

# 15 Salinity Control

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## 15.1 Salinity in relation to Irrigation and Drainage

The application of irrigation water means an input of salts. Irrigation water, even if of excellent quality, is a major source of soluble salts. If soil salinization is to be avoided, these salts have to be leached out of the rootzone by water percolating to the subsoil. This percolation water will cause the watertable to rise and has to be drained off because a second source of salinization in irrigated areas is capillary rise from a watertable. As groundwater is often somewhat saline, even a small amount of capillary rise can add greatly to the salinity of the rootzone. Drainage, either natural or artificial, is a necessary complement to irrigation. Whereas the aim of drainage in a humid area is to control soil water for better aeration, higher temperatures, and easier workability, its primary aim in irrigated land is to control soil salinity.

Section 2 of this chapter discusses soil salinity and sodicity. In view of the extensive literature on saline and sodic soils, only some general aspects of these soils and their classification will be treated. Section 3 deals with the salt balance of the rootzone and the leaching requirement. Because important assumptions are made about capillary rise and the leaching process, these subjects are treated in detail in Sections 4 and 5. Section 6 discusses the long-term salinity level and compares leaching fractions and percolation losses in the light of drain discharge criteria. As the sodicity of irrigation water can affect a soil's structure and permeability – key factors in the leaching process – the sodium hazard of irrigation water is discussed in Section 7. Finally, Section 8 presents some considerations on the reclamation of salt-affected soils, particularly of the leaching process.

## 15.2 Soil Salinity and Sodicity

### 15.2.1 Electrical Conductivity and Soil Water Extracts

Because of the strong relationship between the electrical conductivity, EC, of a soil extract and the soil's salt concentration, the salt content of a soil is commonly expressed by the EC. Measured at a reference temperature of 25 °C, the EC is nowadays expressed in decisiemens per m (dS/m). The older unit for electrical conductivity which is still frequently used is mmho/cm (1 mmho/cm = 1 dS/m). The salt concentration of a solution is expressed in 'old' units g/l, mg/l (= ppm), meq/l or new SI units kg/m<sup>3</sup> and mol/m<sup>3</sup>. Similarly, the ion concentration is expressed in 'old' units meq/l or new (not used here) mol/m<sup>3</sup>. A milliequivalent is the mass of an ion or compound that combines with or replaces 1 mg of hydrogen, and equals the atomic or molar mass of the ion divided by its valency.

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Figure 15.1 shows the relation between the EC, expressed in dS/m, and the salt concentration, expressed in meq/l. For different ions and salts, Table 15.1A presents the relation between mg and meq, and Table 15.1B the average relation between meq/l, dS/m, mg/l, mg/meq, and the ratio meq/l to dS/m. The decrease in the ratio mg/meq is due to the relative increase in  $\text{Cl}^-$  ions over  $\text{SO}_4^{2-}$  and  $\text{HCO}_3^-$  ions with increasing salt concentration. The increase in the ratio meq/l to dS/m is due to the decreasing ion activity with increasing salt concentration. On the average, dividing the salt concentration in meq/l by a value between 10 and 12 yields the EC in dS/m.

To appraise soil salinity, we can measure the EC or the salt concentration in several soil water extracts. The most reliable appraisal is obtained by measuring the salt concentration in soil water at field capacity. This method yields the real salt concentration in soil water under field conditions and is directly related to plant growth. In a laboratory, it is difficult to obtain a sufficient amount of soil water from samples at field capacity.

Most commonly used for the appraisal of soil salinity is the saturation extract. We prepare a saturated paste by adding water to dry soil. We then obtain the saturation extract by applying suction to the saturated soil paste. For most soils – sand and loamy sand excepted – this paste contains about two times the amount of water at field capacity. One should therefore realize that the saturated paste is an oversaturated paste compared with saturation under undisturbed field conditions, and that the

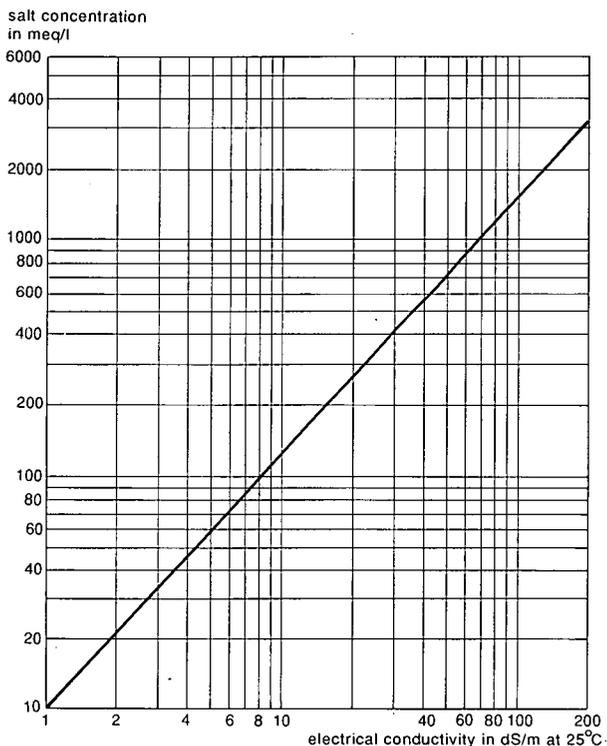


Figure 15.1 Relation between electrical conductivity and salt concentration (after Richards 1954)

Table 15.1A Relation between milligram and milliequivalent

Ion	mg/meq	Salt	mg/meq
Na <sup>+</sup>	23	NaCl	58.5
K <sup>+</sup>	39	CaCl <sub>2</sub>	55.5
Ca <sup>2+</sup>	20	MgCl <sub>2</sub>	47.5
Mg <sup>2+</sup>	12	Na <sub>2</sub> SO <sub>4</sub>	71
Cl <sup>-</sup>	35.5	CaSO <sub>4</sub>	68
SO <sub>4</sub> <sup>2-</sup>	48	MgSO <sub>4</sub>	60
HCO <sub>3</sub> <sup>-</sup>	61	NaHCO <sub>3</sub>	84
CO <sub>3</sub> <sup>2-</sup>	30	Ca(HCO <sub>3</sub> ) <sub>2</sub>	81
		Mg(HCO <sub>3</sub> ) <sub>2</sub>	73

Table 15.1B Average relation between meq/l, dS/m, mg/l, mg/meq, and the ratio meq/l to dS/m

meq/l	dS/m	mg/l	mg/meq	$\frac{\text{meq/l}}{\text{dS/m}}$
10	1	640	64	10
120	10	7000	58.3	12

saturation extract is a diluted solution compared with soil water at field capacity.

If samples are taken from the same soil in order to study changes in soil salinity, one should prepare the saturated paste by always adding the same amount of water to the air-dry soil. Otherwise, differences in EC<sub>e</sub> may be due to differences in the paste's water content instead of those in salt content.

As the preparation of the saturation extract is laborious, soil water extracts 1:1 (100 g water per 100 g dry soil), 2:1, or a higher dilution are prepared for routine purposes. In general, enough water can be obtained by simply filtering the soil solution without using a suction apparatus.

In the case of highly soluble salts (e.g. chloride salts), the EC is almost inversely proportional to the water content and the following expressions can be used for conversion

$$EC_{fc} = 2EC_e \text{ and } EC_{1:1} = 2EC_{2:1}$$

where

fc = suffix denoting field capacity

e = suffix denoting saturation extract

If slightly soluble salts such as lime (CaCO<sub>3</sub>) and gypsum (CaSO<sub>4</sub>) are present in the soil, one must be careful with the conversion of the EC or of the salt concentration obtained in a diluted extract. If solid lime or gypsum are the only salts present, each soil water extract, independent of the water-soil ratio, will contain the same concentration of these salts and will show the same EC.

## 15.2.2 Exchangeable Sodium

The solid phase in the soil has a negative surface charge. The magnitude of the negative charge depends on the amount of clay and organic matter present in the soil, and on the type of clay mineral. The electroneutrality is then provided by certain cations, mainly  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{H}^+$  ions. These cations are adsorbed and are mutually replaceable or exchangeable. For instance, when a soil is percolated with a solution containing calcium ( $\text{Ca}^{2+}$ ) salts, the amount of adsorbed Ca ions will increase at the expense of an equivalent amount of other cations. Similarly, the amount of adsorbed Na ions will increase when a solution containing sodium ( $\text{Na}^+$ ) salts is added. In many soils, the greater part of the adsorbed ions consists of calcium. In salt-affected soils, however, exchangeable sodium can be present in large amounts.

