THE SALINITY AND ALKALINITY STATUS OF ARID AND SEMI-ARID LANDS

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Contents

Summary

Soil salinization is an important problem in arid and semi-arid regions. Salt-affected soils containing high amounts of soluble chloride and sulfate salts of sodium, calcium and magnesium are characterized as saline soils. Salt-affected soils dominated by sodium salts and capable of alkaline hydrolysis are termed sodic (or alkali) soils. Too high a salt content impairs crop growth. The type and amount of anions and sodium in the soil determine whether it is saline or sodic

The amount of sodium expressed as a percentage of the total amount of cations is the exchangeable sodium percentage (ESP) and a measure of the sodicity of the soil. The soil sodicity can also be derived from the concentration of sodium, calcium and magnesium in the soil solution by the sodium absorption ratio (SAR) since there is an equilibrium between the absorbed and dissolved cations. High sodium content (ESP > 15%) usually results in poor physical soil conditions and can be toxic to plant growth.

There are various classification systems of salt-affected soils based either on the electrical conductivity (EC) and the exchangeable sodium percentage (US Salinity Laboratory) or on the ratios of individual cations and anions, the total toxic ions and the depth of the upper boundary of the saline horizon (USSR classification).

The chemical composition of the soil is significantly affected by the quality of the irrigation water, so the electrical conductivity and sodium absorption ratio of the irrigation water determine the salinity and sodicity hazard of the soil. High concentrations of particular cations and anions in the irrigation water may lead to serious toxicity problems, especially sodium, chloride and boron. Special attention should also be paid to biocide hazards and suspended solids in the irrigation water.

Salts that are left behind in the soil can affect crop growth if not leached. The leaching requirement depends on the salinity of irrigation water and the crop tolerance to soil salinity. Some procedures are discussed to increase the leaching efficiency and reduce the water consumption.

1. Introduction

Irrigated agriculture in arid and semi-arid areas is often a source of soluble salts even with water of excellent quality. It is estimated that one third of the irrigated land in the world is affected by salinity problems. The extent of salt-affected soils of some countries is given in Table 1.

Country	Saline soil (1000 ha)	Sodic soil (1000 ha)	Total (1000 ha)
Argentina	32,473	53,139	85,612
Australia	17,269	339,971	357,240
Chile	5,000	3,642	8,642
China	36,221	437	36,658
Ethiopia	10,608	425	11,033
India	23,222	574	23,796
Iran	26,399	686	27,085
Pakistan	10,456	-	10,456
Paraguay	20,008	1,894	21,902
USA	5,927	2,590	8,517
USSR (former)	51,092	119,628	170,720

Table 1. Extension of salt-affected soils in some countries. Source: Abrol *et al*, 1988.

Every soil contains a certain amount of soluble salts without being saline. Saline soil conditions develop only when soluble salts accumulate in the soil and reach a level harmful to plant growth. A soil which is saline and harmful for one crop might be suitable for others, and this means that plant tolerance to salinity might well vary. To avoid soil salinization that interferes with plant growth, the salts in the root zone should be leached by creating an additional water flush in the profile. However, this additional water supply might cause a rise of the water table and should be drained. In other words, the water table should be kept sufficiently deep to prevent accumulation of salts in the

root zone through capillary rise—and even accumulation at the soil surface (see Figure 1).

2. Soil Salinity and Sodicity

The soil solution of a salty soil mainly contains cations like Na^+, Ca^{2+}, Mg^{2+} and K^+ and anions like Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-} and NO_3^-. The dominant cation in salty soils is Na^+, which usually exceeds the concentration of Ca^{2+} and Mg^{2+}. The predominant anions are Cl^- and SO_4^{2-} and some HCO_3^- at normal pH values of 6 to 8, while CO_3^{2-} is found at pH above 8.5.

Figure 1. Surface salinization in Egypt.

