Table 15.5 Irrigation with water in which gypsum predominates (Example 15.2)

1	General data: W_{fc} = 300 m; $\overline{EC}_e$ = 0.5 dS/m; EC_{fc} (h.s.s.)* = 2.7 dS/m; $\overline{EC}_i$ (h.s.s.) = 0.9 dS/m; EC_i = 3.5 dS/m														
2	Ions in irr. water		Na	Mg	Ca	Total cations	HCO_3		Cl	SO_4	Total anions				
	mg/l		72	96	608	--	182		101	1660	--				
	meq/l		3	8	30	41	3		3	35	41				
3	Period		Year	Oct.	Nov.	Dec.	Jan.	Febr.	March	April	May	June	July	Aug.	Sept.
4	Land use		Irrigated fodder crops												
5	E−P	mm	900	40	0	−10	−10	25	50	75	90	150	170	170	150
6	I	mm	1080	60	0	0	0	0	90	90	120	160	200	200	160
7	ΔW	mm	0	0	0	0	0	−25	+25	0	0	0	0	0	0
8	R^x	mm	180	20	0	10	10	0	15	15	30	10	30	30	10
9	Z_1 (h.s.s.)	ECmm		1740	1680	1680	1625	1572	1572	1574	1576	1529	1620	1637	1652
10	ΔZ (h.s.s.)	ECmm	0	−60	0	−55	−53	0	+2	+2	−47	+91	+17	+15	+88
11	Z_2 (h.s.s.)	ECmm		1680	1680	1625	1572	1572	1574	1576	1529	1620	1637	1652	1740
12	EC_e (h.s.s.)	dS/m	2.7	2.9	2.8	2.8	2.7	2.6	2.6	2.6	2.6	2.5	2.7	2.7	2.7
13	EC_e (gypsum)	dS/m	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
14	EC_e (total)	dS/m	6.0	6.2	6.1	6.1	6.0	5.9	5.9	5.9	5.9	5.8	6.0	6.0	6.0

* h.s.s. = highly soluble salts

conductivity of a saturated solution of calcium carbonate and gypsum (3.3 dS/m) to the $EC_{e\,(h.s.s.)}$ to obtain the total EC_e (Line 14).

If we had calculated the amount of irrigation water without making a distinction between highly and slightly soluble salts, we would have found from Equation 15.22, for $EC_e = 6$ dS/m and $EC_i = 3.4$ dS/m, a value for I of 1255 mm instead of 1080 mm and for R^x 355 mm instead of 180 mm, which is twice the real leaching requirement. In the first case, the leaching fraction equals 0.28; in the second case 0.17.

It can be seen from the balance sheet (Table 15.5) that calcium precipitates in the soil in the following way. The calcium supply to the rootzone equals the product of irrigation supply, I, and its calcium concentration (1080 l/m^2 × 30 meq/l = 32400 meq/m^2). The removal of calcium is at most equal to the product of leaching water and its saturated concentration of calcium carbonate and gypsum (180 l/m^2 and 40 meq/l = 7200 meq/m^2). The difference between calcium supply and removal (25200 meq/m^2) represents the precipitation of calcium in the soil. As this will occur mainly in the form of gypsum (equivalent mass of $CaSO_4.2H_20$ = 86 mg/meq), it is estimated that 25200 × 86/10^6 = 2.2 kg of gypsum is precipitated per m^2 of soil, or 22 ton/ha. This precipitate is harmless to plant and soil. Soils irrigated with water containing gypsum will become enriched in gypsum and calcium carbonate and, after centuries of use, may even largely consist of such precipitates.

15.4 Salinization due to Capillary Rise

15.4.1 Capillary Rise

In irrigated areas, during intervals in irrigation or during fallow periods when there is no downward flow of percolation water, water can move upward by capillary forces.

The water will be taken up by the roots or evaporate at the surface and salt will accumulate in the rootzone or in the top layer.

The capillary upward flux varies with soil type, depth of watertable, and soil water gradient. Figure 15.11 presents the relation between capillary flow velocity and depth of watertable for three soil types. The figure was derived from data published by Rijtema (1969), who assumed a stable watertable and a gradual increase of the suction from zero at the groundwater level to a value of 16×10^5 Pa or 16 bar (pF = 4.2) at the soil surface, a value corresponding with a soil water content at wilting point. If the watertable remains at a constant level as a result of seepage inflow, the capillary rise will be considerable (e.g. 180 mm for a period of 6 months, which is 1 mm/d if the watertable remains at a depth of 1 m for a clay loam, at 1.95 m for a loam, and at 2.85 m for a silt loam). These values show that a higher silt content leads to more capillary rise.

If the groundwater is not fed by seepage, the capillary flow will cause the watertable to fall. The lower watertable will cause the capillary flow to decrease because of a decrease in the capillary conductivity. The end result will be that the watertable will have fallen to a depth where the capillary flow velocity approaches a zero value. Figure 15.12 gives an example of the moisture depletion of the soil by capillary flow in the case of a falling watertable, showing that only a small part of the water is provided by the soil profile below the initial watertable.

For the three soils presented in Figure 15.11, the fall of the watertable and the

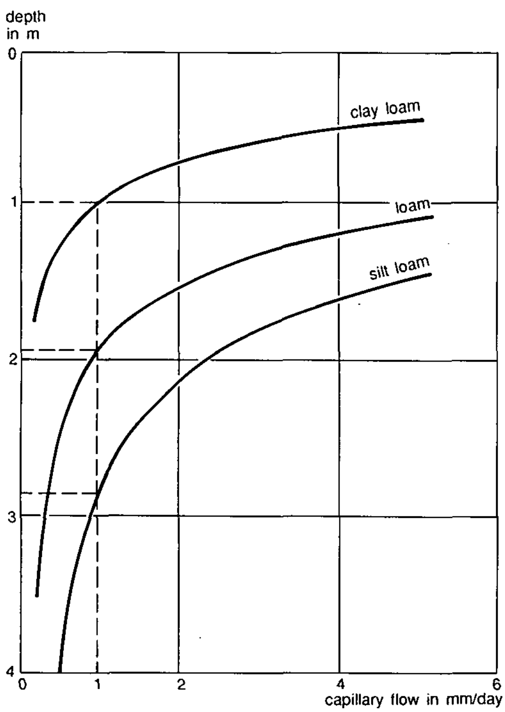


Figure 15.11 Relation between capillary flow velocity and depth of watertable for a suction of 16×10^5 Pa at the surface (after Van Hoorn 1979)

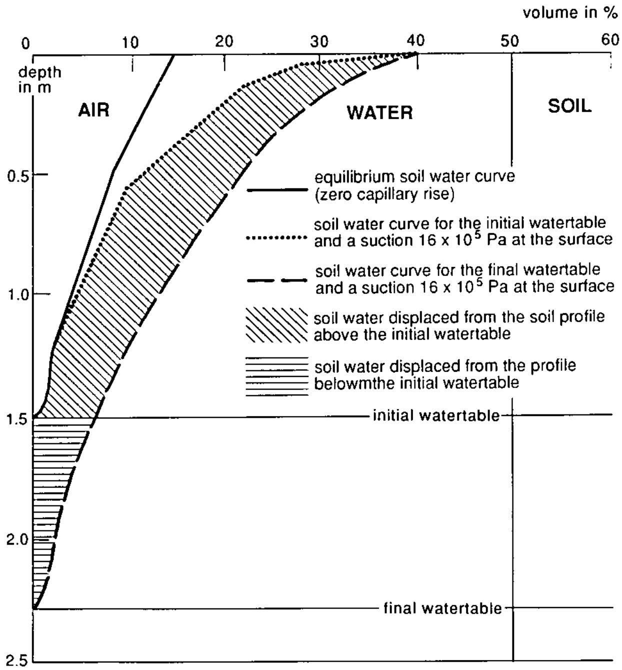


Figure 15.12 Soil water displaced by capillary rise in the case of a falling watertable (after van Hoorn 1979)

capillary rise during a six-month fallow period were calculated, again under the assumption of a gradual increase in the suction to a value of 16×10^5 Pa (pF = 4.2) at the surface. The results are presented in Table 15.6. These, too, show a clear difference between the soil types, the silt loam yielding the highest values. The deeper the watertable, the smaller the amount of capillary rise; moreover, the smaller the percentage of water originating from the soil profile below the initial watertable and the smaller the fall of the watertable during the fallow period.

