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)
Δt = period (d)
P = precipitation (mm)
E = evapotranspiration (mm)
ΔW = water storage (mm)

Figure 17.31 presents the monthly balances of rainfall (P) and evapotranspiration (E) in The Netherlands. It shows that, in summer, the evapotranspiration exceeds rainfall and $\Delta W = P - E$, 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 evapotranspiration plus the storage by 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 watertable 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 watertable 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 watertable are exceeded only once a year on average, so we are dealing with a short-term, unsteady-state situation. The drainage intensity ratio 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. Therefore, and 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 watertable depths to derive normative

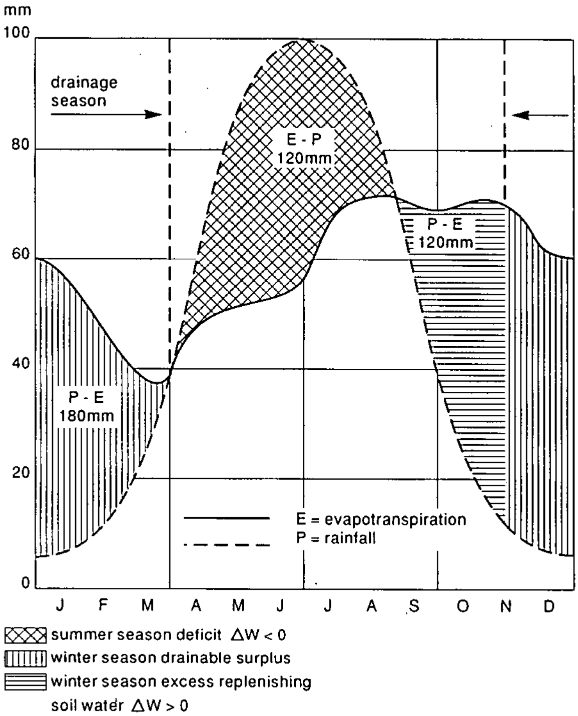

Figure 17.31 Monthly values of rainfall, evapotranspiration, storage, and drainage surplus in The Netherlands

discharges and reference levels of the watertable for a subsurface field drainage system (Table 17.5). The underlying principle is that shallow watertables indicate net groundwater inflow and upward seepage, and deep watertables indicate net groundwater outflow and natural drainage. The table shows that the drainage rates, q_d, diminish as the observed watertables 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 intensity ratio's 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 conditions permit the use of steady-state drainage equations. Since the data 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.

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

Table 17.5 Normative extreme discharge (q_d) and corresponding watertable 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 watertable only once a year (m below soil surface)	Normative discharge (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

that the water level in the collector may exceed the outfall level of the laterals (i.e. 1.0 to 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.

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.

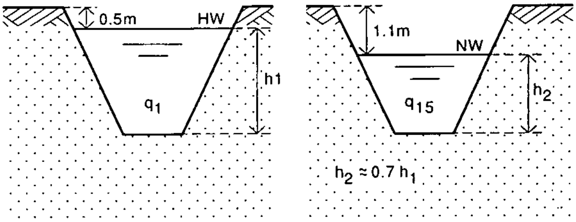

Figure 17.32 High water-level (HW) and normal water-level (NW) criteria used in The Netherlands for the design of collectors

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 one case from Egypt and two from Peru.

Example 17.3 Egypt
For Egypt's Nile Delta, the agricultural drainage criterion reads: 'The seasonal average depth of the watertable 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 watertable 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

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

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 to be 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

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

is only supplementary to the natural drainage.

With the steady-state agricultural criterion for a subsurface field drainage system (i.e. the seasonal average depth of the watertable 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 of the field drainage system, 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 watertable, 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.

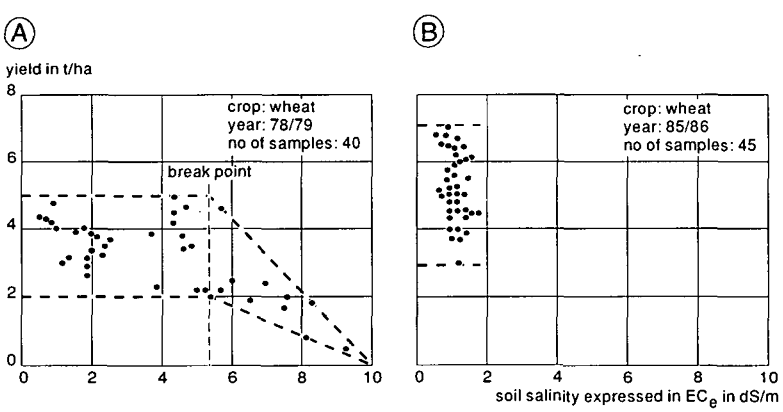

Figure 17.33 Example of the relationship between crop yield and soil salinity (A) before and (B) after the installation of the subsurface drainage system in a pilot area in the Nile Delta, Egypt (Safwat Abdel Dayem and Ritzema 1990)

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 of the collector drains 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 watertable 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.

