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.

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 undrained land as shown in Table 17.3).

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:

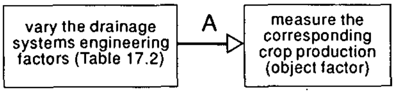

Figure 17.15 Illustration of a straightforward method of analysis of drainage effects on agriculture

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

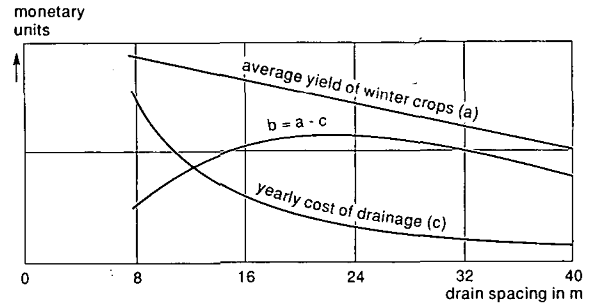

Figure 17.16 Example of Relation A of Figure 17.15 showing net benefit (b) of winter crops as a function of drain spacing in a 60% clay soil in Sweden (Eriksson 1979)

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

- 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 watertable regime is used as an additional intermediate factor, so that Relation A is divided into Relations B and C.

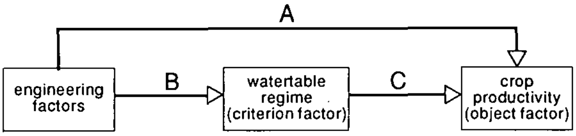

Figure 17.17 Relation A of Figure 17.15 is divided into Relations B and C by means of the watertable regime

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.

17.4.2 Watertable and Crop Production

The use of the watertable 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 watertable 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 watertable during the growing season

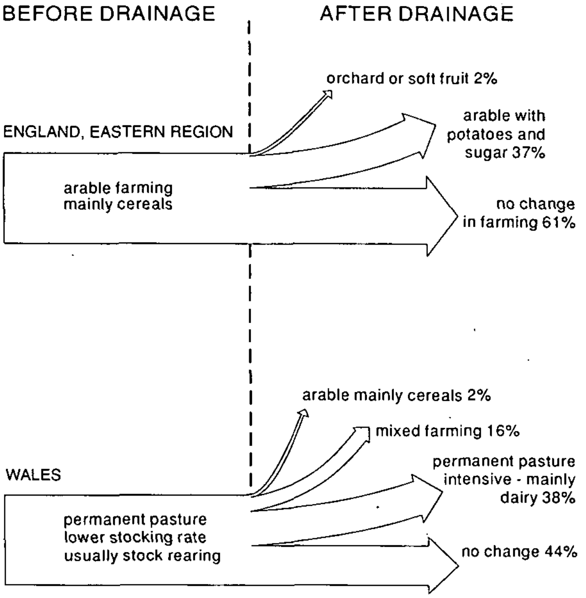

Figure 17.18 Changes in cropping pattern as a result of drainage (FDEU 1972)

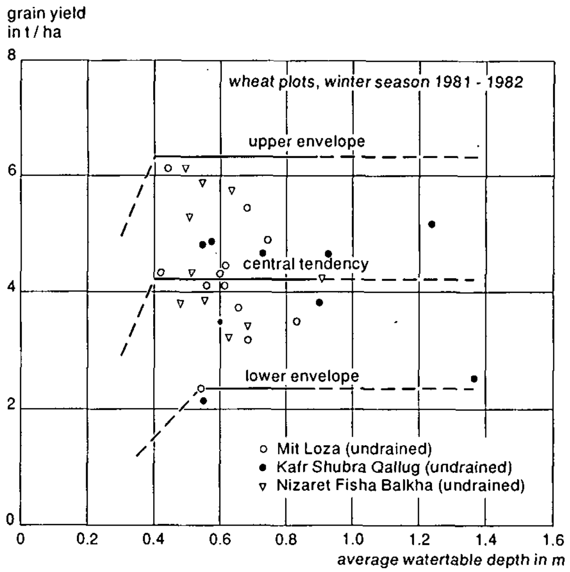

Figure 17.19 A plot of data on the yield of wheat in farmers' fields and the average seasonal depth of the watertable in the Nile Delta, Egypt (Advisory Panel 1982)

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 watertable is 0.5 m or less. There are insufficient data on a watertable 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 watertable but to other, unfavourable, agricultural conditions.