In reality, capillary flow velocity, fall of the watertable, and amount of capillary rise will be less than the values presented in Figure 15.11 and Table 15.6. The assumption of a gradual increase in the suction towards the surface does not hold true because of the development of a surface mulch with a low water content that causes a rupture in the capillary conductivity.

Whether a surface mulch will develop depends on the local conditions of soil type, climate, and crop:

- A winter crop depleting the moisture content of the rootzone favours the development of a mulch layer to a considerable depth;
- Tillage of the surface layer has a similar effect;
- High evaporation exceeding the maximum capillary flow velocity is favourable for the development of a surface mulch, whereas an evaporation rate matching the maximum capillary flow velocity tends to cause a gradual increase in the suction towards the surface and is unfavourable for the development of a surface mulch;

Table 15.6 Fall of the watertable and amount of water displaced by capillary rise during a six-month fallow period

Initial watertable depth (m)	Soil type	Fall of watertable (m)	Average capillary velocity (mm/d)	Total capillary rise (mm)	Capillary rise from below initial watertable (mm)
1.00	Clay loam	0.90	0.3	50	25
	Loam	1.30	1.3	230	75
	Silt loam	1.90	2.0	350	140
1.50	Clay loam	0.50	0.2	35	10
	Loam	0.85	1.0	170	30
	Silt loam	1.45	1.7	300	70
2.00	Clay loam	0.25	0.1	20	5
	Loam	0.55	0.7	120	10
	Silt loam	1.05	1.3	230	30

- Summer rainfall, just wetting the soil and increasing its capillary conductivity, but not providing percolation for leaching, also has an unfavourable effect.

The fall of the watertable and the amount of capillary rise will vary for the same soil type, depending on local conditions. If capillary rise is not fed by seepage, the fall of the watertable will decrease to almost zero because capillary conductivity decreases with increasing depth of the watertable and, moreover, a surface mulch generally increases with time. The water level during the fallow period, at which capillary rise is reduced to almost zero can be defined as the critical depth.

15.4.2 Fallow Period without Seepage

In the case of a falling watertable without seepage, capillary rise originating from the soil profile below the initial watertable at the start of the fallow period will generally be small and can be reduced by lowering the initial watertable and by creating a mulch layer. Although the desiccation of the rootzone may be considerable, even amounting to 200 mm or more, the capillary rise from below the rootzone will usually be restricted to 20-50 mm, even in very dry climates. The best way to obtain data on desiccation and capillary rise is by sampling the soil at the beginning and end of the fallow period. The capillary rise during the fallow period can be regarded as negative percolation.

Under long-term equilibrium conditions and in the absence of seepage from elsewhere, the salt concentration of the soil water below the rootzone corresponds to that of the percolation water ($C_g = C_r$). So

$$EC_g = EC_r = \frac{I\overline{EC_i}}{R^x} \qquad (15.28)$$

in which $\overline{EC}_i$ stands for the average value during the irrigation period. The salt accumulation during the fallow period can be calculated as

$$\Delta Z = GEC_g = G \frac{I\overline{EC}_i}{R^x} \tag{15.29}$$

Table 15.7 illustrates the conditions in a soil that is cropped and irrigated during winter and remains fallow from April to October. The desiccation of the fallow soil is assumed to be 100 mm, the capillary rise 40 mm. This, together with a rainfall of 110 mm during this period, leads to an evapotranspiration of 250 mm. The total amount of irrigation water required can be calculated with Equation 15.22 and is found to be 365 mm. As E – P is 255 mm for the year, the net percolation is 365 – 255 = 110 mm.

It is reasonable to make a distinction between a desiccation of the rootzone (ΔW_r) and a desiccation of the subsoil (ΔW_s). The latter is assumed to be found between the lower boundary of the rootzone and the watertable. When water is applied, it is assumed that the soil water reservoir in the rootzone, which shows a deficit of 100 mm at the end of the fallow period, will be replenished first. Only when the rootzone is at field capacity will the deeper layer be wetted.

In October, the difference between the amount of irrigation water entering the rootzone and the evapotranspiration, I – (E – P), will replenish the soil water reservoir in the rootzone ($\Delta W_r = +65$ mm, Line 9). In November, the amount of I – (E – P) = 60 mm will partly replenish the soil water reservoir in the rootzone ($\Delta W_r = +35$ mm, Line 9) and partly the soil water reservoir in the subsoil ($\Delta W_s = +25$ mm, Line 11). So percolation starts in November, although no drainage will occur as long as the subsoil has not been replenished. In January, with water percolating through the rootzone and the subsoil, drainage will begin ($Dr = R^x - \Delta W_s = 45$ mm, Line 12).

The monthly variation in EC_e is calculated in the same way as in Table 15.3. Salt accumulation occurs during the fallow period and in October, whereas leaching occurs essentially in January and February.

If there is no seepage and we assume that C_g equals C_r, Equations 15.9 and 15.10 do not directly show an effect of capillary flow on the leaching requirement and on the total amount of irrigation water. However, in the case of capillary rise during either the growth or the fallow period, evapotranspiration increases and so, too, do the leaching requirement and the amount of irrigation water.

15.4.3 Seepage or a Highly Saline Subsoil

To illustrate the case of saline seepage from another area, we take the general data from Table 15.7

$$(E - P) = 255 \text{ mm}, \overline{EC}_i = 2.4 \text{ dS/m}, EC_{fc} = 8 \text{ dS/m}$$

If we assume a capillary flow, G, of 40 mm and $EC_g = 20$ dS/m, Equation 15.7 yields

$$R^x = 110 + 86 = 196 \text{ mm}$$

$$R = 196 + 40 = 236 \text{ mm and } I = 255 + 196 = 451 \text{ mm}$$

Table 15.7 Salt and water balance for a seasonally irrigated soil with capillary rise during the fallow period

1	General data: W_{fc} = 300 mm; EC_e = 0.5 EC_{fc}; $\overline{EC_e}$ = 4 dS/m; G = $-R^x$ = 40 mm during fallow									
2	Period		Year	Oct.	Nov.	Dec.	Jan.	Febr.	March	Apr. – Sept.
3	Land use				Irrigated cereals					Fallow
4	E	mm	655	60	60	60	60	75	90	250
5	P	mm	400	40	50	60	50	50	40	110
6	E−P	mm	255	20	10	0	10	25	50	140
7	EC_i	dS/m	2.4	3	3	2	2	2	2	
8	I	mm	365	85	70	0	70	70	70	0
9	ΔW_r	mm	0	+65	+35	0	0	0	0	−100
10	R^x	mm	110	0	25	0	60	45	20	−40
11	ΔW_s	mm	0	0	+25	0	+15	0	0	−40
12	Dr	mm	110	0	0	0	45	45	20	0
13a	Z_1	ECmm		2000	2255	2276	2276	1990	1842	1858
14a	ΔZ	ECmm	+176	+255	+21	0	−286	−148	+16	+318
15a	Z_2	ECmm		2255	2276	2276	1990	1842	1858	2176
13b	Z_1	ECmm		3000	3255	3196	3196	2742	2490	2465
14b	ΔZ	ECmm	−217	+255	−59	0	−454	−252	−25	+318
15b	Z_2	ECmm		3255	3196	3196	2742	2490	2465	2783
13c	Z_1	ECmm		2465	2720	2704	2704	2339	2142	2139
14c	ΔZ	Ecmm	−8	+255	−16	0	−365	−197	−3	+318
15c	Z_2	Ecmm		2720	2704	2704	2339	2142	2139	2457
16	EC_e*	dS/m	4.0	4.1	4.5	4.5	4.5	3.9	3.6	3.5

* EC_e at start of period or month considered

Comparing this result with that obtained in Table 15.7 (R^x = 110 mm and I = 365 mm), we see that the amount of irrigation water must be increased by 86 mm to counterbalance the capillary flow caused by highly saline seepage water. If capillary rise due to saline seepage amounts to 80 mm and evapotranspiration minus rainfall increases to 295 mm, R^x increases to 298 mm and I to 593 mm. So saline seepage leads to a considerable increase in the leaching requirement.