The area in the delta has light-textured soils and it had to be prepared for irrigated sugarcane (Suclla Flores 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 unirrigated period of 4 to 6 months (the ripening or drying period), during which the cane augments its sugar content. The average depth of the watertable in the

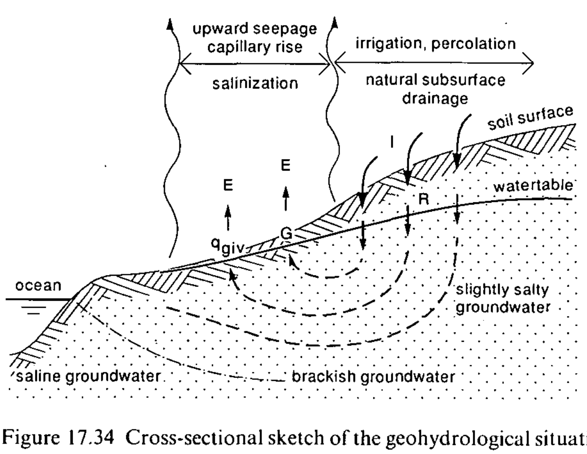

Figure 17.34 Cross-sectional sketch of the geohydrological situation in Coastal Peru (Example 17.4)

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 watertable before irrigation and drainage systems were introduced. In that situation, the topsoil was dry (pF = 4.0) and the seepage rate equalled the steady 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 watertable, 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 watertable 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 seasonal water balance of the soil profile, we may ignore the storage term, and we get

$$q_d = R - G + q_{giv} \tag{17.4}$$

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

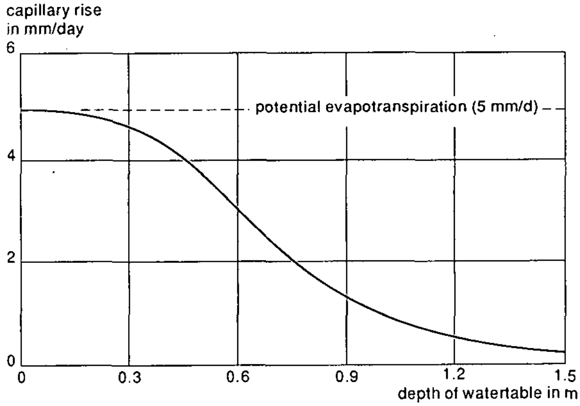

Figure 17.35 The relationship between depth of the watertable and rate of capillary rise in Example 17.4, under the conditions that the watertable depth is steady, the rates of upward seepage and capillary rise are equal, there is no irrigation or rainfall, and the topsoil is dry (pF = 4)

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

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: $q_d = 2.0 - 0.5 = 1.5$ mm/d.

The capillary rise (G = 0.5 mm/d or 90 mm over 180 days) will cause some salinity build-up in the rootzone, 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 watertable 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 spacings 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 spacings 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 spacings. 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);

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

Area	Drain depth g (m)	Depth of the watertable 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 = ∞ m

- 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 watertable, it is a sound technical practice to place the drains as shallowly as possible (i.e. at 1.5 m depth).

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 waterlogging 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 downslope as groundwater flow.

Since the slope (s) of the watertable 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 m^2/d, where D is the level of the watertable above the interface. Over a length of 1000 m (Figure 17.36), this means a horizontal groundwater inflow rate, q_{gih}, of 0.04 mm/d.

Since the land considered is no longer irrigated, the climate is dry, and the watertable remains shallow, we can conclude that the continuous capillary rise from the watertable and the subsequent evapotranspiration 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 watertable (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 downslope of the

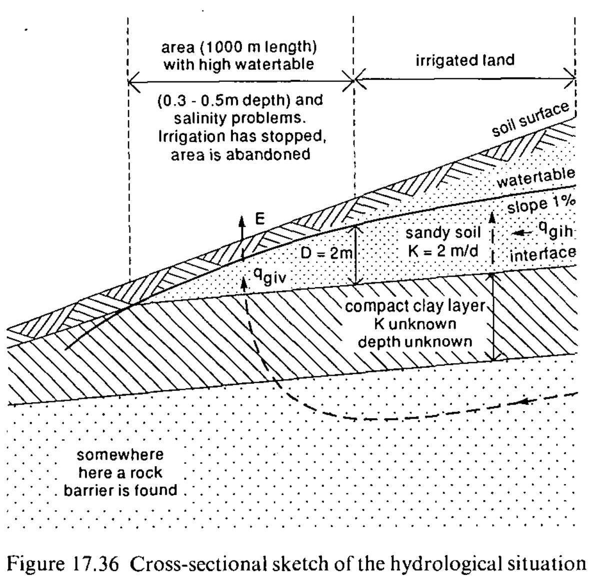

Figure 17.36 Cross-sectional sketch of the hydrological situation in Northern Peru (Example 17.5)

land, there must be an underground barrier to the flow of groundwater which forces this flow upwards.