The solid phase (clay particles, humus) of the soil has a negative charge and it adsorbs positively charged cations from the soil solution in order of adsorption preference: NH^{4+} > Ca^{2+} > Mg^{2+} > H^+ > K^+ > Na^+. These cations are mutually replaceable or exchangeable. Soil colloids containing a high portion of Ca^{2+} and other divalent ions form strong bonds between mineral particles and, consequently a stable structure. Soils rich in Na^+ have loose bonds and a weak soil structure.

The total amount of cations that a soil can absorb is called the Cation Exchange Capacity (CEC). The buffering capacity of a soil increases with a higher cation exchange capacity, and the latter is affected by the type (kaolinite has a low CEC, montmorillonite has a high CEC) and the amount of clay present in the solum.

The CEC of salt-affected soils contain mainly Ca^{2+}, Mg^{2+} and Na^+ and can be expressed by the formula:

$$CEC = A_{Na} + A_{Ca} + A_{Mg} \tag{1}$$

where *CEC* is the cation exchange capacity of a soil expressed in me/100 g of dry soil; and A_{Na}, A_{Ca}, and A_{Mg} correspond to the amount of adsorbed sodium, calcium and magnesium.

The parameters currently used for defining salinity and sodicity are Electrical Conductivity (EC), Exchangeable Sodium Percentage (ESP) and Sodium Absorption Ratio (SAR).

2.1. Electrical Conductivity

The electrical conductivity (EC) of a soil extract is an indirect expression of the total salt concentration in the soil, without reference to the nature and composition of the salts. The EC is expressed in dS/m (or mmhos/cm in older literature); it is measured at a standard temperature of 25 °C to avoid the influence of temperature.

EC may be measured in several soil/water concentrations. It is most relevant to measure EC at field capacity EC_{fc} as this provides the real salt concentration in the field, but because it is difficult to extract sufficient soil water from soil samples at field capacity in the laboratory, the salinity is determined in a standard saturation extract EC_{se} obtained by adding water to a dry soil. Except for sands and loamy sands, a saturated soil contains twice the amount of water at field capacity and the saturation extract is twice diluted compared with the soil water at field capacity. This is indicated by the formula:

$$EC_{fc} = 2EC_{se} \tag{2}$$

A saturated soil paste should thus always have the same amount of water added to the air-dry soil, as otherwise the measured EC might vary due to differences in water content of the soil paste. The preparation of a saturation extract is laborious and, therefore, soil water extracts are currently prepared at fixed ratios, e.g. 1:1 (100 g water per 100 g dry soil), 2:1 or 4:1. The EC value is then inversely proportional to the water content as indicated in the following conversion :

$$EC_{1:1} = 2EC_{2:1} = 4EC_{4:1} \tag{3}$$

It should, however, be recalled that this proportionality between salt concentration and soil moisture content only holds true for highly soluble salts like NaCl and Na_2SO_4. For slightly soluble salts like $CaCO_3$ (lime) and to a lesser extent Ca_2SO_4 (gypsum), smaller values of the concentration ratio apply since precipitation occurs upon concentration.

2.2. Exchangeable Sodium Percentage

The Exchangeable Sodium Percentage (ESP) corresponds to the amount of adsorbed sodium, compared to the CEC and is expressed as:

$$ESP = \frac{A_{Na}}{CEC} 100 \tag{4}$$

The ESP is an expression of the sodicity and dispersion tendency of a soil. The soil solution has a major influence on the chemical properties of the soil adsorption complex since there is an equilibrium between the adsorbed and the dissolved cations as given by the Gapon equation:

$$\frac{A_{Na}}{A_{Ca} + A_{Mg}} = K_G \frac{Na^+}{\sqrt{\dfrac{Ca^{2+} + Mg^{2+}}{2}}} \tag{5}$$

where K_G is the exchange coefficient which has a value of about 0.015 (me/l)$^{-0.5}$; and the cation concentrations Na^+, Ca^{2+} and Mg^{2+} of the soil solution are expressed in me/l. The Gapon equation demonstrates that a more concentrated soil solution results in a greater amount of A_{Na} at the expenses of A_{Ca} and A_{Mg} and, consequently, in an increase of *ESP*. In the case of dilution, A_{Ca} and A_{Mg} will replace A_{Na} and *ESP* will decrease.