If there is no seepage but a highly saline subsoil for which we cannot assume that C_g equals C_r, the increase in the salinity of the rootzone during a fallow period can be estimated in the following way. The amount of salt in a soil profile can be calculated with Equation 15.30

$$S = C \times w \times D \times \frac{\rho_b}{\rho_w} \tag{15.30}$$

where

S = amount of salt (kg/ha)
C = salt concentration (g/l or kg/m^3). To express this in terms of electrical conductivity, C can be replaced by approximately 0.7 EC dS/m
w = water content in mass percentage
D = depth of rootzone (cm)
ρ_b = bulk density of soil (kg/m^3)
ρ_w = density of water = 1000 (kg/m^3)

The increase of EC_e can be calculated by slightly modifying Equation 15.30

$$\Delta EC_e = \frac{\Delta S}{0.7 \times w_e \times \rho_b/\rho_w \times D} \tag{15.31}$$

Table 15.8 gives the increase in salt content of the rootzone due to capillary flow. The following values have been assumed: w_e = 50, ρ_b = 1500 kg/m^3, and D = 50 cm. Moreover, the capillary flow amounts to 400 m^3/ha (= 40 mm). The increase in salt content is then obtained by multiplying the capillary flow by the salt content of the soil water.

Table 15.8 Increase in salt content due to capillary flow

Salinity of subsoil			ΔS from 40 mm capillary rise	ΔEC_e in upper 50 cm
Saturated paste	Soil water			
EC_e (dS/m)	EC (dS/m)	C g/l	(kg/ha)	(dS/m)
25	50	35	14000	5.3
20	40	28	11200	4.3
15	30	21	8400	3.2
10	20	14	5600	2.1
5	10	7	2800	1.1

Even a small amount of highly saline capillary flow is already harmful after one fallow period. If the salt concentration of the capillary flow is low, soil salinity will also increase when the process continues from year to year and the salts are not washed out during the winter period.

15.4.4 Depth of Watertable

The criteria for watertable depth depend, for the irrigation season, on aeration requirements of the crops and, for the fallow season, on the prevention of capillary salinization. For the irrigation season, the following values can be used (FAO 1980):
- For field crops and vegetables, a depth between 1.0 m and 1.2 m;
- For fruit trees, a depth between 1.2 and 1.6 m.

The shallower depths refer to coarse-textured soils, the greater depths to fine-textured soils. The values correspond with the average watertable depth as used in the steady-state equations for drain spacing (Chapter 8). If unsteady-state drain spacing equations are used, the watertable depth should correspond with the minimum depth not to be exceeded:
- For field crops and vegetables, about 0.9 m;
- For fruit trees, between 1.0 m and 1.4 m.

Drainage criteria are discussed in Chapter 17.

During the irrigation season, there is no risk of capillary salinization owing to the prevailing percolation, even if seepage occurs (Figure 15.13). During the fallow season, however, capillary rise can add greatly to the salinization of the rootzone (Figure 15.14).

If there is no seepage, as was pointed out in Section 15.4.1, capillary rise will cause the watertable to fall during the fallow period to a depth at which capillary flow is reduced to almost zero. With long-term equilibrium between rootzone and subsoil, the salt concentration of the upward flow equals that of the percolation water. This leads to a reduction in the net percolation (Section 15.3.1), which means a reduction in the leaching fraction. The real leaching fraction of low and medium salinity water is generally higher than the fraction needed to cover the leaching requirement. In that case, capillary rise is not likely to lead to salinization.

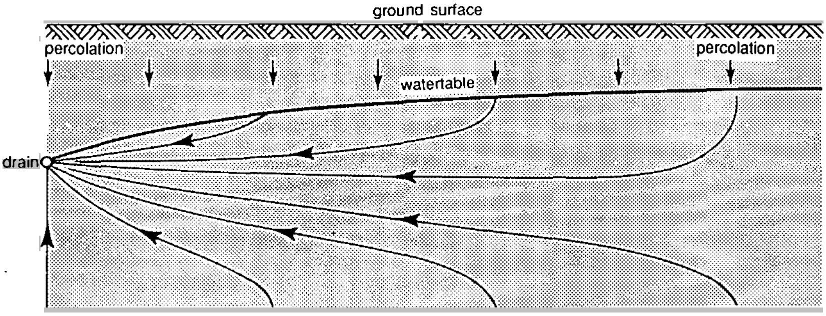


Figure 15.13 Flow lines in the case of irrigation and seepage

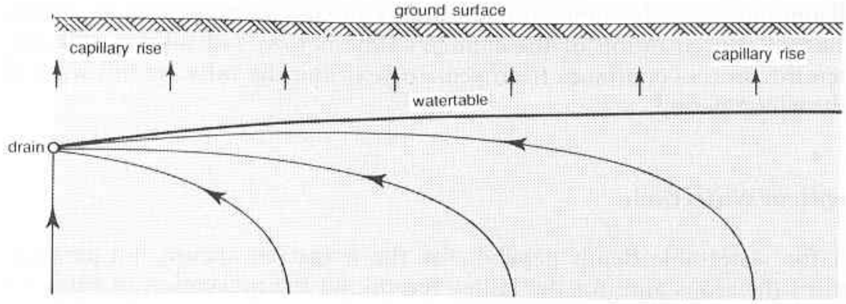


Figure 15.14 Flow lines in the case of evaporation and seepage

If, in contrast, there is seepage or saline subsoil water, capillary rise in the fallow period will contribute greatly to the salinization of the rootzone, as was pointed out in Section 15.4.3.

To reduce the salinization hazard during the fallow season, the watertable should be kept at a depth below about 1.40 m for sandy and clayey soils and below about 1.70 m for silty soils.

Sandy soils have a high capillary velocity, but a limited height of capillary rise. Clay soils have a low capillary velocity, but theoretically a considerable height of capillary rise. In practice, however, this height is quite limited because of the cracks that appear when the soils dry out and cut the capillary system. In contrast, silty soils with a large silt fraction (2-50 μm), which do not form cracks when dry, are the most dangerous ones for salinization because they combine an average capillary velocity with a considerable height of capillary rise.

Keeping the watertable below a depth of 1.40 m for sandy and clayey soils and below 1.70 m for silty soils is not an absolute guarantee against salinization. If capillary rise in the fallow season is not offset by percolation, all soils will become salinized in the long run, even with watertables at depths of 3 to 4 m, as is found in examples of the 'source-sink' system in the Punjab (Figure 15.15). The 'source' (irrigated land) has a shallow watertable, and salinity increasing with depth, a clear indication of prevailing downward percolation. The 'sink' (neighbouring non-irrigated land) has a deep watertable, often between 3 and 4 m, with soil salinity increasing towards the surface, indicating prevailing upward flow.

