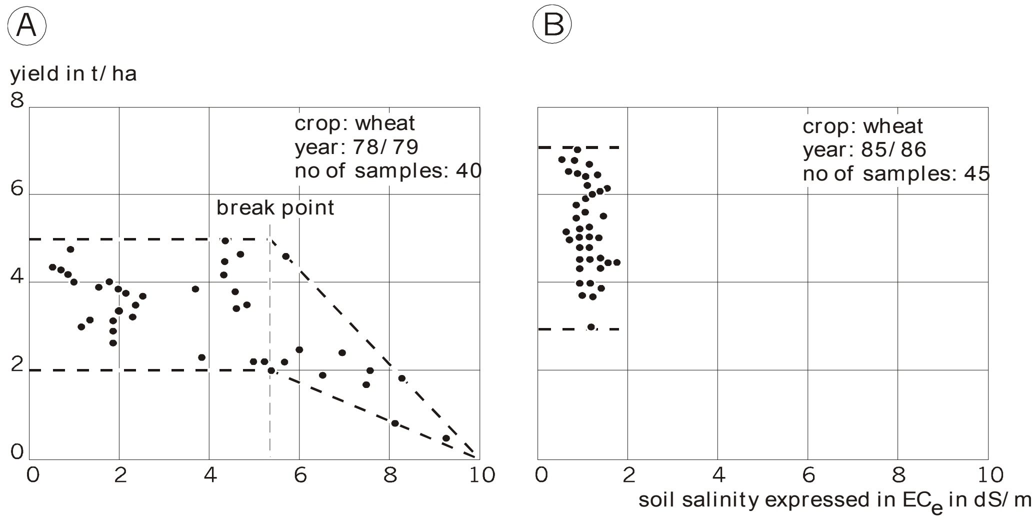



Figure 17.33 Example of the relationship between crop yield and soil salinity (A) before and (B) after the installation of the subsurface drainage system in a pilot area in the Nile Delta, Egypt (Safwat Abdel Dayem and Ritzema 1990)

The subsurface drainage systems of the Nile Delta consist of piped field drains and piped collector drains. The discharge capacity and the required diameter of the collectors should not be based on the average discharge rate, but on a more extreme and less frequent rate. This is because the collector system has a small buffer capacity and it has to function properly during the relatively short periods of peak discharge, otherwise the field drainage system fails. For the design of the collector system, Safwat Abdel-Dayem and Ritzema (1990) proposed to use the discharge rate from maize fields that is exceeded only 10% of the time. This rate was found to be 1.2 mm/d. Such a design discharge would also provide a certain safety margin because it occurs only infrequently.

With the technical criterion: "The collector pipe is just filled to the top at the design discharge", the design procedure can start, based on Manning's steady-state formula, even though the design discharge rate is essentially unsteady.

**Example 17.4 Coastal Peru**

The first Peruvian example concerns an area in the coastal delta of a river that originates in the Andean mountain range. The coastal area is arid, and agriculture is totally dependent on irrigation from rivers descending from the Andes, where rainfall does occur. The irrigation in the river valleys is accompanied by considerable percolation losses. In the underlying deep and permeable aquifers, the percolation losses are transported towards the coast. A salt water wedge intruding from the ocean and a decreasing land slope towards the coast forces the aquifer water to flow upwards, and the water table becomes shallow (Figure 17.34). The continuous upward seepage of groundwater feeds capillary rise into the unsaturated zone. The subsequent evaporation causes salts to accumulate in the topsoil. For these two reasons, irrigation and agriculture can only be practised in seepage zones when a subsurface drainage system is installed.

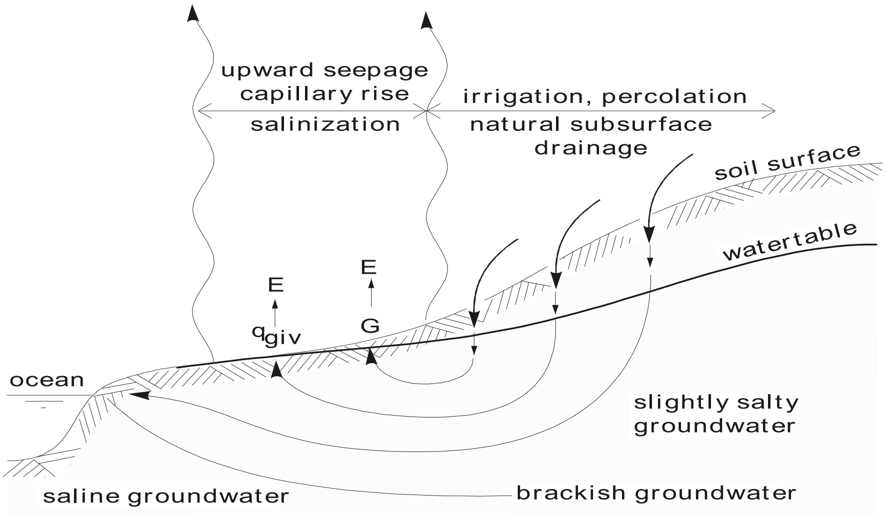



Figure 17.34 Cross-sectional sketch of the geohydrological situation in Coastal Peru (Example 17.4)