The composition of the adsorbed cations is related to the concentrations of the various cations present in the soil solution. In a simple system with only  $\text{Na}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  cations present, this relation is given by the Gapon Equation

$$\frac{\gamma_{\text{Na}}}{\gamma_{\text{Ca}} + \gamma_{\text{Mg}}} = K_G \frac{\text{Na}}{\sqrt{\frac{\text{Ca} + \text{Mg}}{2}}} \quad (15.1)$$

where

- $\gamma_{\text{Na}}$ ,  $\gamma_{\text{Ca}}$ , and  $\gamma_{\text{Mg}}$  = the amount of adsorbed sodium, calcium, and magnesium (meq/100 g)
- Na, Ca, Mg = the concentration of sodium, calcium, and magnesium in the soil solution (meq/l)
- $K_G$  = the exchange coefficient, being a constant for a certain clay mineral and combination of cations present in the soil-water system (meq/l)<sup>-0.5</sup>

The last term of Equation 15.1,  $\text{Na}/\sqrt{(\text{Ca} + \text{Mg})/2}$ , is the Sodium Adsorption Ratio, SAR. The amount of adsorbed sodium is usually expressed as a percentage of the cation exchange capacity, and is called the Exchangeable Sodium Percentage, ESP. In salt-affected soils, the sum of  $\gamma_{\text{Na}} + \gamma_{\text{Ca}} + \gamma_{\text{Mg}}$  usually equals the cation exchange capacity, CEC.

Hence Equation 15.1 can be written as

$$\frac{\frac{\gamma_{\text{Na}}}{\text{CEC}}}{\frac{\gamma_{\text{Ca}} + \gamma_{\text{Mg}}}{\text{CEC}}} = \frac{\text{ESP}}{100 - \text{ESP}} = K_G \cdot \text{SAR}$$

or

$$\text{ESP} = \frac{100 K_G \cdot \text{SAR}}{1 + K_G \cdot \text{SAR}} \quad (15.2)$$

For a range of soils in the west of the United States, the relation between the ESP of the soil and the SAR of the saturation extract is given as (Richards 1954)

$$\text{ESP} = \frac{100 (-0.0126 + 0.01475 \text{ SAR})}{1 + (-0.0126 + 0.01475 \text{ SAR})} \quad (15.3)$$

Because the determination of the ESP requires the analysis of the amount of sodium adsorbed on the soil complex and of the CEC, and because these analyses are rather time-consuming, the ESP is often calculated from the SAR. In the saturation extract, the concentrations of sodium, calcium, and magnesium can easily be determined and the SAR can then be calculated or read from the nomogram in Figure 15.2. For SAR values between 2 and 30, SAR and ESP are approximately equal under equilibrium conditions.

### 15.2.3 Effect of Sodium on Soil Physical Behaviour

As was mentioned in Section 15.2.2, the negative charge of the solid phase is counterbalanced by an equivalent amount of cations present in the adjacent liquid

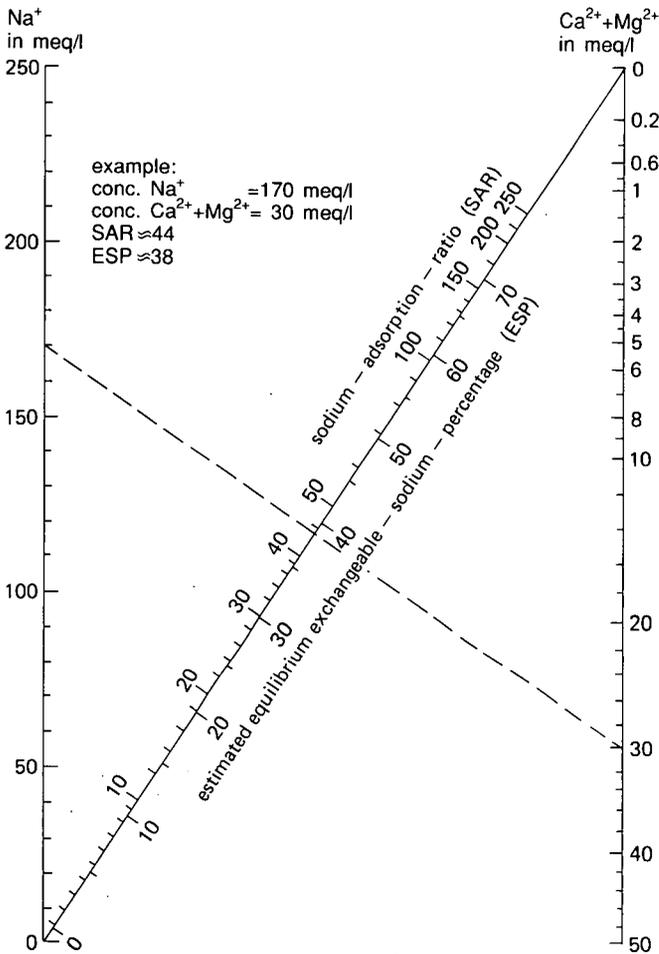


Figure 15.2 Nomogram for determining the SAR of the saturation extract and for estimating the corresponding ESP of the soil (after Richards 1954)

phase. The spatial distribution of negative and positive charges is in principle analogous to that of a plate condenser called 'electric double layer'. Unlike the plate condenser, the cations (or counterions) moving freely in the liquid phase are subject to two opposing tendencies:

- They are attracted towards the surface of the solid phase by the electric field;
  - They tend to distribute themselves evenly throughout the liquid phase by diffusion.
- The resulting distribution is that of a diffuse accumulation zone of cations known as the Diffuse Double Layer or DDL (Figure 15.3). In the DDL, cations are 'attracted' by the surface of the solid phase; at the same time, anions are being 'excluded'. At some distance from the surface of the solid phase, the concentrations of cations and anions are equivalent (the equilibrium solution).

Important factors determining the extent of the DDL are the valency of the counterion and the concentration of the equilibrium solution. Divalent cations ( $\text{Ca}^{2+}$ ) are attracted by the surface of the solid phase more than monovalent cations ( $\text{Na}^+$ ) are. Thus, by increasing the Ca/Na ratio of the soil-water system, the tendency is for a decrease in extent of the DDL, while decreasing this ratio will increase the extent of the DDL. Similarly, upon an increase in the salt concentration of the equilibrium solution (salinization), the DDL will decrease in thickness; upon dilution (leaching), the DDL expands.

The extent of the DDL has a pronounced effect on the soil physical behaviour. At some point within the DDL, the negative charge on the surface of the solid phase is not yet fully neutralized by counterions. Hence, one can state that if two clay particles approach within a distance of twice the extent of the DDL, they tend to separate. Clay particles, however, also attract mutually. At a pH of below 7, the edges of clay particles have a positive electrical charge. If the extent of the double layer is small, the positively charged edges may approach the negatively charged surface of a neighbouring clay particle, close enough to form weakly bonded floccules, similar to a 'card house' arrangement (Figure 15.4). The stability of these floccules is favoured by the presence of organic matter, lime, and gypsum.

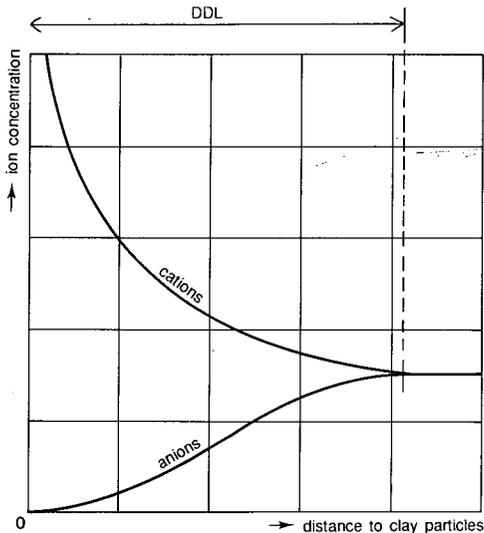


Figure 15.3 Distribution of cations and anions in diffuse double layer

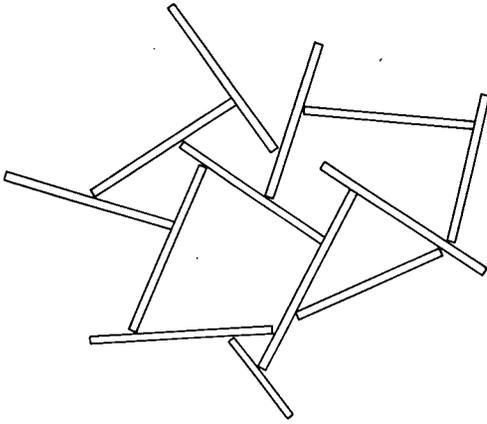


Figure 15.4 Card-house arrangement of clay particles

Provided the soil is sufficiently moist, say at field capacity, the DDL develops to its potential extent. Upon drying, the amount of soil water may fall below the one 'stored' in the DDL, particularly in the case of thick DDL's as found in sodic soils. Then the DDL is truncated. Upon rewetting, the DDL swells. For soils high in exchangeable calcium, this swelling is far less than for soils high in exchangeable sodium. The swelling causes the closure of the inter-aggregate pores, thus reducing the hydraulic conductivity. Moreover, the pressure arising from the swelling forces the individual clay particles away from each other. The soil disperses and soil aggregates fall apart. The fine soil particles loosened in this way clog the soil pores and further reduce the permeability for water and air. Rain or irrigation water will remain ponded on the soil surface for some time; upon drying, the dispersed and suspended clay particles will form a thin curled-up crust.