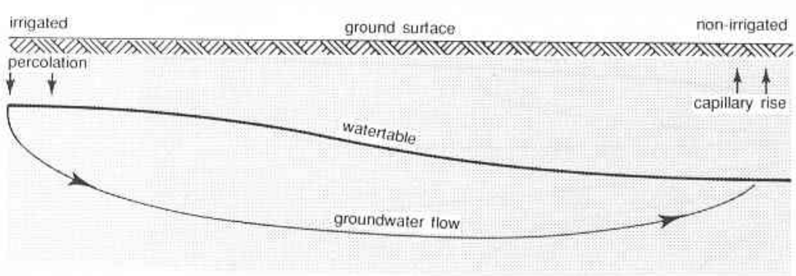


Figure 15.15 Watertable in irrigated and non-irrigated land

In the long run, capillary flow should always be counterbalanced by percolation. As long as the downward movement of water prevails over upward flow, there is no risk of increasing salinity. The salinity level of the soil depends upon the net percolation and the salt concentrations of irrigation water and capillary water from the subsoil.

15.5 Leaching Process in the Rootzone

15.5.1 The Rootzone regarded as a Four-Layered Profile

In Section 15.3.1, the rootzone was regarded as a one-layered profile of homogeneous salinity. In reality, the rootzone is a column in which the water uptake by the crop decreases with depth. The amount of water percolating through the soil profile thus also decreases with depth whereas its salinity increases. As a result, the salinity of the soil increases with depth.

Figure 15.16 shows an example of the calculation of a salinity profile expected to develop after the long-term use of irrigation water (EC_i = 1 dS/m) at five leaching fractions. The calculation assumes the following water-uptake pattern:
- 40% from the upper one-quarter of the rootzone;
- 30% from the second quarter;
- 20% from the third quarter;
- 10% from the lowest quarter.

The amount of irrigation water applied to the first layer and the amount of water percolating from the fourth layer can be calculated for the successive values of the leaching fraction, LF, by the following equations, which are derived by combining Equations 15.8 and 15.11.

$$I = (E - P)\frac{1}{1 - LF} \qquad (15.32)$$

$$R^x = (E - P)\frac{LF}{1 - LF} \qquad (15.33)$$

Table 15.9 shows the calculations. The percolation from each layer equals the irrigation water of that layer minus the water uptake. Percolation water from the first

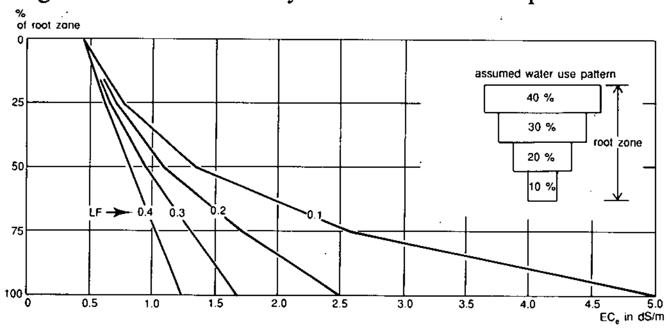


Figure 15.16 Salinity profile expected to develop after the long-term use of irrigation water of EC = 1.0 dS/m at various leaching fractions, LF (after FAO 1985)

Table 15.9 Calculation of the soil salinity in a four-layered profile (EC_i = 1 dS/m, LF = 0.2 → I = 1.25(E-P), R^x = 0.25(E-P))

Layer	Water uptake	I	R^x	EC_i	$EC_{fc} = 2EC_e$	EC_e
1	0.4(E−P)	1.25(E−P)	0.85(E−P)	1.0	1.47	0.74
2	0.3(E−P)	0.85(E−P)	0.55(E−P)	1.47	2.27	1.14
3	0.2(E−P)	0.55(E−P)	0.35(E−P)	2.27	3.57	1.79
4	0.1(E−P)	0.35(E−P)	0.25(E−P)	3.57	5.00	2.50
Average					2.66	1.33

layer serves as irrigation water for the second layer, and so on. The salt equilibrium equation, Equation 15.23, is applied to each of the four layers. For the first layer, EC_i represents the salinity of the irrigation water; for the second layer, the salinity of the water percolating from the first layer, and so on: $(EC_i)_n = (EC_{fc})_{n-1} = (2EC_e)_{n-1}$. The average soil salinity equals the sum of EC_i (soil water salinity at the surface) and the four values of EC_{fc} (soil water salinity at the bottom of each layer) divided by 5.

For the water-uptake pattern described above, Figure 15.17 presents the relation between the salinity of the irrigation water, expressed as EC_i, and the average salinity of the soil profile, expressed as EC_e. It should be understood that the salinity of the water percolating from the bottom of the soil profile is almost twice the average EC_{fc}-value (e.g. in Table 15.9, 5.0 instead of 2.66). The lower the leaching fraction, the

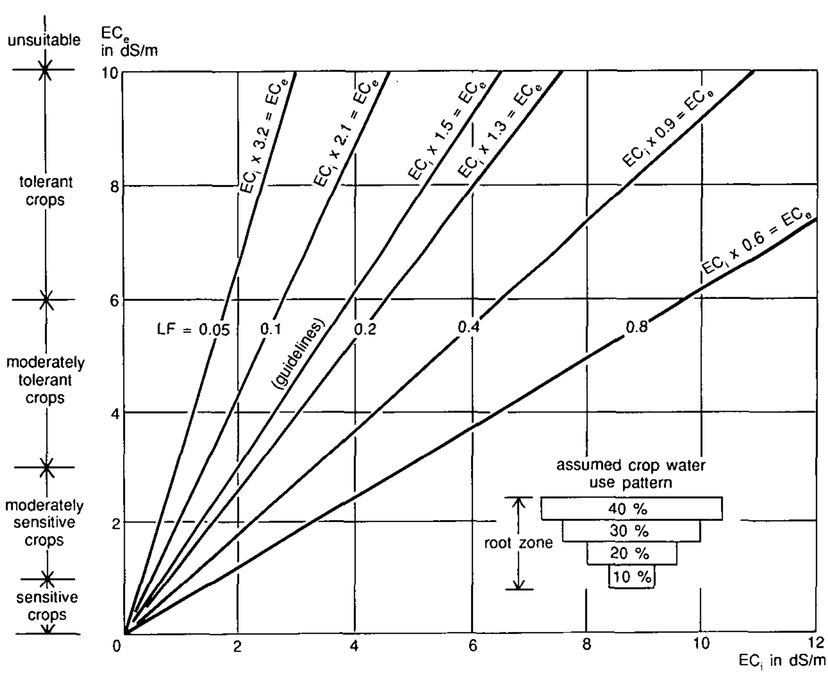


Figure 15.17 Effect of water salinity, EC_i, upon rootzone soil salinity, EC_e, at various leaching fractions, LF (after FAO 1985)

larger the difference between the average salinity and the salinity at the bottom of the root zone.

For the same water-uptake pattern, Figure 15.18 shows the difference between the leaching fraction for a one-layered rootzone and that for a four-layered rootzone, corresponding with the same ratio EC_e:EC_i. By using the concept of a one-layered rootzone, we clearly overestimate the leaching requirement.

An example taken from practice is presented in Figure 15.19. It concerns an irrigation test conducted at the Cherfech Experimental Station in Tunisia. The test consisted of four applications of irrigation water of about 2.3 g/l (EC_i = 3.5 dS/m). The applications I_1, I_2, and I_3 are respectively equal to 1.5, 2, and 2.5 times I_0. In summer, the applications I_0, I_1, I_2, and I_3 correspond to a daily supply of 4, 6, 8, and 10 mm/d, ranging around the consumptive use of 7 mm/d. As can be seen in the figure, there is a marked increase in salinity with depth, and a clear difference in soil salinity due to increasing amounts of leaching water (from I_0 to I_3).