The area in the delta has light-textured soils and it had to be prepared for irrigated sugarcane (Suclla Flora 1972). This cane has a growing season of 14 to 16 months, with irrigation for a period of 10 to 12 months (the vegetative period), followed by an un-irrigated period of 4 to 6 months (the ripening or drying period), during which the cane augments its sugar content. The average depth of the water table in the irrigation season is permitted to be 0.8 m (such a value is also found from Figure 17.7, which refers to sugarcane in Australia), but during the ripening period the average depth should be more than 1.3 m; otherwise the crop uses too much of the capillary rise and the ripening does not proceed well. There are therefore two agricultural criteria for the subsurface drainage system, and the system has to satisfy both. The slight resalinization of the soil during the ripening period is not a problem, because, with the first consecutive irrigations, the accumulated salts will be removed again quickly.

The rate of upward seepage from the deep aquifer (called $q_{giv}$) can be estimated from the equilibrium depth of the water table before irrigation and drainage systems were introduced. In that situation, the topsoil was dry (pF = 4.0) and the seepage rate equalled the rate of capillary rise from the saturated zone (G), which also equalled the rate of evapotranspiration ($q_{giv}$ = G = E). Under such conditions, the rate of capillary rise can be found from the steady-state relationship between depth of water table, hydraulic properties of the soil, and soil-water content (Chapter 11). An example is shown in Figure 17.35. If the average depth of the water table before drainage was 0.8 m, the estimated rate of capillary rise from the saturated zone was 2.0 mm/d, which gives us the value of the average seepage rate $q_{giv}$.
In the water balance of the soil profile, we may ignore the storage term, and we get

$$q_d = R - G + q_{giv} \qquad (17.4)$$

where

| | | |
|---|---|---|
| $q_d$ | = | drainage rate (mm/d) |
| R | = | percolation rate (mm/d) |
| G | = | capillary rise (mm/d) |
| $q_{giv}$ | = | upward seepage (mm/d) |

The irrigation system is designed to apply 2400 mm/yr (i.e. during the vegetative period), of which 800 mm/yr is assumed to be lost as deep percolation. The average percolation rate thus equals R = 800 / 365 = 2.2 mm/d, and the capillary rise G is nil. Hence, the average drain discharge during the irrigation season can be estimated from Equation 17.4 as $q_d$ = 2.2 + 2.0 = 4.2 mm/d (see Table 17.7). During the ripening period, there is no percolation (R = 0), but some capillary rise will take place as the soil becomes dry; it is estimated at G = 0.5 mm/d (Figure 17.35). The drain discharge is now estimated from Equation 17.4: 2.0 - 0.5 = 1.5 mm/d.

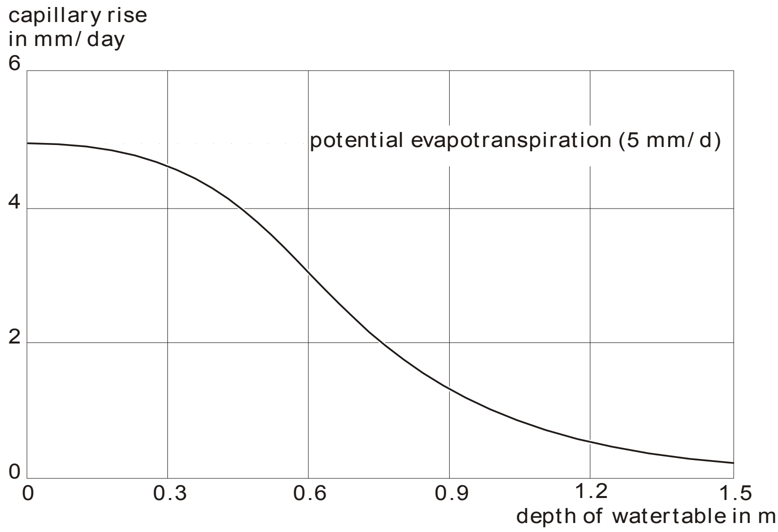



Figure 17.35 The relation between depth of the water table and rate of capillary rise in Example 17.4, under the conditions that the water table depth is steady, the rates of upward seepage and capillary rise are equal, there is no irrigation or rainfall, and the topsoil is dry (pF = 4)

The capillary rise (G = 0.5 mm/d or 90 mm over 180 days) will cause some salinity build-up in the root zone, but the amount of percolation of 800 mm/yr is amply sufficient to cover the leaching requirement, even when its irregular spatial distribution in the field is taken into account.

To satisfy the agricultural criterion for the ripening period, the depth of the drains (g) should be greater than the water table depth (j) of 1.3 m; say 1.5 m. The available hydraulic head (h) during the irrigation period is h = g - j = 1.5 - 0.8 = 0.7 m, and, during the ripening period, it is 1.5 - 1.3 = 0.2 m.