Salt-affected soils may show a good soil structure, even when they contain an appreciable amount of exchangeable sodium. Upon leaching, the salt content decreases and, at a high ESP, the DDL expands strongly and soil structure breaks down. Corrective measures to replace sodium by calcium then become necessary.

The adverse effect of exchangeable sodium on soil physical properties is well known. Not precisely known is at what exchangeable percentage sodium becomes detrimental to soil structure. An ESP of 10-15 is often presented as the critical level. In a sandy soil, an ESP of 25 may not show any effect on soil structure. In contrast, in clay soils, an ESP of 5 is already considered high, particularly in soils containing 2:1 clay minerals (e.g. smectite/montmorillonite).

After parts of The Netherlands were inundated with sea water in 1945 and 1953, experience showed that the critical amount of exchangeable sodium in clay soils could be put at 1.0-1.5 meq/100 g of soil, corresponding to an ESP of 4-8.

A high level of exchangeable sodium, combined with a low salinity, is a condition for a breakdown of soil structure, but what ultimately causes the soil structure to deteriorate is the mechanical impact on soils high in exchangeable sodium. This mechanical impact can be brought about by rain water or irrigation water, which causes the surface soil to slake and puddle. Upon drying, a hard crust is formed,

hampering seed emergence and crop growth. Soil-tillage practices like ploughing and harrowing may cause the formation of a compacted top layer with poor water-transmitting properties.

Subsoils showing a high ESP usually suffer less from a deterioration of soil structure. With increasing depth, the drying and wetting, and hence the shrinking and swelling, become less pronounced and the soil material remains beyond the reach of mechanical impacts.

#### 15.2.4 Classification of Salt-Affected Soils

Salt-affected soils can be defined as soils that show:

- A concentration of soluble salts high enough to interfere with crop growth;
- Exchangeable sodium in a percentage high enough to affect the stability of the soil structure.

Various systems exist for the classification of salt-affected soils. Those of the US Salinity Laboratory, the U.S.S.R., FAO/Unesco, and Soil Taxonomy are presented below.

##### *US Salinity Laboratory*

The classification of salt-affected soils as presented by the US Salinity Laboratory (Richards 1954) is widely used. Developed principally for the purpose of reclaiming salt-affected soils, it is a simple system based on two criteria: the salinity of the soil, expressed as  $EC_e$ , and the exchangeable sodium percentage. Because of its simplicity, it cannot cope with all variations occurring in nature, and should not therefore be applied indiscriminately.

The system classifies salt-affected soils as follows:

- Saline soils, which have an  $EC_e > 4$  dS/m at 25°C and an ESP < 15. The pH, in general, is below 8.5. The dominant anions are  $Cl^-$  and  $SO_4^{2-}$ .  $HCO_3^-$  is present in small quantities;  $NO_3^-$  is rarely found.  $Na^+$ , as a rule, comprises less than 50% of the soluble cations. Calcium carbonate and gypsum may be present;
- Saline sodic soils, which have an  $EC_e > 4$  dS/m at 25°C and an ESP > 15. The pH is seldom higher than 8.5. Often, saline sodic soils have a pH-value near to neutral. The  $Na^+$  ions in the solution are present as neutral salts such as NaCl and  $Na_2SO_4$ . If the pH-value is above 8.5, the ions  $HCO_3^-$  and  $CO_3^{2-}$  are present in the soil solution. Such saline sodic soils tend to be more problematic to reclaim;
- Non-saline sodic soils, which have an  $EC_e < 4$  dS/m at 25°C and an ESP > 15. The pH is usually higher than 8.5; a pH of about 10 is no exception. Sodium is the main cation in the soil solution. The soil often contains  $CaCO_3$ , which, because of its low solubility, does not form a useful storage reservoir of calcium for reclamation purposes unless soil pH is lowered. The soil structure of non-saline sodic soils can often be regarded as poor. The topsoil of some non-saline sodic soils is devoid of calcium carbonate and shows a pH < 7. Accordingly, a higher quantity of exchangeable hydrogen is found adsorbed on the soil complex.

### *U.S.S.R. Nomenclature and Classification of Salt-Affected Soils*

The U.S.S.R. classification system combines the principles of pedogenesis, the geochemistry of salts, and plant physiology. It distinguishes the following soils (after Kovda in FAO-Unesco 1973):

- Solonchak: These are saline soils containing a large quantity of easily soluble salts, usually more than 2%, in the top soil (the upper 0.3 m). The natural vegetation consists of specific succulent halophytes; sometimes the land is barren. Generally, agricultural crops do not yield. Various solonchaks have been differentiated according to the type of salts: puffy solonchak, which contain sodium sulphate; wet mineral solonchak (sabakh soils), which contain hygroscopic magnesium and calcium chloride; soda solonchak; chloride solonchak; and so on.

A subdivision is made according to the depth of occurrence of the watertable: there are active solonchaks with a watertable at shallow depth and residual solonchaks with a watertable at great depth;

- Solonchak-like soils: These are saline soils with a soluble salt content of between 0.5 and 1.5% (corresponding to an  $EC_e$  from 10-45 dS/m) in the rootzone to a depth of 1.0-1.5 m. Yields of agricultural crops are usually low.

A subdivision is made according to the dominant type of salts present and to the depth of the watertable. For instance, saline meadow soils have a watertable at shallow depth; residual solonchak-like soils have a watertable at great depth;

- Solonetz: These soils contain an appreciable amount of exchangeable sodium. As a result of the role of exchangeable sodium in soil formation, solonetz have a textural B horizon (i.e. a soil horizon marked by an illuviation of clay particles and showing a characteristic columnar soil structure).

A further subdivision is made according to the depth to the watertable, the profile development, and the presence of salts.

### *FAO-Unesco System*

In the legend of the FAO-Unesco soil map of the world (FAO-Unesco 1974, FAO 1988), salt-affected soils are already distinguished at the highest level of soil classification: solonchaks and solonetz.

- Solonchaks are soils which, in addition to other characteristics, have a high salinity. A high salinity refers to soils which, at some time during the year, have an  $EC_e$  of 15 dS/m at 25°C or more at some depth within the profile: less than 1.25 m in coarse-textured soils to less than 0.75 m in fine-textured soils. A soil is also considered to be a solonchak if the  $EC_e$  is over 4 dS/m within a depth of 0.25 m and the pH (1:1) is over 8.5;
- Solonetz are soils with a natric B horizon. This is an argillic (clay illuviation) B horizon which has a columnar or prismatic structure and an exchangeable sodium percentage of more than 15%.

### *Soil Taxonomy*

In Soil Taxonomy – the soil classification system developed by the US Soil Conservation Service (USDA 1975) – the specific features of salty land are only introduced in the 3rd category of classification (i.e. at the level of great groups). Salt-affected soils are found in the orders of Entisols, Inceptisols, Alfisols, Mollisols, and Aridisols. In Soil Taxonomy, the diagnostic features of salt-affected soils are:

- The presence of a natric horizon, which is a special kind of argillic horizon, with, in some subhorizon, a columnar soil structure or more than a 15% saturation with exchangeable sodium;
- The presence of a salic horizon, which is a horizon of 0.15 m or more thick and which contains a secondary enrichment of salts more soluble than gypsum. It contains at least 2% salt (i.e. the  $EC_e$  is usually more than 60 dS/m), and the product of its thickness in centimetres and salt percentage by weight is 60 or more.

#### 15.2.5 Crop Growth affected by Salinity and Sodicity

The effect of salinity on crop growth can be ascribed to:

- An osmotic effect: As the salinity of a solution increases, its osmotic potential increases too and reduces the availability of water for the crop. This osmotic effect may explain why vegetable crops, which are known to prefer readily available soil water not exceeding a potential of  $10^5$  Pa ( $= 1$  bar or  $pF \approx 3.0$ ), are so sensitive to salinity;
- A specific ion effect: This causes an imbalanced ion uptake, deficiencies in certain elements, and yield depression. Some ions are toxic, causing characteristic injury symptoms associated with the accumulation of a specific ion in the plant. Leaf-burn of many fruit trees due to an excessive uptake of sodium and chloride are well known.