Because of the equilibrium between the soil and the soil solution it is also possible to measure the sodicity from the Sodium Adsorption Ratio (SAR), derived from the concentration of sodium, calcium and magnesium in the soil solution:

$$SAR_{se} = \frac{Na^+}{\sqrt{\dfrac{Ca^{2+} + Mg^{2+}}{2}}} \tag{6}$$

where SAR_{se} is the sodium adsorption ratio of the saturation extract of the soil. The application of this procedure is interesting because SAR_{se} can be determined more easily than *ESP* and it allows calculating *ESP* from SAR_{se} because the combination of equations (1), (4), (5) and (6) results in:

$$ESP = \frac{K_G SAR_{se}}{1 + K_G SAR_{se}} 100 \tag{7}$$

For a range of soils in western USA, the following relation was found between SAR_{se} and *ESP*:

$$ESP = \frac{100(-0.0126 + 0.01475\,SAR_{se})}{1 + (-0.0126 + 0.01475\,SAR_{se})} \tag{8}$$

The concentration of Na^+, Ca^{2+} and Mg^{2+} in the saturation extract of a soil can easily be determined and SAR_{se} can then be calculated or read from the nomogram (Figure 2). Within the range $SAR_{se} = 2\text{-}30$ is $SAR_{se} \approx ESP$.

2.3. Physical Soil Properties

Exchangeable sodium exerts an adverse effect on the soil physical properties. High values of ESP or SAR are usually an indication of poor physical soil conditions and high pH. Dispersion problems may appear at greater ESP or SAR. A limit beyond which the ESP is harmful to the soil structure is difficult to assess. In general, no problems are experienced in soils with ESP < 15% under arid climates. However, the ESP is not the only indicator of soil stability because the salt concentration of the soil solution also affects soil dispersion.
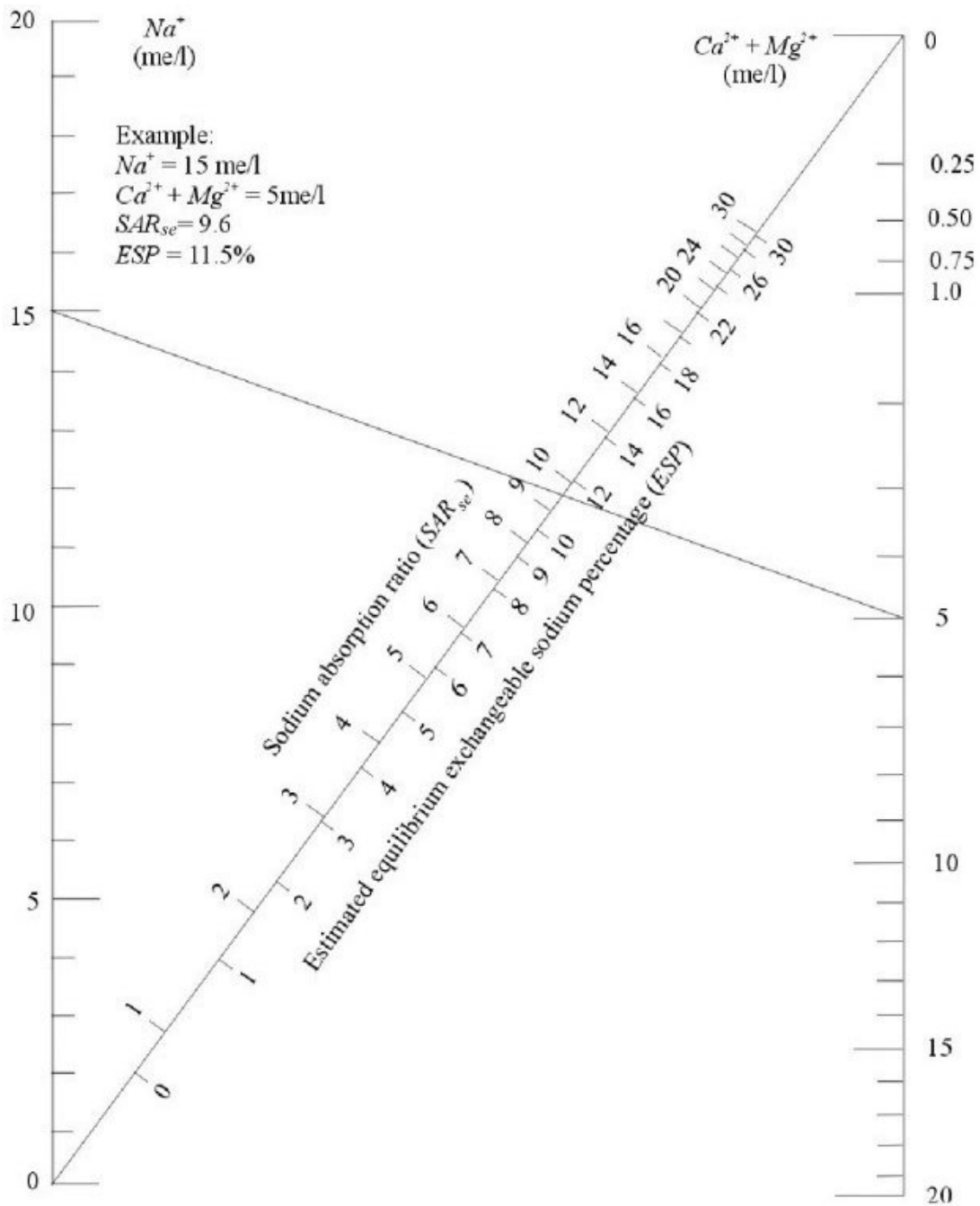
Figure 2. Nomogram for determining the SAR of the saturation extract of a soil solution (SAR_{se}) or irrigation water (SAR_{iw}) and for estimating the corresponding *ESP* of a soil in equilibrium with the water. Source: Richards, 1954.