The required drain spacing for the irrigation and ripening periods can now be calculated with the equations given in Chapter 8. The drain spacing adopted should be the one that satisfies both drainage criteria. It should also be possible to vary the drain depth (say from 1.5 to 1.7 m) so that an optimum combination of drain depth and drain spacing can be found. Table 17.8 presents an example of the result of calculations for areas with different seepage rates. The table shows that the required drain spacing are wider as the drain depth increases and the seepage diminishes. In Area B, which has the highest seepage rate, the ripening period appears to be critical for drainage design, because this period requires the smaller drain spacing. In Area C, which has the lowest seepage rate, the vegetative period (corresponding to the irrigation season) is critical. In Area A, the seasonal influence on the required drain spacing depends on the drain depth. The possible combinations are therefore:

- Area A: 1.5 m depth with 77 m spacing, and 1.7 m depth with 120 m spacing, determined by, respectively, the ripening period and the vegetative period (irrigation season);
- Area B: 1.5 m depth with 51 m spacing, and 1.7 m depth with 91 m spacing, both determined by the ripening period;
- Area C: 1.5 m depth with 120 m spacing, and 1.7 m depth with 150 m spacing, both determined by the vegetative period.

In view of the difficulty of installing drains below the water table, it is a sound technical criterion to place the drains as shallowly as possible (i.e. at 1.5 m depth).

Table 17.7 Estimate of the drain discharge from the components of the water balance for irrigated sugarcane in Coastal Peru (Example 17.4)

| Area | Seepage rate $q_{giv}$ (mm/d) | Percolation rate R (mm/d) | Capillary rise G (mm/d) | Drain discharge $q_d = q_{giv} + R - G$ (mm/d) |
|---|---|---|---|---|
| | | Irrigation season | | |
| A | 2.0 | 2.2 | 0 | 4.2 |
| B | 3.0 | 2.2 | 0 | 5.2 |
| C | 1.0 | 2.2 | 0 | 3.2 |
| | | Ripening season | | |
| A | 2.0 | 0 | 0.5 | 1.5 |
| B | 3.0 | 0 | 0.5 | 2.5 |
| C | 1.0 | 0 | 0.5 | 0.5 |

Table 17.8 Calculation of drain depth and spacing (Example 17.4 Coastal Peru)

| Area | Drain depth g (m) | Depth of the water table j (m) | Hydraulic head h = g - j (m) | Drain discharge* $q_d$ (mm/d) | Calculated drain spacing** L (m) |
|---|---|---|---|---|---|
| | | | Irrigation season | | |
| A | 1.5 | 0.8 | 0.7 | 4.2 | 96 |
| B | 1.5 | 0.8 | 0.7 | 5.2 | 81 |
| C | 1.5 | 0.8 | 0.7 | 3.2 | 120 |
| | | | Ripening season | | |
| A | 1.5 | 1.3 | 0.2 | 1.5 | 77 |
| B | 1.5 | 1.3 | 0.2 | 2.5 | 51 |
| C | 1.5 | 1.3 | 0.2 | 0.5 | 196 |
| | | | Irrigation season | | |
| A | 1.7 | 0.8 | 0.9 | 4.2 | 120 |
| B | 1.7 | 0.8 | 0.9 | 5.2 | 100 |
| C | 1.7 | 0.8 | 0.9 | 3.2 | 150 |
| | | | Ripening season | | |
| A | 1.7 | 1.3 | 0.4 | 1.5 | 140 |
| B | 1.7 | 1.3 | 0.4 | 2.5 | 91 |
| C | 1.7 | 1.3 | 0.4 | 0.5 | 355 |

* From Table 17.7

** Calculation based on the method presented in Figure 8.4 (Chapter 8) using a hydraulic conductivity K = 1.0 m/d, a drain radius r = 0.1 m, and a depth of the impermeable layer D = $\infty$ m

Note

The requirement of a fairly deep drain depth in this example is dictated more by the specific crop requirements during the ripening period than by the need for salinity control, which is automatically fulfilled by the percolation losses. Under most agricultural conditions, drain depths can be shallower than 1.5 m, which often enhances ease of installation and reduces installation cost per m length of drain. This offsets the disadvantage of needing more drains per ha than with deeper drains.

**Example 17.5  Northern Peru**

Figure 17.36 shows a cross-section through sloping agricultural land in Northern Peru. The land is arid and is equipped with an irrigation system. The land had to be abandoned, however, owing to problems of water logging and salinity. The soil is sandy, but at some depth the presence of a compact clay layer was noted. At the downslope end of the land, this clay layer rises to the soil surface, but farther upslope it is deeper. Here, massive irrigation occurred and the resultant percolation losses continued down slope as groundwater flow.