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

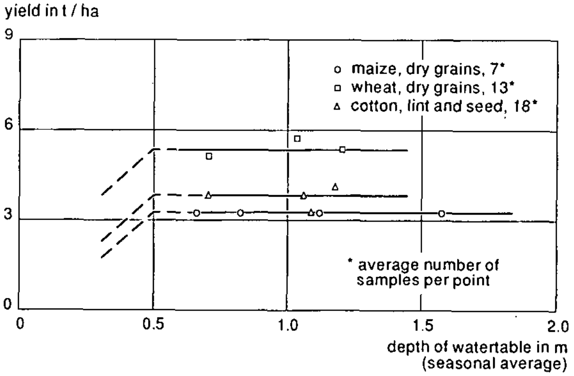

Figure 17.20 The yield of some irrigated crops versus seasonal average depth of the watertable. Data from the Mashtul Pilot Area in the Nile Delta, Egypt (Safwat Abdel-Dayem and Ritzema 1990)

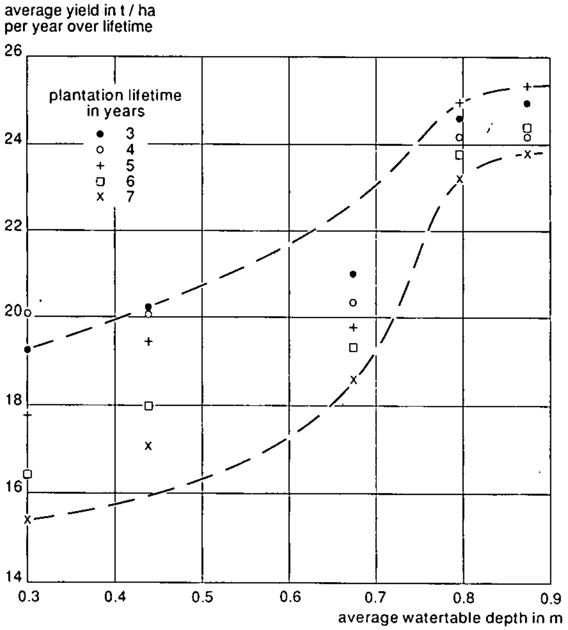

Figure 17.21 Relationship between banana yield, plantation age, and average depth of the watertable in Surinam (Lenselink 1972)

that the area is adequately drained, because no clear relationship can be detected between the average depth of the watertable and the yields, and all seasonal average depths of the watertable were deeper than 0.5 m. Some fields in the pilot area were even excessively drained (i.e. the watertable is much deeper than required). As in Figure 17.19, the critical value of the watertable for the crops investigated in Figure 17.20 cannot be determined accurately because of the lack of data on very shallow watertables. Anyway, it is likely that depths of 0.6 to 0.7 m are safe for all three crops.

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

Table 17.4 shows the relative yields of potatoes, onions, maize, and carrots in

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

Crop	Number of years	Depth of watertable (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

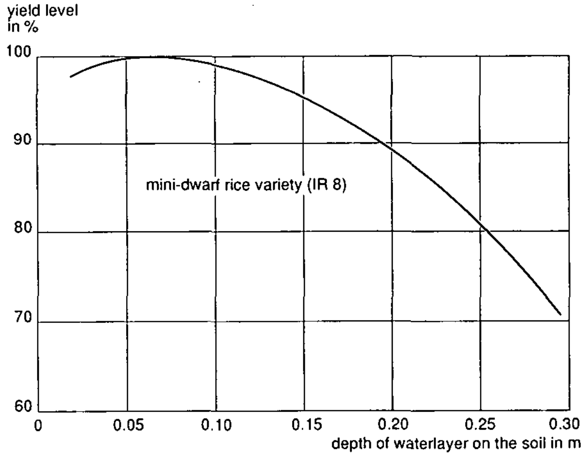

Figure 17.22 Production of a dwarf rice variety as a function of the depth of the standing water layer on the soil surface (personal communication from K.J. Lenselink and J. de Wolf, ILRI, Wageningen, The Netherlands)

dependence of the depth of the watertable 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.