15.5.2 The Leaching Efficiency Coefficient

In a porous medium, salt is displaced by mass flow and molecular diffusion. The most simple case of salt displacement is by piston flow. This displaces one solution with another, with a sharp boundary between the two solutions and, when the volume of the effluent equals the volume of water initially present in the pore volume, an abrupt change in the concentration of the effluent from C_o to C_i (Figure 15.20). Even in a homogeneous medium with a uniform pore size distribution, however, such an abrupt change is not likely to occur because the molecular diffusion at the boundary between the two solutions will prevent it. The lower the flow velocity, the more diffusion will occur and the less steep will be the slope of the breakthrough curve.

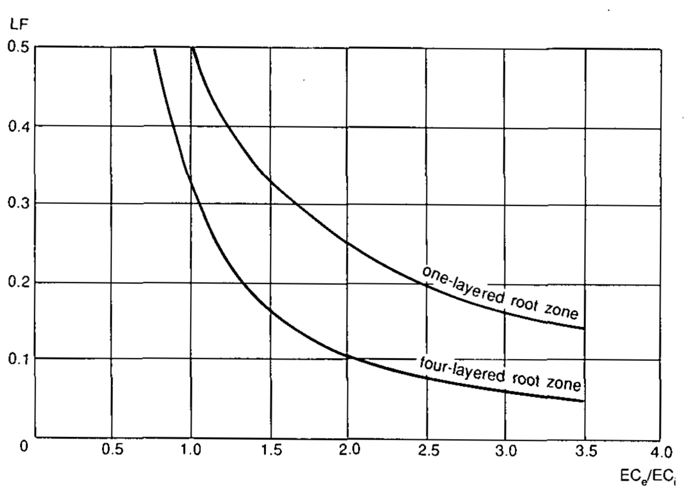


Figure 15.18 EC_e/EC_i versus the leaching fraction, LF, for a one-layered rootzone and a four-layered rootzone

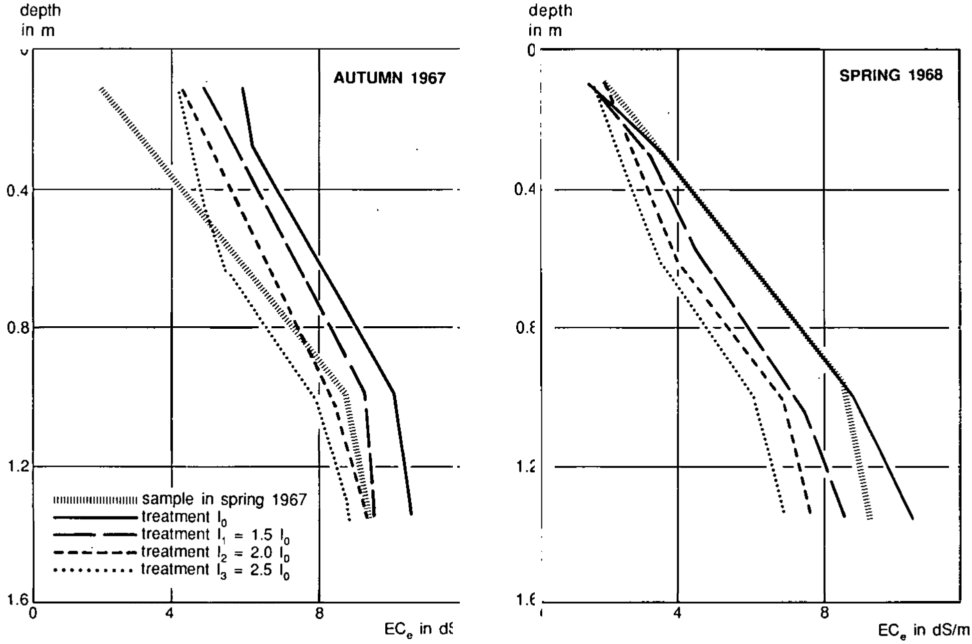
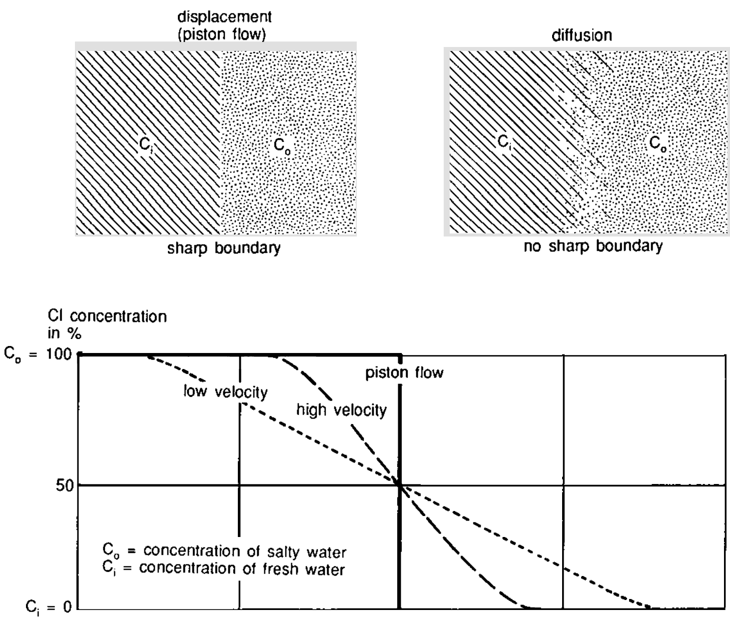


Figure 15.19 Irrigation test showing increase in salinity with depth and difference in soil salinity due to increasing amounts of leaching water



In a heterogeneous porous medium like soil, water moves through a complicated network of tortuous pores of different sizes. Because the flow velocity is higher in large pores than in small ones and is, moreover, higher in the centre of a pore than along its wall, the flow velocity is not equally distributed. Two solutions moving through such a medium will therefore mix. The mixing caused by the uneven distribution of the flow velocity is called dispersion. As diffusion also occurs in the cavities formed by the pores, the solutions are mixed by a combination of dispersion and diffusion, which is called miscible displacement (Biggar and Nielsen 1960). Other processes that affect salt displacement are ion exchange and precipitation or dissolution of salts.

In a soil profile, the incoming water may either completely mix with the soil solution or only partially – some of the water passing through large channels or pores without making contact with the soil solution.

Figure 15.21 shows the chloride concentration of soil water at increasing depth, versus the amount of drainage water, when a soil profile consisting of 1 m sandy loam on coarse sand is leached. It appears that the chloride concentration of the drainage water, being the same as that of the soil water at a depth of 1.075 m in the underlying sand layer, soon reduces to values less than those at depths of 0.675 and 0.925 m. After about 300 mm of drainage water, part of the percolation water apparently moves directly from the upper layers through large, already desalinized pores in the lower layers, towards the sand layer without mixing with the soil water in the lower layers.