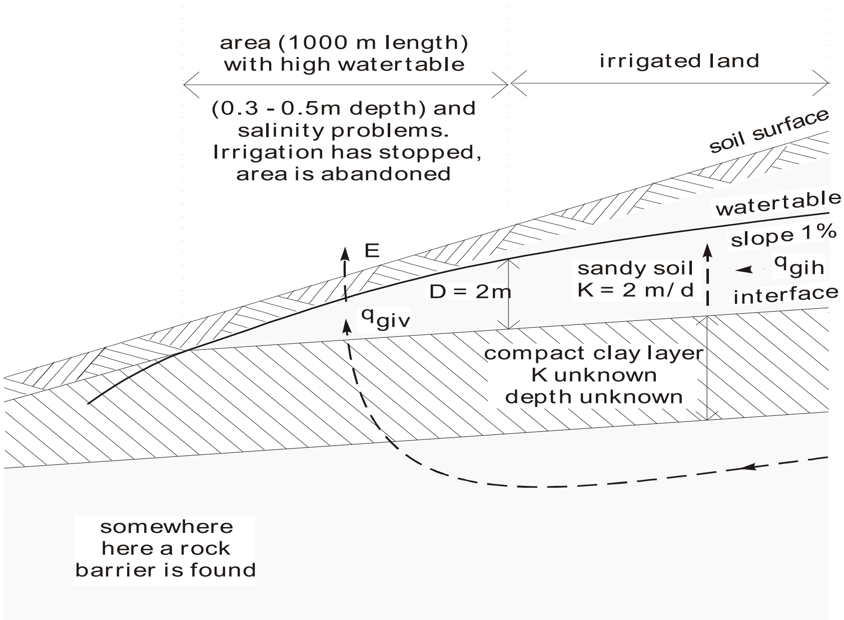



Figure 17.36 Cross-sectional sketch of the hydrological situation in Northern Peru (Example 17.5)

Since the slope (s) of the water table at the right-hand side of the figure equals the slope of the interface of the clay layer, which is about 1% (s = 0.01), and the hydraulic conductivity of the sandy soil could be estimated at K = 2 m/d, the amount of horizontal groundwater flow per metre width through the sandy layer could be calculated, with Darcy, as K.D.s = 2 × 2 × 0.01 = 0.04 m²/d, where D is the level of the water table above the interface. Over a length of 1000 m (Figure 17.36), this means a horizontal groundwater inflow rate, $q_{giv}$, of 0.04 mm/d.

Since the land considered is no longer irrigated, the climate is dry, and the water table remains shallow, we can conclude that the continuous capillary rise from the water table and the subsequent evapo-transpiration of the weeds and shrubs is fed by an inflow of groundwater. According to the physical principles of steady-state capillary rise, its rate can be estimated from the depth of the water table (Chapter 11). Thus the rate of capillary rise could be estimated at G = 3 mm/d. Hence, the upward seepage of groundwater, $q_{giv}$, also equals 3 mm/d.

The value of $q_{giv}$ is almost 100 times greater than the value of $q_{gih}$. This leads to the conclusion that the clay layer has sufficient permeability to permit the passage of the seepage flow. Hence, the greater part of the groundwater seeping up into the land originates from a great depth, and there must be a deep and permeable aquifer below the clay layer. We can therefore conclude that, somewhere down slope of the land, there must be an underground barrier to the flow of ground water which forces this flow upwards.

The technical solution to the problem of water logging would be to install a regular subsurface field drainage system or to introduce pumped wells, employing the usual agricultural criteria for subsurface field drainage systems

(Section 17.3.7), while ensuring that irrigation can be effectively resumed. For example, we could use the agricultural criterion that the average depth of the water table during the irrigation season should be 0.8 m, which satisfies the requirements of most crops. We can find the corresponding design discharge from a water balance, taking into account the percolation stemming from the irrigation and the upward seepage of the groundwater, both taken as an average rate during the season considered.

The example of Northern Peru shows that the mere horizontal flow of groundwater contributes little to the subsurface drainage problem, but that the main causes must be sought in vertical recharges from percolation and/or upward seepage. Intercepting the almost horizontal flow, $q_{gih}$, would therefore not alleviate the problem. The reasons are two-fold:

- If the impermeable layer is shallow, an interceptor drain would catch 100% of the groundwater flow, but the amount of flow is so small that it cannot create an extensive problem of water logging, so the interceptor drain is hardly needed;
- If the impermeable layer is deep, there is an aquifer with a high transmissivity which can cause water logging over an extensive area, but an interceptor drain would catch only a very small fraction of the groundwater flow and would not significantly solve the extensive water logging problem.

### 17.5.3 Irrigated Lands in Sub-Humid Zones

Sub-humid zones are often characterized by a rainy season with high rainfalls (say more than 100 mm per month, and with extreme rainfalls up to 100 mm per day), followed by a dry season. The rainy season may coincide with a cool winter period (e.g. as in North-West Africa), or with a hot summer period (e.g. the monsoon in South-East Asia and West Africa, south of the Sahara). However, also in tropical areas without distinct winter or summer seasons, there may be pronounced rainy and dry seasons (e.g. East Africa).