A crop's salt tolerance can be appraised by:

- The relative yield of the crop on a saline soil as compared with its yield on a normal, non-saline soil under comparable growing conditions. Because it provides a good basis of comparison between crops, this agronomic criterion is normally used to list the salt tolerance of crops;
- The absolute yield of a crop on a saline soil. Although the previous criterion allows a comparison of the salt tolerance of crops, in the final analysis the absolute yields of crops and their economic value are decisive for the choice of a crop rotation under saline conditions.

Literature contains many data on plant tolerance to salinity. In general, these tolerances agree fairly well, notwithstanding differences in climate, variety, and cultural practices. Climate has an effect on salt tolerance. Crops grown during a cooler period of the year are more tolerant than when growing during periods of higher temperature and lower humidity.

In literature from the U.S.S.R., plant tolerance is usually expressed in terms of salt content on a dry-weight basis. Also taken into account are the different types of salt present in the soil. More in vogue is to express plant salt tolerance in terms of the electrical conductivity of the saturation extract.

The relation between yield and salinity may be approached by a straight line for the important range of yield decrease from about 0.95 to 0.25. Figure 15.5 shows the relation between the relative yield and  $EC_e$  in dS/m for a large number of crops determined under field conditions in Tunisia. Here, the  $EC_e$  represents the average of spring and autumn samples taken from the rootzone between 0 and 0.80 m (Unesco

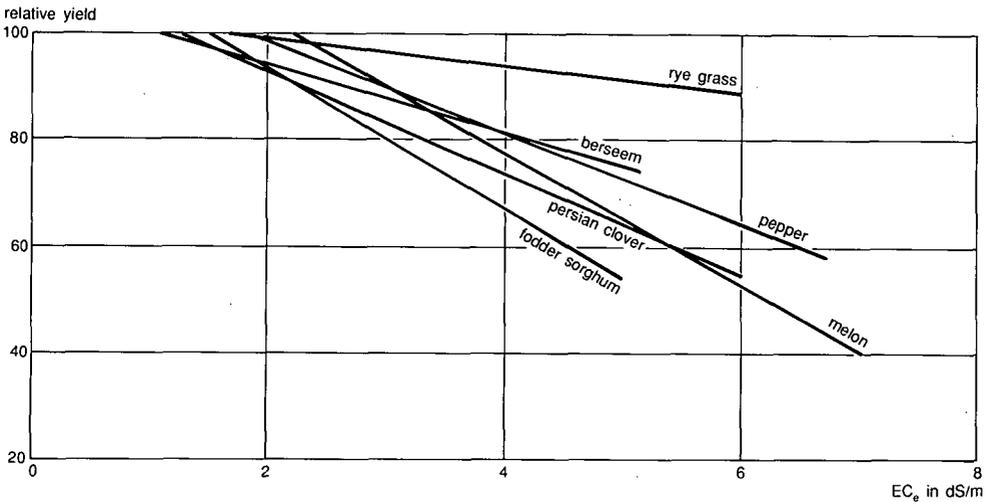
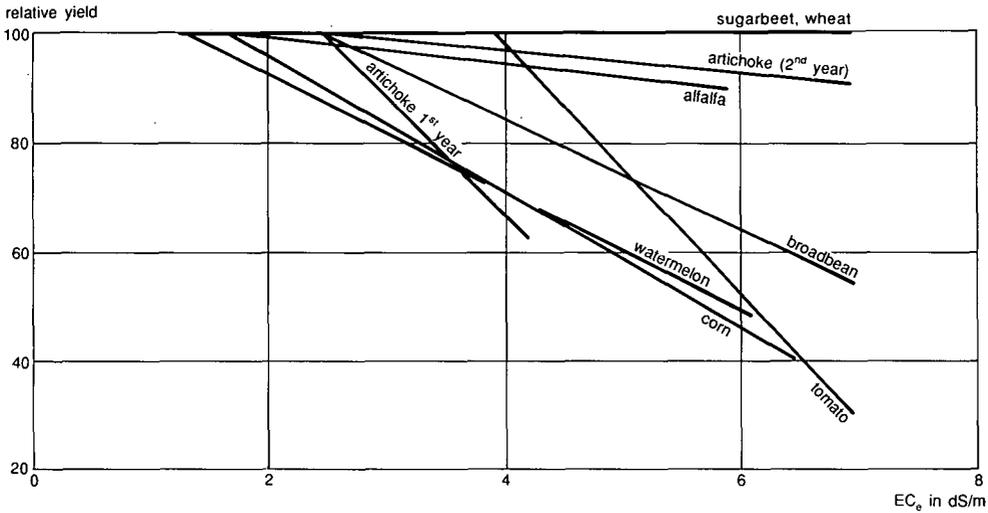


Figure 15.5 Relation between yield and soil salinity in soil layer 0-0.80 m (Unesco 1970)

1970). For many crops, the yield starts declining from an  $EC_e$ -value of 2 dS/m onwards, and already shows a depression of 20 to 25 per cent at an  $EC_e$ -value of 4 dS/m.

Table 15.2 presents the  $EC_e$ -values used for salinity classification. The values in this table and those in Figure 15.5 refer to medium and fine textured soils, for which  $EC_e$  equals about  $0.5EC_c$  because of the relationship between the water contents at field capacity and in the saturated paste. Since, in the case of sand and loamy sand,  $EC_e$  equals about  $0.25EC_c$ , the limits of Table 15.2 at which crops are affected must be divided by two; otherwise the salinity of these soils will be underestimated.

Exchangeable sodium affects plant growth in two ways: it causes nutritional problems and poor soil structure. The soil solution of sodic soils often contains more

Table 15.2 Soil salinity classification

EC <sub>e</sub> (dS/m)	Classification	Crop yields
0-2	Non-saline	Not affected
2-4	Slightly saline	Sensitive crops affected
4-8	Saline	Many crops affected
8-16	Strongly saline	Only tolerant crops possible
> 16	Extremely saline	A few very tolerant crops possible

sodium than calcium. The nutritional problems encountered on sodic soils are therefore related to an unbalanced uptake of cations. Plants grown on sodic soils usually have a higher sodium content and a lower calcium content than those grown on non-sodic soils. Some crops are extremely sensitive to sodium (*viz.* citrus and nut trees). In soils with an ESP of 5-10, these tree crops may accumulate toxic amounts of sodium. At that level of exchangeable sodium, a soil is not considered sodic (see Section 15.2.4). Most crops, however, are more tolerant to exchangeable sodium.

At an ESP-value of about 10, the second effect (*viz.* that of poor soil structure) may become apparent. With a breakdown of soil structure, plant growth is affected by poor aeration in the rootzone, together with reduced water movement and waterlogging in the rootzone or on the soil surface. The root growth is restricted. Upon the alternating effect of being moistened by irrigation water or rain and then drying, these soils form a dense and hard surface crust, which hinders the emergence of seeds and retards the development of young seedlings.

An exact ESP-value above which the soil structure is likely to deteriorate cannot be given. Too many factors determine soil structure or influence its stability. Thus, from a reclamation point of view, the critical ESP-level ranges from 5 in fine-textured soils that contain swelling clay minerals (e.g. smectite/montmorillonite) to 25 in coarse-textured soils.

## 15.3 Salt Balance of the Rootzone

### 15.3.1 Salt Equilibrium and Leaching Requirement

If we regard the rootzone as one layer with a homogeneous distribution of water and salt and consider a rather long period (e.g. one year), so that the water content is the same at the beginning and at the end of that period, we can write the water balance of an irrigated soil (Figure 15.6) as

$$I + P + G = E + R \quad (15.4)$$

where

- I = Irrigation (mm)
- P = precipitation (mm)
- G = capillary rise (mm)

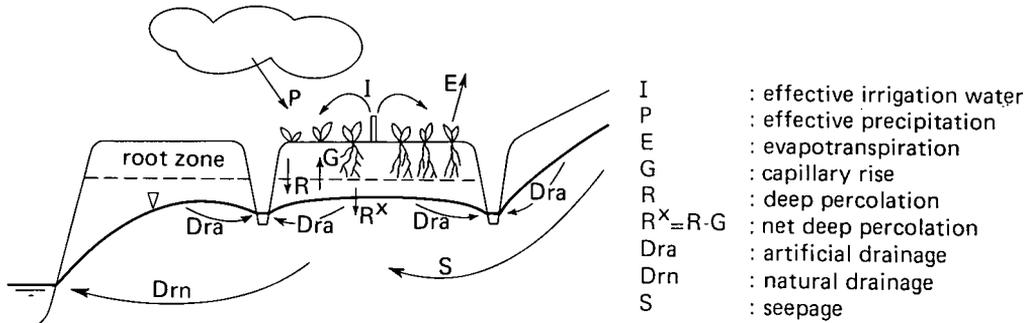


Figure 15.6 Components of the water balance of an irrigated soil

$E$  = evapotranspiration (mm)  
 $R$  = percolation (mm)

The time period over which the balance components are taken is immaterial, as long as it is the same for each of the components. It is convenient to express all components in mm or  $1/m^2$ .  $I$  and  $P$  are defined here as effective quantities because they relate to quantities that actually infiltrate into the soil. For irrigation water, this is the supply to the field less surface runoff.