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 yield reductions. Nevertheless, there are many sturdy rice varieties that can withstand much higher depths.

Figure 17.23 shows that, in farmers' rice fields in the Nile Delta, the average seasonal

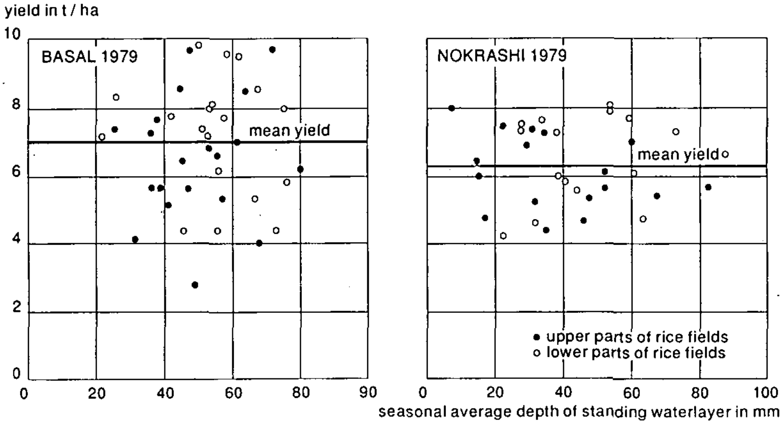

Figure 17.23 A plot of rice yields in farmers' fields versus seasonal average depth of the standing water layer on the soil surface in the Nile Delta, Egypt (Nijland and El Guindy 1986)

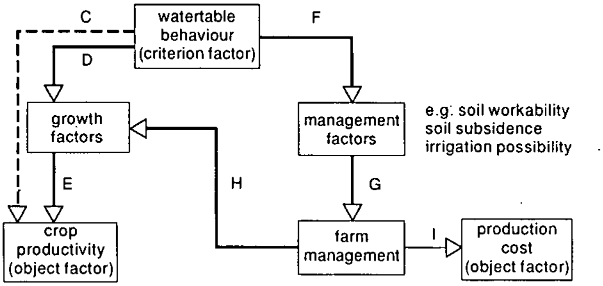

Figure 17.24 A further breakdown of Relation C of Figure 17.15 into Relations D, E, F, G, H, and I, using soil-related growth and management factors

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.

17.4.3 Watertable and Soil Conditions

To enable a wider application of the relationship between the depth of the watertable 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).

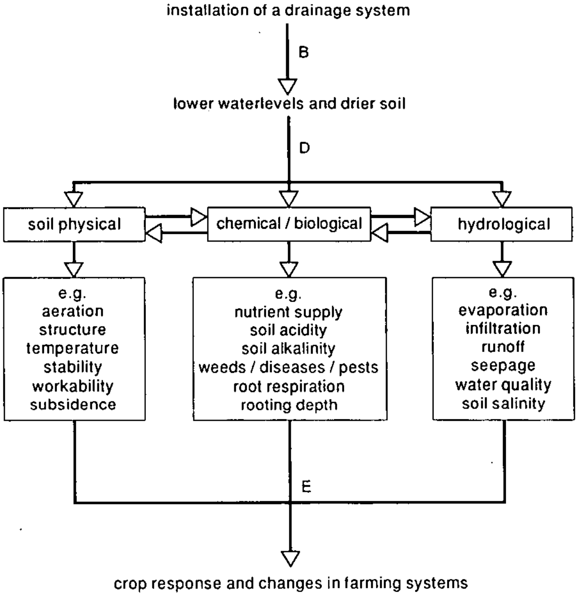

Figure 17.25 Soil physical, chemical/biological, and hydrological interactions in Relations D and E of Figure 17.24

Figure 17.24 also 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.