In the sub-humid zones, irrigation is often practised during the dry season, but also during the rainy season if the rainfall is erratic. When drainage problems occur, salinity problems are often also apparent. The drainage systems to solve these problems should be clearly distinguished in surface drainage systems for the rainy season, subsurface drainage systems for the dry (irrigated) season, and perhaps combined surface and subsurface drainage systems for the rainy season. The drainage criteria have to reflect this differentiation. In addition, a thorough study is required to check whether the drainage problem is entirely the result of local rainfall or of incoming groundwater, or whether inundations from side slopes, rivers, lakes, or seas are the main cause. Where such inundations occur, a drainage system should not be implemented without a flood control system, and perhaps this alone will be sufficient to relieve the water logging.

In the following, an example will be given of the development of criteria for subsurface field drainage systems by pipes in North-West India, which has a monsoon climate. Unfortunately, the practice of combined surface and subsurface drainage systems in sub-humid zones is not well developed, so that we have little experience on drainage criteria for combined systems to draw from. In irrigated lands of the sub-humid zones, drainage systems are often lacking or, if present, are either solely surface or solely subsurface systems. When there is only surface drainage, salinity problems are not counteracted, and when there is only subsurface drainage, the surface drainage problems either persist or are tackled with an excessively expensive subsurface system geared to cope with very high discharges.

**Example 17.6 North-West India**

Rao et al. (1990) describe the results obtained with subsurface drainage by pipes in an experimental area in North-West India. The area was waterlogged during the monsoon period and was very saline. Pipe drainage systems were installed at a depth of 1.75 m and with spacings of 25, 50, and 75 m. The average drain discharge was, respectively, 2.7, 1.1, and 0.9 mm/d during the irrigation season from October to February. This reveals that the discharge of the drainage system with 25 m spacing was high, that more irrigation water was applied there, and that the irrigation was less efficient.

After drain installation, the area's annual rainfall of about 700 mm, occurring mainly in the months of July to September (the monsoon season), desalinized the soil. The rain water was conserved in the field by strong bunds, so surface drainage was impeded and infiltration was enhanced. Table 17.9 shows the measured soil salinities. The initial soil salinity corresponded to an electric conductivity of a saturated paste ($EC_e$) of about 50 dS/m in the surface layer of 0.20 m, and about 20 dS/m in the deeper layers down to 1.2 m. Within 4 months, the soil salinities had come down to levels that were generally below 10 dS/m. The reduction in soil salinity as well as the yield increase of the crops was faster with the 25 m spacing than with the larger spacing. After a period of three years, however, significant differences were no longer observed.

Table 17.9 Soil salinity ($EC_e$ in dS/m) in the Sampla pilot area before (June 1984) and at the end of the first monsoon season after drain installation (October 1984) (Rao et al. 1990)

| Depth of soil layer (m) | Drain spacing (m) | | | | | |
|---|---|---|---|---|---|---|
| | 25 | | 50 | | 75 | |
| | June | Oct. | June | Oct. | June | Oct. |
| 0 - 0.2 | 50.7 | 5.3 | 50.7 | 8.1 | 46.1 | 8.3 |
| 0.2 - 0.4 | 23.6 | 4.0 | 19.4 | 4.7 | 26.4 | 9.1 |
| 0.4 - 0.6 | 19.4 | 3.7 | 15.8 | 7.9 | 13.4 | 9.0 |
| 0.6 - 0.9 | 17.0 | 4.8 | 16.8 | 11.1 | 11.1 | 9.4 |
| 0.9 - 1.2 | 12.2 | 7.6 | 15.5 | 14.3 | 12.6 | 10.2 |

The faster reclamation with the 25 m spacing was achieved at the cost of a much more expensive drainage system and of less efficient irrigation in the post-monsoon season.

With the 25, 50, and 75 m spacing, the water table rose above 1.0 m for about 85, 90, and 108 days, respectively, during the 5-year period from 1984 to 1988. During the monsoon season, the time-averaged depth of the water table remained well below 0.8 m with all spacing. This suggests that the spacing can be fairly wide (> 75 m) and/or that the drain depths can be considerably reduced.

The discharge rates during the monsoon season (i.e. from July to September) for the 25, 50, and 75 m spacing were, respectively, 8.1, 2.2, and 1.1 mm/d. The rate for the 25 m spacing is very high, and is difficult to explain. It is much higher than the leaching requirement. In such a situation, one ought to consider a combination of surface and subsurface drainage systems to relax the subsurface drainage requirements, or one ought to examine whether water conservation could be improved. The last objective could be achieved by restricting the drain outflow (Qorani et al. 1990), but also by reducing drain depth and increasing the spacing (Oosterbaan and Abu Senna 1990).

The evacuation of the salty drainage water in the dry season is not desirable because it would contaminate the river water below the outlet. It was found that the drainage water can be re-used for irrigation in the dry season when the salt concentration of the drainage water is reduced from the usual 12 kg/m$^3$ to 6 kg/m$^3$ by mixing it with fresh irrigation water (Sharma et al. 1990). With such a mix, the crop production is hardly affected, provided that the resulting accumulation of salts in the soil is removed by drainage during the rainy season. Evacuating the salty drainage water in the rainy season is not harmful owing to the high river discharges so that the contamination of the river water is negligible. Instead of pumping the drainage water for irrigation, one can also refrain from pumping, letting the crops use groundwater directly (Rao et al. 1992), thereby saving irrigation water.