To obtain a salt balance, we make the following assumptions:

- All salts are highly soluble and do not precipitate;
- The amount of salts supplied by rainfall is negligible;
- The amounts of salts supplied by fertilizers and exported by crops are negligible.

In the case of salt equilibrium (i.e. without a long-term change in salt content), the salt balance of the rootzone then reads

$$IC_i + GC_g = RC_r \quad (15.5)$$

where

$C$  = salt concentration (meq/l)  
 $i$  = suffix denoting irrigation water  
 $g$  = suffix denoting groundwater  
 $r$  = suffix denoting deep percolation water

By combining Equations 15.4 and 15.5, we get

$$R = \frac{(E - P)C_i + G(C_g - C_i)}{C_r - C_i} \quad (15.6)$$

Introducing  $R^x = R - G$  for the net deep percolation, we obtain

$$R^x = (E - P) \frac{C_i}{C_r - C_i} + \frac{C_g - C_r}{C_r - C_i} \quad (15.7)$$

and

$$I = E - P + R^x \quad (15.8)$$

Equation 15.7 can be regarded as a basic equation in which no assumption has been made about the salt concentration of upward capillary flow.

If the groundwater in the area is fed by seepage from elsewhere, as is shown in the examples of Figure 15.7, the salt concentration of the capillary flow,  $C_g$ , will not be equal to the salt concentration of the percolation water,  $C_r$ . In such circumstances, we can use Equation 15.7 to calculate the amount of net deep percolation water,  $R^x$ , and afterwards use Equation 15.8 to obtain the amount of irrigation water,  $I$ . If there is no seepage, the percolation water will in the long run create a belt of water below the rootzone, the concentration of which corresponds to the average concentration of the percolation water. The salt concentration of the upward capillary flow will then be equal to the salt concentration of the percolation water:  $C_g = C_r$ . A certain amount of time must pass, however, before long-term equilibrium is established. Especially in newly reclaimed areas, the salt concentration below the rootzone, often increased by the salts washed down during leaching operations, may remain high for some time.

If all the irrigation water is mixing thoroughly with the soil water in the rootzone, the salt concentration of the soil water at field capacity will equal the salt concentration of the water percolating from the rootzone:  $C_{fc} = C_r$ .

We can simplify Equation 15.7 by making the following assumptions:

– No seepage, long-term equilibrium between the rootzone and the subsoil:

$$C_g = C_r;$$

– All irrigation water mixes with the soil water in the rootzone at field capacity:

$$C_{fc} = C_r.$$

Under these conditions, Equation 15.7 changes to

$$R^x = (E - P) \frac{C_i}{C_{fc} - C_i} \quad (15.9)$$

Combining Equations 15.8 and 15.9 yields

$$I = (E - P) \frac{C_{fc}}{C_{fc} - C_i} \quad (15.10)$$

With Equation 15.9, we can calculate the amount of leaching water needed to maintain salt equilibrium, and, with Equation 15.10, the total amount of irrigation water needed to cover both the consumptive use of the crop and the leaching of the soil. In these equations,  $(E - P)$  represents the influence of climate on the amount of irrigation water needed,  $C_i$  the influence of water quality, and  $C_{fc}$  the agronomic criterion which takes into account the influence of salinity on crop yield.

Combining Equations 15.9 and 15.10 yields the leaching fraction, LF

$$LF = \frac{R^x}{I} = \frac{C_i}{C_{fc}} \quad (15.11)$$

If  $C_{fc}$  is chosen according to the salt tolerance of the crops to be grown, the amount of net deep percolation water calculated with Equation 15.9 and the fraction of irrigation water calculated with Equation 15.11 both express the leaching requirement. In literature (Richards 1954), the leaching requirement is defined as the fraction of the irrigation water that must be leached through the rootzone to control soil salinity

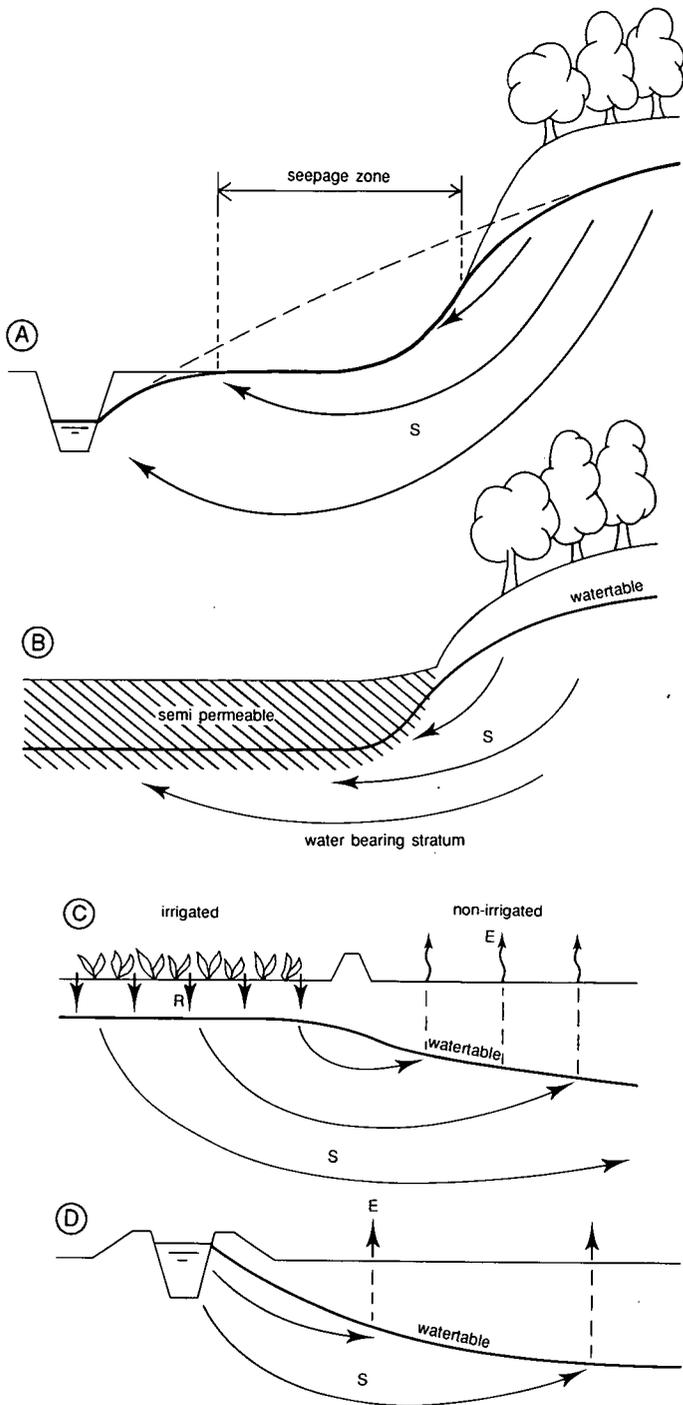


Figure 15.7 Examples of seepage flow: A) Seepage at the foot of a hill; B) Seepage into a valley; C) Seepage from an irrigated field towards fallow land; and D) Seepage from an irrigation canal

at any specified level. We must always express the leaching requirement as a fraction in order to check whether the fraction is not too high compared with the fraction for consumptive use and in view of the permeability of the soil. If the leaching requirement is too high, we must choose a higher value of  $C_{fc}$ ; in practice, that means a shift towards more salt-tolerant crops.

If the leaching fraction equals 0.25, the net percolation equals 1/4 of the amount of irrigation water, and the soil water becomes four times as concentrated as the irrigation water. We can express this relation by introducing the concentration factor,  $n$ , which equals the inversed value of the leaching fraction

$$n = \frac{1}{LF} = \frac{C_{fc}}{C_i} \quad (15.12)$$

### 15.3.2 Salt Storage

In the preceding section, we assumed that there was no difference between the amount of salts stored in the rootzone at the beginning and at the end of the period under consideration. Though this may be true for long periods – say one year – the amounts will change within such a period because of seasonal variations in climate, crops, water applications, and water quality. Such short-term changes in salt content – say over a month or a season – can be calculated with the salt storage equation, which will be derived in this section.