Soil Structure

A good soil structure favours both the soil 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 watertable (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 watertable. As a result, when the depth of the watertable 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 watertable at a depth greater than 0.4 m exerts a beneficial influence on soil structure and structurally-determined soil properties.

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 E, 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 watertable 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 watertable at 0.4 m depth. This example shows that excessive drainage should be avoided.

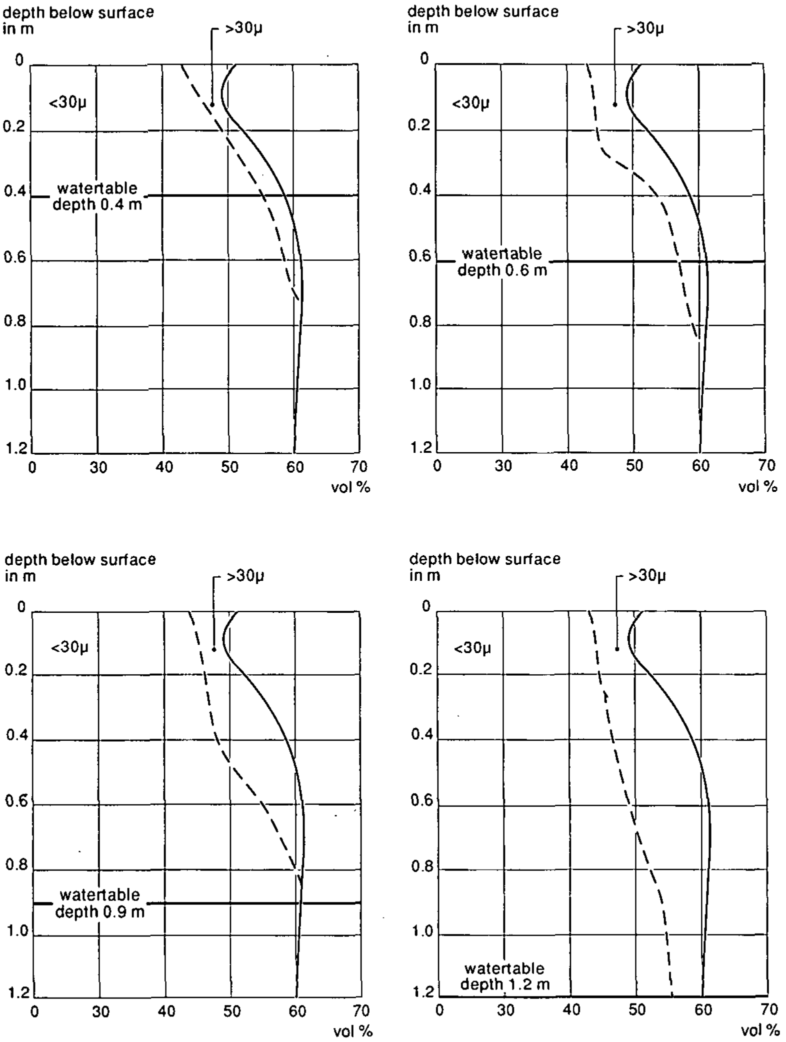

Figure 17.26 Influence of groundwater depth on water and air content, and pore-size distribution (Van Hoorn 1958)