The technical solution to the problem of waterlogging 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 watertable 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 horizontal groundwater flow, but the amount of flow is so small that it cannot create an extensive problem of waterlogging, so the interceptor drain is hardly needed;
- If the impermeable layer is deep, there is an aquifer with a high transmissivity which can cause waterlogging 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 waterlogging 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 waterlogging.

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 rainwater was conserved in the field by 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 spacings. After a period of three years, however, significant differences were no longer observed.

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.

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	Drain spacing (m)					
	25		50		75	
(m)	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

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

The average discharge rates during the monsoon season (i.e. from July to September) for the 25, 50, and 75 m spacings 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 watertable should be 0.8 m to ensure sufficient dryness of the soil;
- During the dry season, the average depth of the watertable should be 0.5 m to ensure an efficient irrigation and to provide an opportunity for the plants to use groundwater by capillary rise, yet providing sufficient soil aeration.

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 watertable 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. Waterlogging 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 waterlogging. 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 spacings. 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)
ΔW_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 ΔW_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 $q_{so} = \Sigma D_i/t$.

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.

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

Duration t (d)	Cumulative rainfall P (mm)	Surface runoff: Cumulative D_c (mm)	Surface runoff: Daily D_i (mm)	Average surface runoff rate $q_{so} = D_c/t$ (mm/d)
1	2	3	4	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 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).

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 ΔW_i and cumulative dynamic storage ΔW_c =

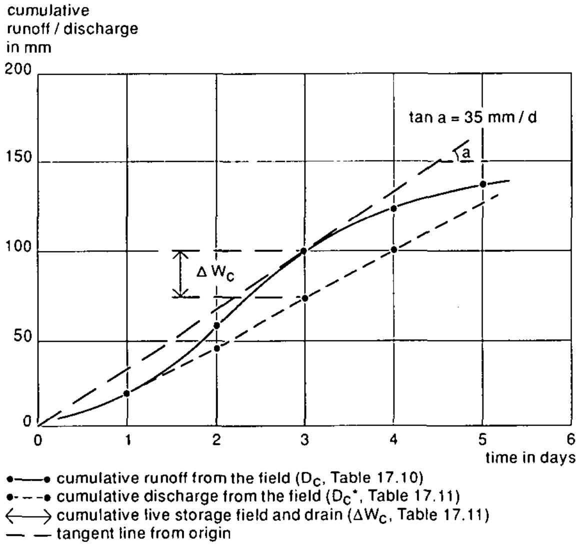

Figure 17.37 Runoff and discharge versus time in the example of Guyana

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

Time	Storage		Discharge	
	Daily ΔW_i	Cumulative ΔW_c	Cumulative D_c^*	Daily D_i^*
(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

$\Sigma\Delta W_i$ with time. Further, it shows the cumulative discharge $D_c^* = D_c - \Delta W_c$ and the daily discharge $D_i^* = D_i - \Delta W_i$. Note that $D_c^* = \Sigma D_i^*$.

It can be seen from Table 17.11 that the daily storage ΔW_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_i^* = 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 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 collector drainage system.

The above analysis shows that the design of the collector 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 plantations and to recommend criteria for improved drainage systems and to calculate a benefit/cost ratio.

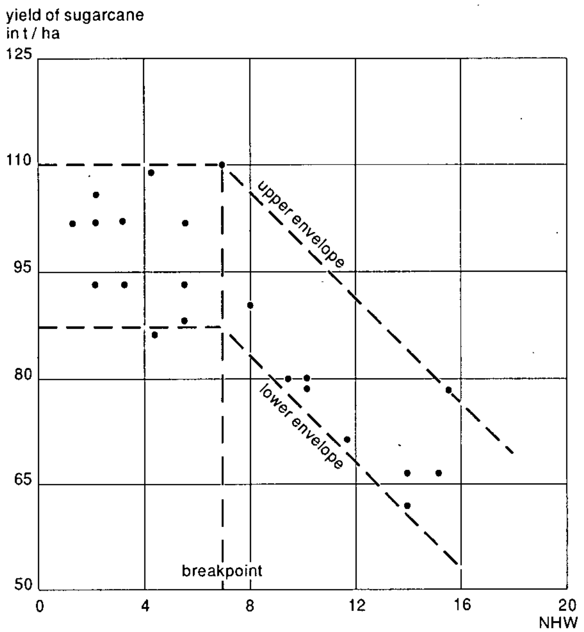

Figure 17.38 Crop yield versus number of days (NHW) with a high water level (above 90 cm below soil surface) in the collector system in the example of Guyana (Naraine 1990)

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.

The climate is characterized by 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 sea shore 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 $q = q_d/1000$ m/d, as

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

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 watertable, j, is found at $j = g - h = 0.5 - 0.2 = 0.3$ m below the soil surface. For short periods with high intensity rainfalls, the watertable 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

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

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. Therefore, the drains are equipped with check gates.

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 watertables may have a favourable effect on the soil structure or the quality of the soil's organic matter. There are indications that maintaining the watertable 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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