If the quantity of salts in the rootzone,  $Z'$ , at the beginning of the period ( $Z'_1$ ) differs from that at the end ( $Z'_2$ ), we can write

$$\Delta Z' = Z'_2 - Z'_1 \quad (15.13)$$

where

$$\begin{aligned} \Delta Z' &= \text{change in salt quantity in the rootzone (meq/m}^2\text{)} \\ Z'_2 &= \text{salt quantity in the rootzone at the end of the period (meq/m}^2\text{)} \\ Z'_1 &= \text{salt quantity in the rootzone at the begin of the period (meq/m}^2\text{)} \end{aligned}$$

We can regard the amount of salt in the rootzone ( $Z'$ ) as being dissolved in the soil water. Because the downward movements of water and salt generally take place at water contents near field capacity, we can logically consider  $Z'$  to be dissolved in an amount of water  $W_{fc}$ , which is the amount of soil water at field capacity in the rootzone expressed in mm or l/m<sup>2</sup>.  $W_{fc}$  can be determined from

$$W_{fc} = \theta_{fc} D \quad (15.14)$$

where

$$\begin{aligned} W &= \text{water content of the rootzone (mm)} \\ \theta &= \text{volumetric soil water content (-)} \\ D &= \text{depth of the rootzone (mm)} \end{aligned}$$

At field capacity, the salt concentration ( $C_{fc}$ ) of the soil water in the rootzone is

$$C_{fc} = \frac{Z'}{W_{fc}} \quad (15.15)$$

If we consider a period in which  $Z'$  changes from  $Z'_1$  to  $Z'_2$ , the average salt concentration ( $\bar{C}_{fc}$ ) of the soil water at field capacity during that period is

$$\bar{C}_{fc} = \frac{Z'_1 + Z'_2}{2W_{fc}} = \frac{Z'_1}{W_{fc}} + \frac{\Delta Z'}{2W_{fc}} \quad (15.16)$$

Assuming  $C_g = C_r = C_{fc}$ , we can write for the change in salt content of the rootzone

$$\Delta Z' = IC_i - R^x \bar{C}_{fc} \quad (15.17)$$

Substituting the expression of Equation 15.16 for  $\bar{C}_{fc}$  into Equation 15.17 yields

$$\Delta Z' = \frac{IC_i - \frac{R^x Z'_1}{W_{fc}}}{1 + \frac{R^x}{2W_{fc}}} \quad (15.18)$$

Equation 15.18 is the salt storage equation. If we know the initial salt content of the rootzone,  $Z'_1$ , (e.g. from soil sampling), we can calculate  $\Delta Z'$  directly. Equation 15.18 can then be used to predict the desalinization of saline soils under the influence of irrigation water. If, however, we are interested in finding the seasonal deviations from the long-term equilibrium soil salt content,  $Z'$  will not be known, and the only condition is that the sum of the quantities  $\Delta Z'$  should be zero over a long period. The procedure will be illustrated with an example (Example 15.1) in Section 15.3.4.

### 15.3.3 The Salt Equilibrium and Storage Equations expressed in terms of Electrical Conductivity

Hitherto, we have expressed the salinity of the water as the salt concentration ( $C$ ) in meq/l.  $C$  may stand either for the total salt concentration or for the concentration of a specific ion (e.g. chloride, sodium, boron). As already outlined in Section 15.2.1, the electrical conductivity is roughly proportional to the salt concentration and can be obtained in dS/m by dividing the salt concentration in meq/l by a value of about 12. Since, for most soils – sand and loamy sand excepted – the water content of the saturated paste is about twice that of field capacity,  $EC_c$  equals  $0.5EC_{fc}$  if highly soluble salts only and no solid lime or gypsum are present in the soil. Hence we can write

$$EC_c = 0.5EC_{fc} = \frac{C_{fc}}{24} = \frac{Z'}{24W_{fc}} \quad (15.19)$$

where  $EC$  is expressed in dS/m,  $C$  in meq/l,  $Z'$  in meq/m<sup>2</sup>, and  $W$  in mm. If the calculations are done with  $EC$  instead of  $C$ -values, the symbols  $Z$  and  $\Delta Z$  are used instead of  $Z'$  and  $\Delta Z'$ .

$$Z = \frac{Z'}{12} \text{ and } \Delta Z = \frac{\Delta Z'}{12} \quad (15.20)$$

in which  $Z'$  and  $\Delta Z'$  are expressed in meq/m<sup>2</sup> and  $Z$  and  $\Delta Z$  as the product of dS/m and mm. For the sake of convenience, we shall henceforth write  $EC_{mm}$  instead of

the physically correct notation (dS/m)mm. Equations 15.9, 15.10, 15.11, and 15.18, when expressed in terms of electrical conductivity, change into

$$R^x = (E - P) \frac{EC_i}{2EC_e - EC_i} \quad (15.21)$$

$$I = (E - P) \frac{2EC_e}{2EC_e - EC_i} \quad (15.22)$$

$$LF = \frac{R^x}{I} = \frac{EC_i}{2EC_e} \quad (15.23)$$

$$\Delta Z = \frac{IEC_i - \frac{R^x Z_i}{W_{fc}}}{1 + \frac{R^x}{2W_{fc}}} \quad (15.24)$$

If we express the amounts of irrigation water etc., in mm, we obtain Z and ΔZ in ECmm. Inversely, we find the electrical conductivity of the soil water at field capacity and that of the saturation extract from

$$EC_{fc} = \frac{Z}{W_{fc}} \text{ and } EC_e = \frac{Z}{2W_{fc}} \quad (15.25)$$

in which Z is expressed in ECmm and  $W_{fc}$  in mm.

#### 15.3.4 Example of Calculation

Table 15.3 presents an example of the application of the salt equilibrium and storage equations to permanently irrigated soils. This table contains three parts:

- I Basic information;
- II Maximum percolation in summer;
- III Maximum percolation in autumn.

##### *Example 15.1*

###### *Part I: Basic Information*

The basic information supplied and the assumptions to be made in advance are given in Part I of the table, Lines 1 to 7. These concern:

- The soil: the amount of water in the rootzone at field capacity, the relation between  $EC_e$  and  $EC_{fc}$ ;
- The agronomic conditions: the agronomic criterion (in this case an average  $EC_e$  value of 6 dS/m and a maximum value of 8 dS/m) and the land use;
- The climate: evapotranspiration and precipitation;
- The quality of the irrigation water.

A considerable variation is apparent in the salinity of the irrigation water (Line 7), but its quality is generally poor, especially in summer and autumn. As the amount of irrigation water varies in general with the deficit (E - P), the weighted mean  $\overline{EC}_i$

Table 15.3 Salt and water balance for a permanently cropped soil, all salts remaining in solution (Example 15.1)

Part I		Basic Information													
1	General data: $W_{fc} = 300$ mm; $EC_e = 0.5 EC_{fc}$ ; $\overline{EC}_e = 6$ dS/m; $EC_{max} = 8$ dS/m; no capillary rise														
2	Period	Year	Oct.	Nov.	Dec.	Jan.	Febr.	March	April	May	June	July	Aug.	Sept.	
3	Land use	• Irrigated fodder crops													
4	E	mm	1300	90	60	60	60	75	90	105	120	150	170	170	150
5	P	mm	400	50	60	70	70	50	40	30	30	0	0	0	0
6	E-P	mm	900	40	0	-10	-10	25	50	75	90	150	170	170	150
7	$EC_i$	mm	3.0	3	2	2	1	2	2	2	2	3	3	4	3
Part II		Distribution of irrigation water with maximum percolation in summer													
8	I	mm	1200	60	0	0	0	0	90	90	120	180	240	240	180
9	$\Delta W$	mm	0	0	0	0	0	-25	+25	0	0	0	0	0	0
10	$R^x$	mm	300	20	0	10	10	0	15	15	30	30	70	70	30
11a	$Z_1$	ECmm	<u>5000</u>	4852	4852	4693	4539	4539	4493	4449	4254	4364	4097	4101	
12a	$\Delta Z$	ECmm	-775	-148	0	-159	-154	0	-46	-44	-195	+110	-267	+4	+124
13a	$Z_2$	ECmm		4852	4852	4693	4539	4539	4493	4449	4254	4364	4097	4101	<u>4225</u>
11b	$Z_1$	ECmm	<u>3000</u>	2981	2981	2884	2789	2789	2829	2867	2822	3068	3072	3290	
12b	$\Delta Z$	ECmm	+491	-19	0	-97	-95	0	+40	+38	-45	+246	+4	+218	+201
13b	$Z_2$	ECmm		2981	2981	2884	2789	2789	2829	2867	2822	3068	3072	3290	<u>3491</u>
11c	$Z_1$	ECmm	<u>3780</u>	3710	3710	3588	3470	3470	3476	3482	3379	3571	3470	3604	
12c	$\Delta Z$	ECmm	-5	-70	0	-122	-118	0	+6	+6	-103	+192	-101	+134	+171
13c	$Z_2$	ECmm		3710	3710	3588	3470	3470	3476	3482	3379	3571	3470	3604	<u>3775</u>
14	$EC_e$	dS/m	5.9	6.3	6.2	6.2	6.0	5.8	5.8	5.8	5.8	5.6	6.0	5.8	6.0

Table 15.3 (cont.)