Suitable drainage criteria appear to be the following:

- During the monsoon season, the average depth of the water table should be 0.8 m to ensure sufficient dryness of the soil;
- During the dry season, the average depth of the water table should be 0.5 m to ensure an efficient irrigation and to provide an opportunity for the plants to use groundwater by capillary rise.

With these criteria, an adequate salt balance of the soil is guaranteed and environmental requirements are met.

The design discharge during the monsoon season follows from the average excess rainfall in that period. During the dry season, the water balance will show that the design discharge is nil, so that no drainage is required. The required depth of the water table is brought about naturally.

### 17.5.4 Rain-Fed Lands in Tropical Humid Zones

The humid tropics are characterized by long-lasting rainy seasons (more than 8 months) with an annual rainfall exceeding 2000 mm. Water logging occurs frequently in the flat areas. As in the sub-humid zones, one has to assess the extent to which inundations from rivers, lakes, or seas contribute to the water logging. When the inundations have a strong influence, no attempt should be made to implement a drainage system without a flood-control scheme. Further, investigations ought to be made to check whether an adjustment of the cropping system would be sufficient to eliminate the drainage problem. If a drainage system is still found to be necessary, a surface drainage system is usually the appropriate choice, because subsurface drainage systems in the humid tropics are often prohibitively expensive as they would have to be designed for very high discharge capacities and would need very narrow spacing. Only when the soil's hydraulic conductivity is very high could the spacing be wide enough to be practically feasible.

In the following paragraphs, an example will show how the discharge capacity was determined for the collectors serving a surface drainage system in a coastal plain in Guyana. Another example will demonstrate the effects of subsurface drainage systems on agriculture in a coastal plain of Kalimantan, Indonesia.

**Example 17.7 Guyana**

This example concerns the collectors for surface drainage systems in sugarcane plantations in the coastal region of Guyana (Naraine 1990).

According to Equation 16.4 (Chapter 16), the surface water balance, for a period of one day, reads

$$D_{so} = P - I - E_0 + D_{si} - \Delta W_s \qquad (17.5)$$

where

| | | |
|---|---|---|
| $D_{so}$ | = | runoff depth (mm) |
| $P$ | = | precipitation (mm) |
| $I$ | = | infiltration (mm) |
| $E_0$ | = | evaporation from the surface (mm) |
| $D_{si}$ | = | surface inflow depth (mm) |
| $\Delta W_s$ | = | change in storage of surface water (mm) |

In this example, the term $D_{si}$ can be set equal to zero. Because we consider a short period with intensive rainfall, the term $E_0$ can also be neglected. Thus Equation 17.5 can be reduced to

$$D_{so} = P - I - \Delta W_s$$

The Curve Number Method (Chapter 4) uses this balance (Equation 4.2) to calculate the runoff. This will also be done here.

Table 17.10 shows data on the cumulative 5-day rainfall with a 10-year return period and the resulting cumulative surface runoff $D_c$ calculated with the Curve Number method, using a Curve Number value of 40. This empirical method takes into account the storage $\Delta W_s$ and infiltration I in the sugarcane fields, but not the dynamic storage in the fields that is needed to induce the discharge, as will be explained below. Table 17.10 also shows the daily surface runoff $D_i$ and the surface runoff rate $q_{so}$ as a time average of the cumulative surface runoff: $q_{so} = D_c/t$, where t is the time (days). Note that $D_c = \Sigma D_i$ and $q_{so} = \Sigma D_i/t$.

Table 17.10 Example of a rainfall-runoff relationship with a return period of 10 years in the case study of Guyana, using the Curve Number method with a Curve Number value CN = 40

| | | Surface runoff | | |
|---|---|---|---|---|
| Duration t<br>(d)<br>1 | Cumulative rainfall (P)<br>(mm)<br>2 | Cumulative $D_c$<br>(mm)<br>3 | Daily $D_i$<br>(mm)<br>4 | Average surface runoff rate $q_{so} = D_c/t$<br>(mm/d)<br>5 |
| 1 | 150 | 14 | 14 | 14 |
| 2 | 250 | 59 | 45 | 29 |
| 3 | 325 | 104 | 45 | 35 |
| 4 | 360 | 128 | 24 | 32 |
| 5 | 375 | 138 | 10 | 28 |

The design discharge of the main drainage system can be chosen as the maximum value of the average surface runoff rate: $q_{design} = q_{so(max)} = 35$ mm/d. It occurs after 3 days, which is the critical period because, with shorter or longer durations, the $q_{so}$ values are less than 35 mm/d.

The cumulative surface runoff ($D_c$, Column 3 in Table 17.10) is plotted in Figure 17.37 against the time. It shows a curve with an S-shape. The slope of the tangent line from the origin to this curve indicates the required discharge capacity of the collectors, with a return period of 10 years ($q_{design} = 35$ mm/d).