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

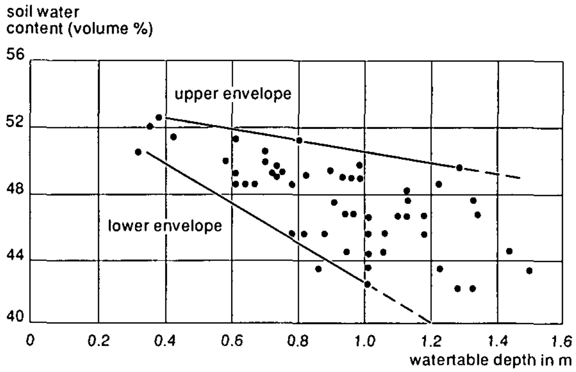

Figure 17.27 Relation between soil water content at 0.15 m depth and watertable depth in a silt loam soil in S. Carolina, U.S.A., from January through May 1970 (Young and Ligon 1972)

(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 watertable 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 watertable 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 watertables than with shallow ones. On the other hand, a deep watertable and an intensive subsurface drainage system are no absolute guarantees of a soil-water content below field capacity, especially not on rainy days.

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

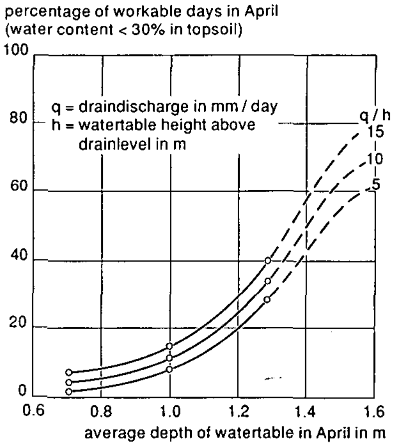

Figure 17.28 Drainage and workability of a silt loam soil under Dutch climatic conditions. Data obtained with a simulation model covering a period of 35 years (adapted from Wind and Buitendijk 1979)

(q/h ratio), and the average depth of the watertable. The figure shows that the average depth of the watertable 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. Unfortunately, the calculations were made only up to watertable 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).

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 watertable 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 watertable. When the shrinkage is used as an object factor, this average depth can also be used as a drainage criterion.

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 Romero 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 watertable. 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.

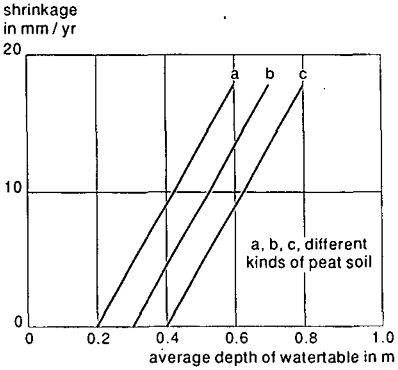

Figure 17.29 Subsidence of peat soils in The Netherlands as a function of average watertable depth (Schothorst 1978)

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 watertable 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 watertable 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 watertable on grassland in peat soil in The Netherlands. With shallow watertables, a high N-dose has a considerable effect on the yield, but when the watertable 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 undrained 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 watertable is shallow and as ammonia when the watertable 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).

Soil Sodicity

Sodic soils are soils with an excess sodium at the exchange complex and they have a pH above 8. Sodic soils containing $CaCO_3$ can be reclaimed by incorporating acidifying materials in the soil, either through organic matter, sulphur compounds, or a reclamation crop. (Many grasses serve this purpose.) The acids dissolve the precipitated $CaCO_3$. If necessary, gypsum can also be added. The Ca^{2+} in the gypsum

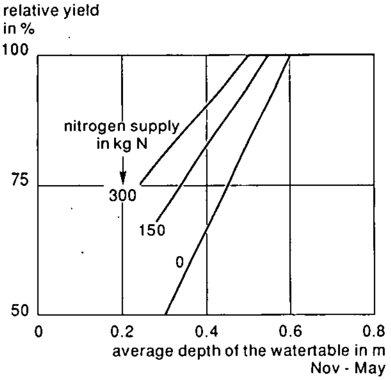

Figure 17.30 Nitrogen supply, average depth of watertable, and yield of grassland in The Netherlands (Feddes and Van Wijk 1977)

or in the dissolved $CaCO_3$ displaces sodium from the exchange complex. Subsequently, the excess sodium needs to be leached. 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 sulphuric 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. 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 waterlogging (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.