Part III		Distribution of irrigation water with maximum percolation in autumn													
15	I	mm	1200	90	50	0	0	0	90	90	120	180	200	200	180
16	$\Delta W$	mm	0	0	0	0	0	-25	+25	0	0	0	0	0	0
17	$R^x$	mm	300	50	50	10	10	0	15	15	30	30	30	30	30
18a	$Z_1$	ECmm		<u>5000</u>	4480	3883	3756	3633	3633	3631	3629	3512	3629	3912	4301
19a	$\Delta Z$	ECmm	-594	-520	-597	-127	-123	0	-2	-2	-117	+180	+220	+289	+105
20a	$Z_2$	ECmm		4480	3883	3756	3633	3633	3631	3629	3512	3692	3912	4301	<u>4406</u>
18b	$Z_1$	ECmm		<u>3000</u>	2778	2451	2371	2293	2293	2356	2416	2414	2699	3013	3486
19b	$\Delta Z$	ECmm	+668	-212	-337	-80	-78	0	+63	+60	-2	+285	+314	+475	+182
20b	$Z_2$	ECmm		2788	2451	2371	2293	2293	2356	2416	2414	2699	3013	3486	<u>3668</u>
18c	$Z_1$	ECmm		<u>4065</u>	3689	3214	3109	3007	3007	3036	3063	3000	3229	3493	3923
19c	$\Delta Z$	ECmm	-1	-376	-475	-105	-102	0	+29	+27	-63	+229	+264	+430	+141
20c	$Z_2$	ECmm		3689	3214	3109	3007	3007	3036	3063	3000	3229	3493	3923	4064
21	$EC_e$	dS/m	5.5	6.8	6.1	5.4	5.2	5.0	5.0	5.1	5.1	5.0	5.4	5.8	6.5

will be taken as the annual average electrical conductivity of the irrigation water

$$\overline{EC}_i = \frac{\sum EC_i(E - P)}{\sum(E - P)} = 3.0 \text{ dS/m}$$

The first step consists of using the salt equilibrium equation to calculate the total amounts of irrigation water and percolation water. Using Equations 15.22 and 15.21, we find  $I = 1200 \text{ mm}$  and  $R^s = 300 \text{ mm}$  (Lines 8 and 10). The leaching fraction equals 25% of the amount of irrigation water and less than 20% of the total amount of irrigation water and rainfall. Because these values are not excessive from a practical point of view, we need not change the agronomic criterion to obtain a lower leaching requirement.

The second step consists of using the salt storage equation to calculate the changes in salinity during the year. In this way, we find out whether leaching can be postponed from a period of peak consumptive use until a period of low consumptive use. Parts II and III show two possibilities of distributing the irrigation water over the year, both following the trend of the deficit  $(E - P)$  but differing in the amount of surplus water.

#### *Part II Maximum Percolation in Summer*

The net deep percolation is maximum in summer when the irrigation applications themselves are highest. No irrigation water is applied during late autumn and winter. The monthly changes in water content of the rootzone ( $\Delta W$ ) are zero (Line 9), except for the month of February, when evapotranspiration exceeds the rainfall by 25 mm – a deficit that is restored in March. The monthly net percolation (Line 10) is calculated as  $R^s = I - (E - P) - \Delta W$ . To calculate the monthly change  $\Delta Z$ , we have to estimate the salt content  $Z_1$  of the rootzone. We do this by applying the following reasoning. The average value of the electrical conductivity of the saturated extract ( $\overline{EC}_e$ ) should not exceed 6 dS/m (agronomic condition); hence  $\overline{EC}_e = 12 \text{ dS/m}$  (Equation 15.25) and consequently the average value  $= \bar{Z} = \overline{EC}_e W_{fc} = 12 \times 300 = 3600 \text{ ECmm}$ . As we have chosen the month of October, at the beginning of the rainy season, to start the calculation (in principle it could start in any arbitrary month), we can take the initial value  $Z_1$  higher than  $\bar{Z}$ : 5000 ECmm (Line 11a). With this value, we find the change in salt storage ( $\Delta Z$ ) over October to be 148 (Line 12a). The salt storage at the end of October ( $Z_2$ , Line 13a) is therefore  $5000 - 148 = 4852$ . We then regard this value as the initial storage ( $Z_1$ ) in November (Line 11a). Continuing the calculations in this way, we find that next year at the end of September,  $Z_2$  is 4225 ( $\Sigma\Delta Z = -775$ ). This value does not agree with the starting value  $Z_1$  of 5000 for October, which has apparently been chosen too high. Starting again, with a  $Z_1$  value of 3000 (Line 11b), we obtain  $Z_2 = 3491$  (Line 13b) in September and  $\Sigma\Delta Z = +491$ . Obviously, the value of 3000 is too low. Linear interpolation (Figure 15.8) between the two pairs of values (5000, -775) and (3000, +491) yields (3780, 0). Checking the value  $Z_1 = 3780$  (October, Line 11c) by repeating the salt storage calculations yields  $Z_2 = 3775$  (September, Line 13c), which is sufficiently close to the starting value and satisfies the condition that the sum of the quantities  $\Delta Z$  should be zero over a long period (Section 15.3.2).

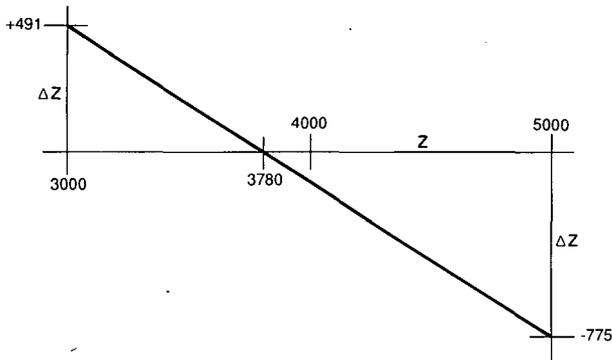


Figure 15.8 Linear interpolation to find the best estimate of the initial salt content of the rootzone,  $Z_1$

The electrical conductivity of the saturation extract,  $EC_e$ , calculated according to Equation 15.25, varies between 6.3 and 5.6 dS/m, values which are lower than the maximum permissible value of 8 dS/m. The average  $\overline{EC}_e$  is 5.9 dS/m, slightly lower than the permissible value of 6.

### Part III: Maximum Percolation in Autumn

The net deep percolation is maximum in autumn so as to decrease the peak demand in summer, on both the irrigation and the drainage system. The variation in the  $EC_e$ -value, between 6.8 and 5.0 dS/m, is greater than in the previous case, but the  $EC_e$  never exceeds the maximum permissible value of 8. The average  $\overline{EC}_e$  is 5.5 dS/m, lower than in Part II, because the salt input from the irrigation water is slightly lower (90 ECmm, which means a difference of 0.15 dS/m in  $EC_e$ ) and most of the leaching occurs in autumn, decreasing the  $EC_e$ -value well below 6 dS/m. This example shows how we can use the salt equilibrium equation to calculate the leaching requirement (i.e. the minimum amount of leaching water needed to maintain long-term salt equilibrium). It also shows how the salt storage equation can be used to calculate the monthly variation in  $EC_e$ . In this way, we can also check whether we can reduce the irrigation applications during the period of peak demand to a level equal to the consumptive use without creating a temporarily harmful salinity level. When irrigation water is scarce in summer, water must be saved.

Figure 15.9 illustrates the principle of long-term salt equilibrium differing according to the salt tolerance of the crops, and short-term salt fluctuation.