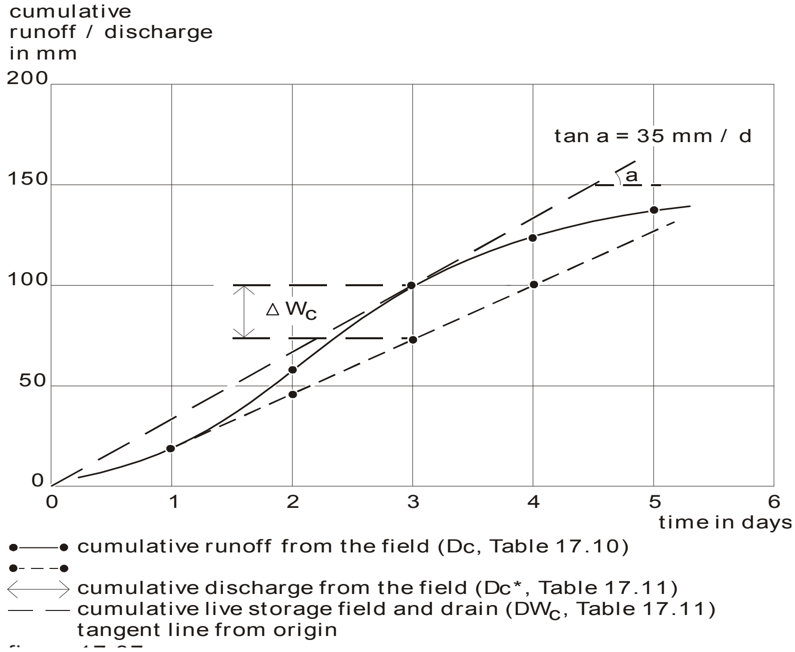



Figure 17.37 Runoff and discharge versus time in the example of Guyana

The S-shape of the runoff curve, which is initially quite flat, shows that the drainage system cannot immediately function at its maximum capacity: there is a delay in the functioning and a necessary dynamic storage. The daily dynamic storage can be found from

$$\Delta W_i = D_i - q_{so} \tag{17.6}$$

Table 17.11 shows the development of daily $\Delta W_i = D_i - q_{so}$ and cumulative dynamic storage $\Delta W_c = \Sigma \Delta W_i$ with time. Further, it shows the cumulative discharge $D = D_c - \Delta W_c$ and the daily discharge $D = D_i - \Delta D_i$. Note that $D = \Sigma D$.

It can be seen from Table 17.11 that the daily storage $\Delta D_i$ is positive up to the critical time t = 3 days, after which it becomes negative. The cumulative storage $\Delta W_c = \Sigma \Delta W_i$ therefore increases up to t = 3 days, and afterwards decreases. The table also shows that the maximum daily discharge (D = 35 mm/d) occurs during the 3rd day and it equals the design discharge $q_{design}$ determined from the tangent line in Figure 17.37 and from $q_{so(max)}$ in Table 17.10.

Naraine (1990) plotted the yield versus the number of high-water days (NHW), defined as the number of days per season during which the water level in the main collectors exceeded a level corresponding to a depth of 0.9 m below the soil surface (Figure 17.38). The figure shows that there is a tendency towards decreasing crop yields when the NHW value is greater than about 7. Therefore NHW = 7 can be taken as a design criterion for the main drainage system.

Table 17.11 Daily and cumulative dynamic storage and discharge derived from Table 17.10

| Time | Storage | | Discharge | |
|---|---|---|---|---|
| | Daily $\Delta W_i$ | Cumulative $\Delta W_c$ | Cumulative D | Daily D |
| (d) | (mm) | (mm) | (mm) | (mm) |
| 1 | 0 | 0 | 14 | 14 |
| 2 | 16 | 16 | 43 | 29 |
| 3 | 10 | 26 | 78 | 35 |
| 4 | -6 | 20 | 108 | 30 |
| 5 | -18 | 2 | 136 | 28 |