The degree to which the incoming water mixes with the soil solution can be expressed by a leaching efficiency coefficient, which can be defined in two ways:

- With respect to the percolation water at the bottom of the rootzone: the leaching efficiency coefficient, f_r, is then defined as the fraction of water percolating from

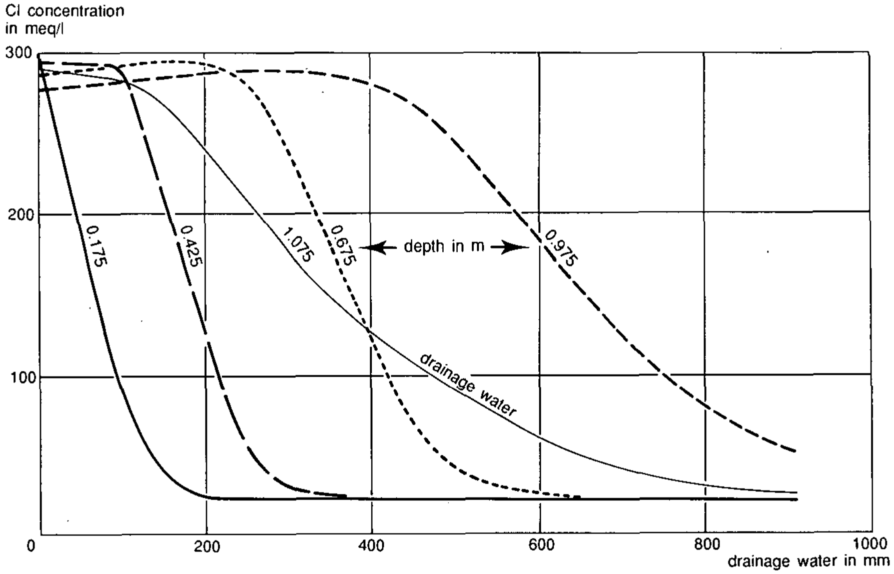


Figure 15.21 Chloride concentration of drainage water and of soil water at increasing depth versus amount of drainage water during leaching of a sandy loam profile (after Van Hoorn 1981)

the soil solution. This concept of leaching efficiency was originally introduced by Boumans for reclamation experiments in Iraq (Dieleman 1963);
- With respect to the irrigation water: the leaching efficiency coefficient, f_i, is then defined as the fraction of irrigation water mixing with the soil solution.

The concept of the leaching efficiency coefficient is presented in Figure 15.22.

If we consider a cycle at the start and the end of which the soil water content is the same (equilibrium condition), we can write for the amount of percolation water at the bottom of the rootzone

$$R^x = f_r R^x + (1 - f_r) R^x \tag{15.34}$$

and

$$R^x = (f_i I - E + P) + (1 - f_i) I \tag{15.35}$$

Since $(1 - f_r)R^x = (1 - f_i)I$, we obtain the following relation between f_r and f_i

$$f_r R^x = f_i I - E + P \tag{15.36}$$

Example 15.3
$P = 0$, $E = 600$ mm, $I = 1000$ mm, $f_i = 0.8$.
So $R^x = 400$ mm and $f_r = (0.8 \times 1000 - 600)/400 = 0.5$; 200 mm of water percolates from the soil solution and 200 mm passes through the bypass.

The coefficient, f_r, is not an independent variable, but depends upon the leaching efficiency coefficient, f_i, and upon the amounts of water (irrigation, rainfall, evapotranspiration). Figure 15.23 presents the relation between f_r, f_i, $(E-P)/I$, and R^x/I, showing a decrease in f_r if f_i and the fraction of percolation water R^x/I decrease. In contrast, the coefficient, f_i, the fraction of irrigation water mixing with the soil solution, can be considered an independent variable, determined by soil texture, structure, and irrigation method.

Fine-textured soils show a lower value for f_i because of the presence of cracks in these soils. The amount of water applied and the irrigation method also considerably influence the value of f_i. In general, the larger the water applications, the smaller the leaching efficiency coefficient. The highest efficiency is obtained with low intensity sprinkling or with rainfall.

Field experiments in Tunisia showed a variation of f_i from 0.60 to 0.95 on the same soil profile, the differences being due to the different ways in which water was applied (Unesco 1970). For medium- and fine-textured soils and moderate water applications, which caused drainage of about 20% of the amount of precipitation and irrigation,

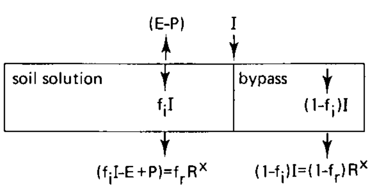


Figure 15.22 The concept of the leaching efficiency coefficient

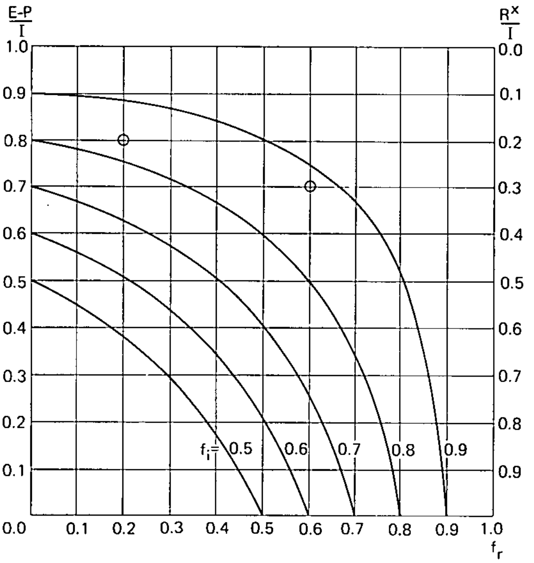


Figure 15.23 Relation between the fraction of water percolating from the rootzone, f_r, and the fraction of irrigation water mixing with the soil solution, f_i

a value of 0.85 was obtained for f_i, whereas on a sandy soil values between 0.95 and 1.0 were obtained.

Field experiments in Iraq showed the leaching efficiency coefficient, f_r, as ranging from 0.2 for clay to 0.6 for silty loam (Dieleman 1963). The large range may be abscribed partly to a difference in the value of f_i and partly to the smaller fraction of water that percolates from clay soils; for instance, combining in Figure 15.23 an R^x/I-value of 0.2 with an f_r-value of 0.2 or an R^x/I-value of 0.3 with an f_r-value of 0.6 yields in both cases an f_i-value of about 0.85.

15.5.3 The Leaching Efficiency Coefficient in a Four-Layered Profile

The four-layered concept, in assuming a decreasing water uptake with depth, certainly far better describes the water and salt movement and the salinity profile to be expected than the one-layered concept. Nevertheless, when we change from the simple concept of a one-layered profile to the more complicated concept of a four-layered profile so as to approach reality better, we must also take into account the reality that a part of the water is passing through large channels and pores and is not efficient in leaching salts.

If part of the water only is efficient for leaching, the leaching fraction is not equal to the ratio between the amounts of percolation and irrigation water, R^x/I, but equals the ratio between the amount of water percolating from the soil solution, $f_iI - E + P$, and the amount of irrigation water mixing with the soil solution, f_iI. Thus

$$LF_b = (f_iI - E + P)/f_iI \qquad (15.37)$$

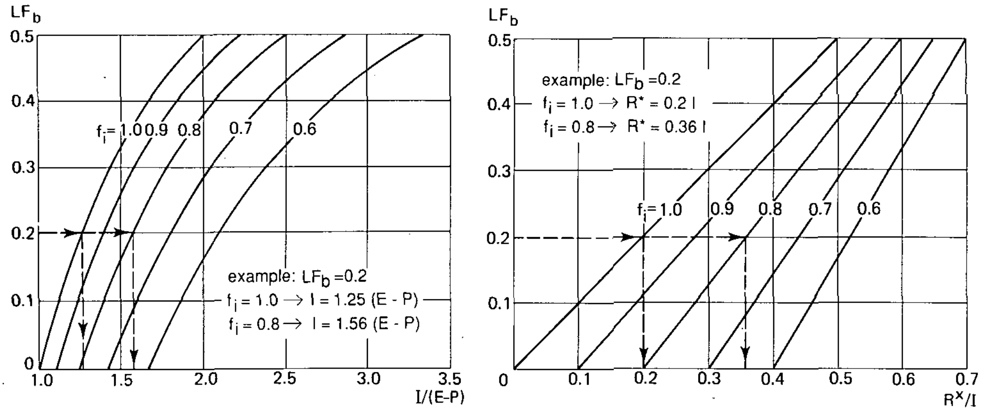


Figure 15.24 Relation between LF_b, f_i, $I/(E-P)$, and R^x/I

where the subscript b stands for bypass
and

$$I = (E - P)\frac{1}{f_i(1 - LF_b)} \tag{15.38}$$

Substituting Equation 15.38 into Equation 15.35 gives

$$R^x = (E - P)\frac{1 - f_i(1 - LF_b)}{f_i(1 - LF_b)} = I - (E - P) = I\{1 - f_i(1 - LF_b)\} \tag{15.39}$$

Now the values of I and R^x are calculated with Equations 15.38 and 15.39 or obtained from Figure 15.24.