Figure 15.10 shows an example of long-term salt development towards equilibrium from autumn 1965 onwards, as well as of short-term salt fluctuation. This irrigation test, which was conducted at the Cherfech experimental station in Tunisia, comprised three rates of water application, kept respectively at 75% ( $I_1$ ), 100% ( $I_2$ ), and 125% ( $I_3$ ) of the consumptive use, which ranged around 7 mm/d in summer. This means that the water application  $I_1$  stands for water saving and  $I_3$  for frequent leaching. During the first two months after the crop had been sown, when consumptive use was low, the water applications were the same and corresponded to the amount of water needed to cover the field. As this amount then exceeded the consumptive use, leaching occurred with each application at the start of the growing season and also

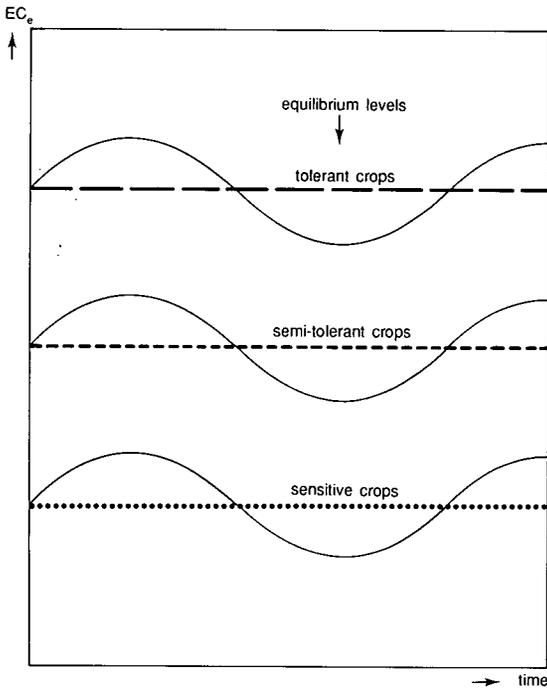


Figure 15.9 Long-term salt equilibrium at different levels and short-term salt fluctuation

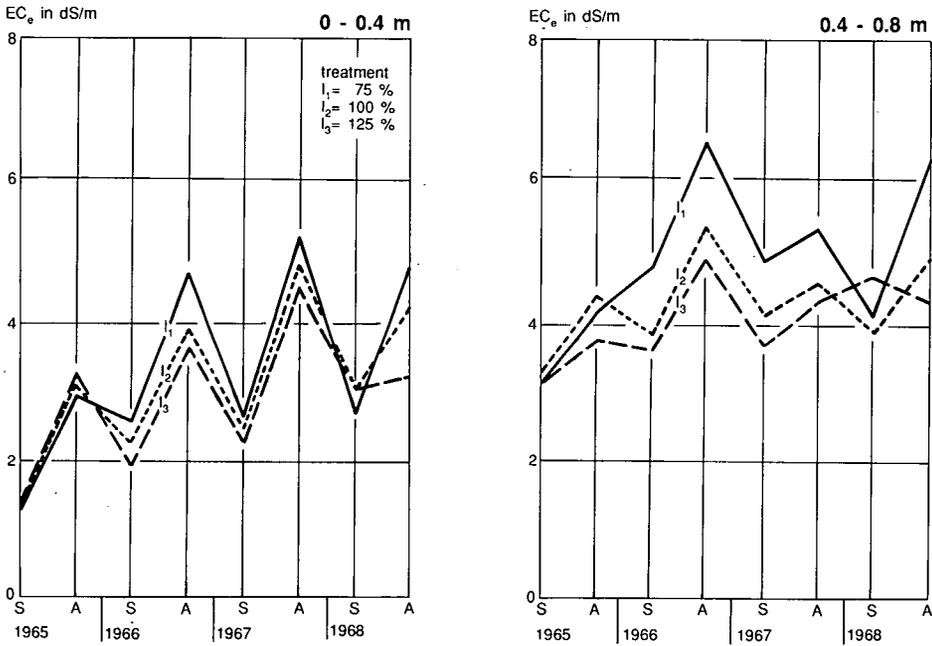


Figure 15.10 Irrigation test showing long-term development towards equilibrium and seasonal salt fluctuation for three rates of water application (S = spring; A = autumn)

during winter owing to a combination of rainfall and irrigation. The aim of the test was to remain as close as possible to practice and to investigate whether frequent leaching in the period of peak demand was necessary or whether water saving in that period could be permitted. Although the rates of water application had an effect on soil salinity, the differences were small, not justifying frequent leaching in summer. The seasonal variation, due to leaching in winter, was more important than the differences due to the applications. Frequent leaching in periods of peak consumptive use means that not only are greater amounts of water being applied but also that greater amounts of salts are brought into the soil. So this surplus amount of salt counterbalances to a certain extent the advantage of more leaching.

Field irrigation losses, which provide leaching, are seldom evenly distributed over the field. In part of the field, the losses may be in excess of the leaching requirement, whereas in other parts the reverse may be true. If, however, the losses are considerably higher than the leaching requirement, no extra volume of irrigation water need be added for leaching.

### 15.3.5 Effect of Slightly Soluble Salts on the Salt Balance

In the preceding sections, we assumed that all salts are highly soluble and that they remain in solution. We shall now consider the situation in which some of the salts are slightly soluble and that they precipitate.

Salts that precipitate at concentrations too high for crop growth are considered highly soluble: all chlorides, the sulphates of sodium and magnesium, and sodium bicarbonate. Their solubility at a temperature of 20°C exceeds 100 meq/l. Gypsum and calcium carbonate, of which the saturation concentrations never reach levels intolerable for crop growth, are defined as slightly soluble salts.

In complex solutions, which generally occur in soils, the solubility of most salts changes. In mixtures of salts with dissimilar ions, the solubility of the component with the lower solubility increases. Table 15.4A shows that the solubility of calcium carbonate (lime) increases with the concentration of dissimilar ions and with the carbon dioxide pressure of the soil air. For average soil conditions, the solubility of calcium carbonate can be set roughly between 5 and 10 meq/l, which contributes approximately 0.8 dS/m to the EC of the soil water.

Table 15.4B shows that the solubility of gypsum depends on the presence of the other salts. As a rule, the presence in a solution of salts with a common ion causes the solubility of these salts to drop (e.g. the solubility of gypsum in the presence of

Table 15.4A Solubility of lime ( $\text{CaCO}_3$ ) in meq/l, depending on carbon dioxide pressure and total concentration of dissimilar ions

Total concentration of dissimilar ions	P-CO <sub>2</sub> (Pa)				
	50	100	500	1000	5000
10 meq/l	1.5	1.9	3.3	4.1	7.0
100 meq/l	2.0	2.6	4.4	5.5	9.2

Table 15.4B Solubility of gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) in meq/l in pure water and in different solutions

Pure water	170 meq/l NaCl	1700 meq/l NaCl	140 meq/l $\text{Na}_2\text{SO}_4$	180 meq/l $\text{CaCl}_2$
30	49	98	22	17

$\text{Na}_2\text{SO}_4$  or  $\text{CaCl}_2$ ). The solubility of gypsum increases in the presence of dissimilar ions (e.g. in a solution of NaCl). Under average conditions, the solubility gypsum can be put at 30 meq/l. If gypsum is present in the soil, calcium carbonate is also generally present. Their concentration equals approximately 40 meq/l, which corresponds to an EC of 3.3 dS/m.

If one or both slightly soluble salts are present in the solid state, their contribution will be constant and will be equal to their saturation concentration: for calcium carbonate alone, corresponding with an EC of about 0.8 dS/m, and for calcium carbonate and gypsum together, corresponding with an EC of approximately 3.3 dS/m. Therefore the simplest way to make adjustments in the salt equilibrium and storage equations is to consider the highly and slightly soluble salts separately. If calcium carbonate is present in the soil, Equation 15.19 changes into

$$EC_e = EC_{e(\text{CaCO}_3)} + EC_{e(\text{highly soluble salts})} = 0.8 + 0.5EC_{fc(\text{h.s.s.})} \quad (15.26)$$

Similarly, if both calcium carbonate and gypsum are present in the soil, Equation 15.19 changes into

$$EC_e = EC_{e(\text{CaCO}_3 + \text{CaSO}_4 \cdot 2\text{H}_2\text{O})} + EC_{e(\text{h.s.s.})} = 3.3 + 0.5EC_{fc(\text{h.s.s.})} \quad (15.27)$$

It should be noted that, because the solubility of the slightly soluble salts is rather variable, Equations 15.26 and 15.27 are approximations for practical use. Equations 15.21, 15.22, 15.23, and 15.24 can be applied in the normal way for the highly soluble salts, after which the corrections for the slightly soluble salts can be introduced. How this is done will be explained with Example 15.2.

### Example 15.2

Table 15.5 presents the monthly salt and water balance of a soil irrigated with water in which gypsum predominates. The high values of Ca and  $\text{SO}_4$  (Line 2) indicate that the water is nearly saturated with gypsum, which will precipitate as soon as the irrigation water changes into more concentrated soil water.

Remaining in solution are all chlorides (3 meq/l) and all bicarbonates and sulphates not bound to Ca, estimated at 8 meq/l (i.e.  $\text{HCO}_3 + \text{SO}_4 - \text{Ca}$ ). The total concentration of highly soluble salts in the irrigation water is therefore 11 meq/l, with a corresponding  $EC_{i(\text{h.s.s.})}$  of  $11/12 = 0.9$  dS/m. We now use this value to calculate the total amounts of irrigation and percolation water with Equations 15.22 and 15.21. Then, for the irrigation water, we choose a distribution that follows the trend of the deficit ( $E - P$ ). We now calculate  $\Delta W$  and  $R^x$  for each month in the same way as in Example 15.1 (Table 15.3). We use Equation 15.24 to calculate the monthly salt storage for the highly soluble salts (Line 10). Next, Equation 15.25 determines the  $EC_e$  of the highly soluble salts at the beginning of each month (Line 12). We add the