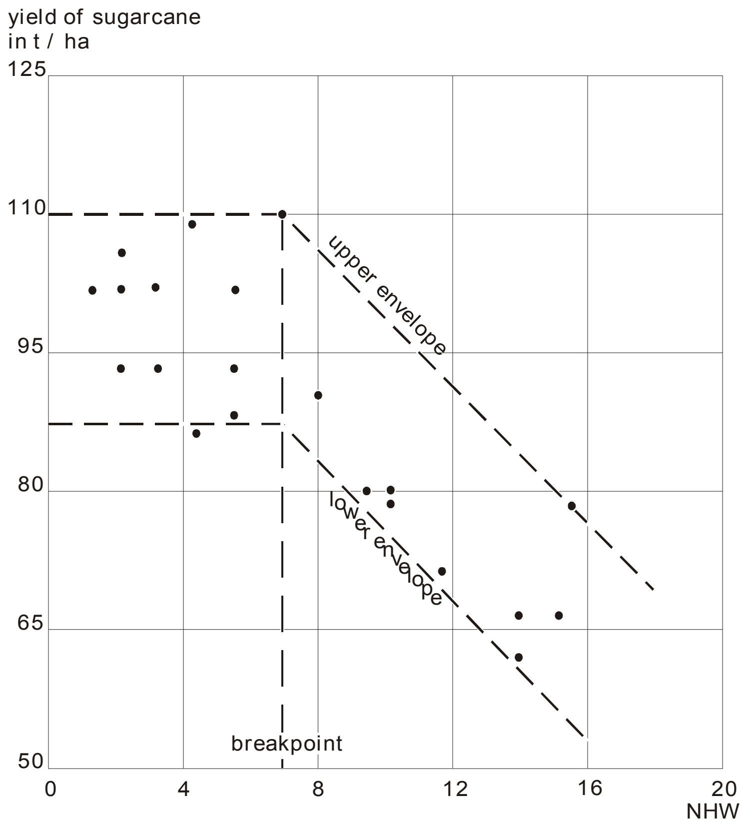



Figure 17.38 Crop yield versus number of days (NHW) with a high water level (above 90 cm below soil surface) in the collector system in the example of Guyana (Naraine 1990)

The above analysis shows that the design of the main drainage system can be based on criteria that use the same principles as described for collector drainage systems in The Netherlands (Section 17.5.1); only the quantitative values need to be adjusted:

- There should be a high water-level criterion (HW) specifying the water level in the drain that may be exceeded only once in 10 years. (In the example of Guyana, however, this level has not yet been determined.) The corresponding discharge is 35 mm/d;
- There should be a normal water-level criterion (NW) specifying that the water level in the drain may be shallower than 90 cm below soil surface only for 7 days per season. (The corresponding discharge in the example of Guyana has yet to be defined).

Despite the relative shortcomings in the example of Guyana, the analysis permitted Naraine to distinguish the well drained and the poorly drained estates and to recommend criteria for improved drainage systems and to calculate a benefit/cost ratio.

**Example 17.8 Indonesia**
The coastal area of Southern Kalimantan, Indonesia, is characterized by the presence of large, deep rivers, between which flat marine and alluvial soils have formed. The soils often contain large amounts of organic matter and/or large amounts of acidifying sulphuric material.

There is an annual rainfall of about 2800 mm, of which roughly 2000 mm evaporates. The excess rainfall, therefore, is about P - E = 800 mm/yr. Despite the high excess rainfall, few inundations from the rivers occur owing to their enormous hydraulic transport capacity. Inundations are only apparent near the seashore and stem from oceanic tides.

Long ago, the inhabitants dug canals from the riversides into the interior of the land. These hand-dug canals are 5 to 10 km long and are spaced at 300 to 500 m. They have an important drainage function as they evacuate the main part of the excess rainfall; they are also used for transport by boat.

A research project in the region has established that the hydraulic conductivity of the soils is extremely high (AARD and LAWOO 1992). Over a depth of D = 2 m or more, the highly cracked soils have a hydraulic conductivity of K = 100 to 300 m/d. The soils' hydraulic transmissivity values therefore range between KD = 300 and 800 $m^2$/d. During the months with the highest rainfalls (November to May), the excess rainfall P - E (equalling the net recharge $R_d$) can be estimated at 700 mm to 800 mm, giving an average of about $R_d$ = 3 mm/d. From Equation 17.1 (Section 17.3.4), setting $\Delta h = 0$, we find that the average drain discharge $q_d$ also equals 3 mm/d. Using a canal spacing of L = 500 m and a transmissivity value KD = 500 $m^2$/d, we can calculate the hydraulic head h, using Hooghoudt's drainage formula (Chapter 8) and taking $q = q_d/1000$, as

$$h = \frac{qL^2}{8KD} - \frac{0.003\,(500)^2}{8 \times 500} = 0.2 \text{ m}$$

Since the water level in the canals has an average depth, g, of about 0.5 m below the soil surface, the average depth of the water table, j, is found at j = g - h = 0.5 - 0.2 = 0.3 m below the soil surface. Hence, for short periods with high intensity rainfalls, the water table may rise close to the soil surface, so that the hydraulic head equals h = 0.5 m. The discharge rate of the canals then becomes

$$q = \frac{8KDh}{L^2} - \frac{8 \times 50 \times 0.5}{500^2} = 0.008 \text{ m/day}$$

This is a high value, and many farmers in the region have observed that it is difficult to maintain a permanent water layer on their rice fields, and that high water levels in their fields after intensive rainfall drop in a matter of 2 or 3 days.

It is not yet possible to decide whether the region is excessively drained by the traditional hand-dug canals or not. To evaluate the agricultural drainage criteria, it would be necessary to take into account the drainage requirements of crops other than rice, the extent to which rice fields and fields with other crops are contingent, and the possibility that occasionally deeper water tables may have a favourable effect on the soil structure or the quality of the soil's organic matter. There are indications that maintaining the water table at a modest depth below the soil surface during a period with non-rice crops, has a positive effect on the soil's fertility and acidity (AARD & LAWOO 1992).

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