Table 15.10 draws a comparison between a one-layered rootzone with an f_i-value of 1 and a four-layered rootzone with different f_i-values. The ratio EC_e/EC_i varies from 1.5 to 2.5. This means that the salt concentration of the soil water ranges from three to five times that of the irrigation water, which may be considered a normal range under good irrigation and drainage conditions. Table 15.10 was obtained by taking, for the three EC_e/EC_i ratios, the corresponding LF-values from Figure 15.17 and by calculating the values I and R^x with Equations 15.38 and 15.39 respectively.

Table 15.10 Comparison between a one-layered rootzone with an f_i-value of 1 and a four-layered rootzone with various $f_i$values. R^x and I are expressed in % of the values calculated for the one-layered concept

	Leaching requirement R^x			Irrigation water I		
EC_e/EC_i	1.5	2.0	2.5	1.5	2.0	2.5
f_i = 1.00	40	35	35	80	84	87
0.95	53	53	58	84	88	92
0.90	67	72	83	89	93	97
0.85	83	94	112	94	99	102
0.80	100	119	144	100	105	109

It appears that, for an f_i-value of 0.85, the differences in the amount of irrigation water are less than 10%, whereas the differences in the leaching requirement are somewhat greater, but do not exceed 20%; for an f_i-value of 0.95, the difference in I will be between 8 and 16% and the differences in R^x will rise to about 50%.

When a high leaching efficiency coefficient can be expected (e.g. under drip, sprinkler, or careful surface irrigation on coarse-textured soils), the use of the one-layered concept will overestimate the amount of irrigation water and especially the leaching requirement. In that case, it may be better to use the four-layered concept. For an average f_i-value between 0.8 and 0.9, the differences between the two concepts are small. The overestimate of the leaching requirement by assuming a rootzone with a homogeneous water and salt distribution is offset by the fact that, in reality, irrigation water is not fully efficient in leaching. For practical purposes, we can just as well estimate the leaching requirement by using the simple concept of a one-layered rootzone with complete mixing of irrigation and soil water. In reality, the salinity of the upper part of the rootzone will tend to be somewhat lower than the average value and that of the lower part will be somewhat higher.

15.6 Long-Term Salinity Level and Percolation

By using the one-layered concept with complete mixing, no saline seepage, and no precipitation of salts, we can estimate the long-term salinity level of the rootzone as found with Equation 15.23

$$EC_e = \frac{EC_i}{2LF} = \frac{n\,EC_i}{2} \tag{15.40}$$

in which n stands for the concentration factor of the irrigation water, which equals the inversed value of the leaching fraction, LF, or net percolation. We then adapt the choice of the crops to this estimated level. Instead of first choosing the crops and then calculating the leaching requirement for the salinity level corresponding with those crops, it is more practical to estimate first the salinity level from the quality of the irrigation water and the long-term percolation losses, which means the real leaching fraction, and then to choose the crop. Figure 15.17, in which the crop classes are indicated along the axis of the soil salinity, follows this approach.

To estimate the long-term salinity level of the rootzone in areas where leaching is provided by a combination of irrigation water and rainfall, we should use a weighted average of the salt concentration of these combined waters. Neglecting the salt concentration of rainfall, we can use the following expression

$$EC_{i+p} = \frac{I}{I+P} \times EC_i \tag{15.41}$$

and, to estimate the long-term salinity level of the rootzone,

$$EC_e = \frac{n}{2} \times \frac{I}{I+P} \times EC_i = \frac{1}{2LF} \times \frac{I}{I+P} \times EC_i \tag{15.42}$$

Table 15.11 presents the water balance of a tile-drained field of the Experimental

Table 15.11 Percolation losses (R) from irrigation (I) and precipitation (P), measured as drain discharge on a tile-drained field in Tunisia

		Summer					Winter				
		1964	1965	1966	1967	1968	64–65	65–66	66–67	67–68	68–69
I	(mm)	452	645	530	860	1373	110	100	467	182	445
P	(mm)	112	19	69	4	53	441	445	323	324	221
R	(mm)	121	141	138	217	304	139	56	200	141	131
R/(I+P)	(%)	21	21	23	25	21	25	10	25	28	20

Station at Cherfech in Northern Tunisia. The net percolation losses, carried off as drainage water, equalled 0.22 of the total amount of irrigation water and precipitation. During summer, the losses were mainly due to an excess of irrigation water and, during winter, to a combination of irrigation water and rainfall.

The average amount of irrigation water equalled about 1000 mm and the precipitation 400 mm, leading to a factor of 0.7 for I/(I + P). The long-term salinity level in the rootzone could then be estimated at $EC_e = 1.5EC_i$. Since the weighted average of EC_i equalled 3.3 dS/m for the field over the period of 5 years, the estimated EC_e-value ranged around 5 dS/m, corresponding quite well with soil analysis data of the rootzone.

Figure 15.25 shows the long-term effect of the salinity of irrigation water on soil salinity as determined in a water-quality test at the same experimental station, where four different water qualities were applied: A 0.3, B 2.1, C 3.5, and D 5.2 dS/m. In the upper 0.40 m, a clear seasonal fluctuation can be seen, which is attributable to less irrigation water and more rainfall during winter. Differences between successive years are also apparent because of changes in leaching conditions (crop, irrigation regime, and irrigation method).

Table 15.12 summarizes the average values of EC_i, EC_e, and EC_{i+p} as well as the ratios EC_e/EC_i and EC_e/EC_{i+p} for the rootzone between 0 and 0.80 m. For the EC_i-values of 2.1 and 3.5 dS/m, the ratio EC_e/EC_i is about 1.5 and the ratio EC_e/EC_{i+p} between 2.2 and 2.5. This means a concentration factor for the soil water between 4.4 and 5 and a leaching fraction between 0.20 and 0.23. The lower ratios for an EC_i-value of 5.2 dS/m can be ascribed to the precipitation of $CaCO_3$ and $CaSO_4$. The large discrepancy for an EC_i-value of 0.3 dS/m can be ascribed to the presence of $CaCO_3$ and $CaSO_4$ in the soil. In evaluating the leaching process, it is often better to express soil salinity in terms of chloride concentration instead of electrical conductivity, because the chloride ion is not involved in precipitation or adsorption reactions in the soil.

Table 15.13 presents another example of the effect of irrigation-water salinity on soil salinity. The lower limits of soil salinity are the same for approximately the same salinity of the irrigation water. The lower EC_e of 2.5 at Ksar Gheriss can be ascribed to the coarse texture of the soil (i.e. loamy sand), which gives too optimistic an index of salinity when expressed as EC_e. With sand and loamy sand, w_e equals three to four times w_{fc}, so that EC_{fc} equals three to four times EC_e instead of two times EC_e. The higher EC_e-value of 5 at Tozeur can be ascribed to the gypsum content of the soil.