Salt-affected soils with an appreciable amount of exchangeable sodium (ESP > 15%) may have a good structure and will not disperse as long as the salt concentration of the soil solution is high. When the salt concentration in the soil solution decreases, e.g. due to rain or irrigation, soils may become more susceptible to dispersion. An amendment with calcium may then be required to replace the sodium.

An ESP of 25% in a sandy soil hardly affects soil structure. In clay soils, the type of clay mineral (swelling or non-swelling clay) determines the liability to dispersion as swelling clays are more susceptible to dispersion than non-swelling clays. *Vertisols* (strongly swelling and shrinking clay soils) in Gezira, Sudan and elsewhere, however, are examples of soils that do not exhibit dispersion problems in spite of values of ESP ranging between 20 and 25%.

The impact of rain or irrigation water on soils high in exchangeable sodium but with a low salinity may cause the breakdown of soil structure and cause the surface soil to slake and puddle. Soil tillage may result in a compacted soil layer with poor water transmission. Upon drying, a hard crust that hampers seed emergence and crop growth is formed.

2.4. Classification of Salt-affected Soils

There are various classification systems of salt-affected soils. The most universally applied system is the one introduced by the USDA Salinity Laboratory (Richards, 1954), and later integrated in the USDA Soil Taxonomy classification of soils. The USSR system developed by Bazilevich and Pankova (1969) is more detailed but also more complicated and has therefore only received a regional application; it is discussed in short for reference only.

The most widely used system is the classification of the US Salinity Laboratory, mainly because it is based on easily obtainable parameters like EC and ESP (Table 2) and it has a practical implementation in plant growth and tolerance levels of crops. In this system the salt-affected soils are in the first place characterized by their pH. Saline soils have a pH below 8.5, while sodic soils have a pH above 8.5; the pH of saline sodic soils is near to neutral.

Diagnostic parameters	$EC_{se} \leq 4$ dS/m	$EC_{se} > 4$ dS/m
$ESP \leq 15\%$	Non-saline and non-sodic soil	Saline soil
$ESP > 15\%$	Sodic (or alkali) soil	Saline sodic soil

Table 2. Classification of salt-affected soils by the US Salinity Laboratory
Source: Richards, 1954.