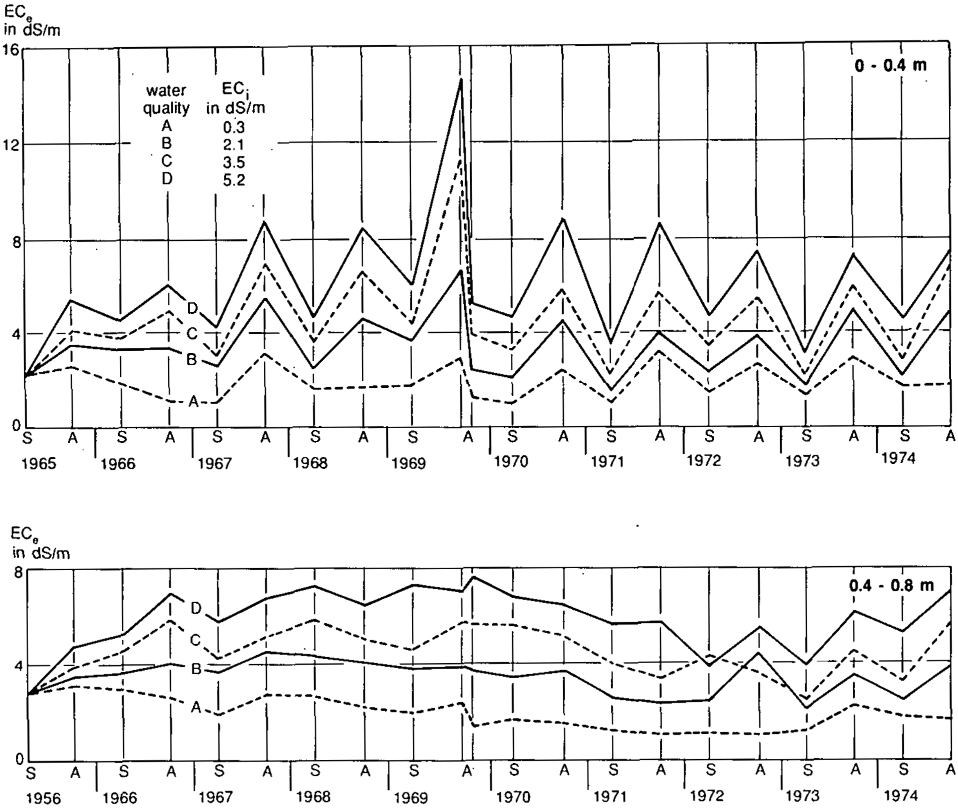


Figure 15.25 Water-quality test showing different long-term soil salinity levels

The upper limits of soil salinity vary widely because of differences in irrigation regime and method during summer.

With increasing salt concentrations in the irrigation water, the examples presented in Figure 15.25 and Table 15.13 clearly show increasing levels of soil salinity, which can be estimated from the salt concentration of the irrigation water, precipitation, and long-term percolation losses. The choice of crops should be adapted to these levels.

The relation $EC_e = 1.5 EC_i$, indicated in Figure 15.17, is used in FAO's Irrigation

Table 15.12 Long-term salinity levels in water-quality test

Quality		A	B	C	D
EC_i	(dS/m)	0.3	2.1	3.5	5.2
EC_e	(dS/m)	1.8	3.6	5.0	6.2
EC_e/EC_i	(-)	6.0	1.7	1.4	1.2
EC_{i+p}	(dS/m)	0.2	1.4	2.3	3.5
EC_e/EC_{i+p}	(-)	9.0	2.5	2.2	1.8

Table 15.13 Upper and lower limits of soil salinity attained under different conditions in Tunisia

Station	Soil texture	Rainfall, mm/year	EC_i dS/m	EC_e (dS/m) in soil layer 0–0.40 m	
				Min.	Max.
Cherfech	Fine	420	0.3	1	3
			2.0	2	5
			3.5	3	7
			5.2	4	9
Messaoudia	Fine	280	2.8	3	9
Nakta	Medium	200	5.5	4	12
Ksar Gheriss	Coarse	150	4.9	2.5	10
Tozeur	Coarse, gypsum	90	3.1	5	8

and Drainage Paper 29 (FAO 1985) as a guideline for estimating the average salinity of the rootzone. The relation corresponds quite well with the examples from Tunisia, which were obtained on medium- and fine-textured soils under good irrigation and drainage conditions, and where precipitation provided about one-third of the total amount of water. But it should be clearly understood that this relation may change in the absence of rainfall or under different soil and drainage conditions that affect percolation.

On coarse-textured soils with a high infiltration rate and excellent natural drainage, high leaching fractions of 0.40 are possible. On such soils, therefore, under desert conditions and for salt-tolerant crops, high-salinity water, even with an EC_i of 6 dS/m, can be used.

On medium- and fine-textured soils, according to experience on clay loam and silty clay loam soils in Tunisia, an increase in the fraction of percolation water above about 0.25 should be avoided; otherwise, crops will suffocate from excessive watering and waterlogging. When using high-salinity water on such soils, it is useless to apply large amounts of water in an attempt to reduce soil salinity. One merely increases the risk of water stagnation and conditions that are too wet for plant growth. Instead of applying more leaching water, it is better to adapt the choice of the crops to the salinity level of the soil, as is commonly done in practice.

On heavy clay soils of low permeability (e.g. silty clay and clay soils in river basins), the net percolation fraction may not exceed 0.10, even if a good drainage system is present. On such soils, therefore, low-salinity water, preferably with an EC_i less than 0.5 dS/m, should be used.

Percolation losses vary with irrigation method, application practices, and soil types, as is shown in Table 15.14. The term 'fine' in the table refers to a range of finer-textured permeable soils, and 'coarse' to a range of coarser soils with a good-to-fair water-holding capacity. The fractions given do not apply to soils with extreme values of hydraulic conductivity and infiltration rate.

Although the losses are not equally distributed over the field – their pattern varying from year to year according to the irrigation method and the amount of water applied – the minimum percolation losses with surface irrigation and sprinkling can be

Table 15.14 Estimated deep percolation fractions as related to water application efficiency, irrigation method, and soil type (FAO 1980)

Irrigation method	Application practices	Field application efficiency in %		Average deep percolation as fraction of irrigation water delivered to the field	
		Soil texture		Soil texture	
		Fine	Coarse	Fine	Coarse
Sprinkler	Daytime application, moderately strong wind	60	60	0.30	0.30
	Night application	70	70	0.25	0.25
Trickle		80	80	0.15	0.15
Basin	Poorly levelled and shaped	60	45	0.30	0.40
	Well levelled and shaped	75	60	0.20	0.30
Furrow, Border	Poorly graded and sized	55	40	0.30	0.40
	Well graded and sized	65	50	0.25	0.35

estimated at around 0.20-0.25 for a large range of soils, if provided with sufficient drainage. The percolation losses will be higher for very coarse soils (e.g. sand) and lower for very fine soils (e.g. silty clay and clay).

Table 15.15 presents the relation between the leaching fraction (LF), the concentration factor ($n = 1/LF$), and the electrical conductivity of the saturation extract for a range of increasing conductivities of irrigation water. In this table, EC_i can be replaced by EC_{i+p}, if rainfall provides a contribution to leaching.

A comparison between the percolation fractions of Table 15.14 and the leaching fractions of Table 15.15 leads to the conclusion that, if we take an EC_e-value of about 2 as criterion, the percolation fraction exceeds the leaching requirement for low-salinity water (EC_i 0.25-0.5 dS/m) and for medium-salinity water (EC_i 0.5-1.0 dS/m). For high-salinity water ($EC_i > 1.0$ dS/m), a percolation fraction of about 0.20-0.25 is needed for leaching, but, on most soils, higher losses should be avoided to prevent damage from excessive water. The amount of subsurface water to be drained off in irrigated areas should therefore be based on the expected percolation fraction and not on the leaching requirement.

Salinity control can normally be achieved by draining off the percolation losses

Table 15.15 Long-term salinity of the rootzone, expressed as EC_e in dS/m

LF	0.025	0.05	0.10	0.20	0.25	0.40
n (= 1/LF)	40	20	10	5	4	2.5
EC_i 0.25 (dS/m)	5	2.5	1.2	0.6	0.5	0.3
0.5	10	5	2.5	1.2	1	0.6
1.0	20	10	5	2.5	2	1.2
2.0			10	5	4	2.5
4.0				10	8	5
6.0					12	7.5