Salinity affects crop growth for two main reasons:

- Osmotic effect: The osmotic forces increase with increasing salinity of the water and reduce the availability of water for the plant. Crops show early signs of moisture stress which is one of the main causes of the poor growth of crops.
- Toxic effect: A high concentration of a particular cation or anion, or an unfavorable salt composition in the soil solution results in an excess or imbalanced uptake by plants. Well-known is the leaf burn of fruit trees as a result of excessive uptake of Na^+ and Cl^-.

For practical reasons and in order to better meet the tolerance levels of crops, the initial classification as defined in Table 2 has been slightly refined and adapted, as shown in Table 3. The data in this Table refer to medium and fine textured soils, for which $EC_{se} = 0.5 \ EC_{fc}$. For the coarser textured sandy soils, for which $EC_{se} = 0.25 \ EC_{fc}$, the limits should be halved, otherwise the soil salinity of such soils will be underestimated.

EC_{se} (dS/m)	Classification	Crop yield
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

Table 3. Agronomic classification of soil salinity based on EC.

The USSR-classification of salt-affected soils (Bazilevich and Pankova, 1969) also takes into consideration the nature of the salts and their relative concentration. Hence, it is much more detailed but also requires much more analytical information. It is based on three criteria: the type of salinization (Table 4), the degree of salinity (Table 5) and the depth of the saline horizon (Table 6).

Type of salinization	Ratios of me cations		
	Na/Mg	Na/Ca	Mg/Ca
Sodium	>1	>1	-
Magnesium-Sodium	>1	>1	>1
Calcium-Sodium	>1	>1	<1
Calcium-Magnesium	<1	<1	>1
Sodium-Magnesium	<1	>1	>1
Sodium-Calcium	>1	<1	<1
Magnesium-Calcium	<1	<1	<1
Magnesium	<1	-	>1

Table 4. Type of salinization according to the cation ratios (Bazilevich and Pankova, 1969).

The type of salinization is determined from the ratio of the anions and completed with the ratio of the individual cations (Table 4) and not from their amounts.

The degree of salinity is based on the relative toxicity of the ions to plant growth. As the toxicity of the various ions differs, the total effect of toxic ions is expressed in chloride equivalents so that $1 \ Cl^- = 0.1 \ CO_3^{2-} = 2.5\text{-}3 \ HCO_3^- = 5\text{-}6 \ SO_4^{2-}$. Table 5 gives the soil classification according to the degree of salinity at which the lower indices are valid for single salts and the higher indices for salt mixtures.

Salinity degree	Total effect of toxic ions (CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-})

	in me Cl$^-$
Non-saline	< 0.3
Weakly saline	0.3 - 1.0 (1.5)
Medium saline	1.0 (1.5) - 3.0 (3.5)
Strongly saline	3.0 (3.5) - 7.0 (7.5)
Very strongly saline	>7.0 (7.5)

Table 5. Salinity degrees considering the total effect of toxic ions.
Source: Bazilevich and Pankova, 1969.

The third criterion in this system is the depth of the saline horizon (Table 6). It is less rigorous for irrigated than for non-irrigated soils because of the important seasonal salt migration which is a current feature in these soils.

Soil	Depth of the upper boundary of the saline horizon (cm)	
	Non-irrigated soil	Irrigated soil
Solonchak and solonchak-like	0 - 30	0 - 50
Shallow solonchakous	30 - 50	
Solonchakous	50 - 100	50 - 150
Deeply solonchakous	100 -150	
Deeply saline	150 - 200	150 - 200

Table 6. Soil classification according to the depth of the saline horizon.
Source: Bazilevich and Pankova, 1969.

Furthermore, a soil with an appreciable amount of exchangeable sodium in the B horizon — a soil horizon marked by an illuviation of clay particles and a characteristic columnar soil structure — is called a *solonetz soil*.

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Biographical Sketch

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