Food and Agriculture Organization of the United Nations

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AGRICULTURE FOR TOMORROW

WASAG | The Global Framework on Water Scarcity in Agriculture

THEMATIC 1

FARMERS' GUIDELINES ON SOIL AND WATER MANAGEMENT IN SALT-AFFECTED AREAS

WASAG WORKING GROUP ON SALINE AGRICULTURE

Thematic 1: Farmers' guidelines on soil and water management in salt-affected areas

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Contents

Foreword

The Global Framework on Water Scarcity in Agriculture (WASAG)[a] was officially launched by FAO and its partners during the COP22 of the UNFCCC in Marrakesh, Morocco in November 2016, calling for concerted efforts among stakeholders to respond to the challenges posed by water scarcity in agriculture, which are exacerbated by climate change and a growing world population. To date, more than 70 members consisting of government institutions, international organizations, research institutions, membership and civil society organization have joined WASAG, and new applications for membership continue to be received. FAO coordinates the work of WASAG and provides support services.

WASAG aims to foster collaboration among partners for the development and implementation of policies and programs for the sustainable use of water in agricultural sectors, using context-specific approaches and processes. It seeks to identify priority actions for the adaptation of agriculture to climate change and for the scaling up of successful responses to the threats to agricultural production posed by increasing water scarcity. In so doing, the Global Framework aims to help countries, communities and businesses satisfy their needs for increased food production in the face of climate change, while conserving ecosystems and the services they provide.

WASAG established six working groups, which are led by its partners, including the one on Saline Agriculture (SA). The SA working group focuses on supporting sustainable food production in increasingly saline environments while contributing to the restoration and/or protection of productive natural capital affected by salinity and water scarcity. The working group delivered two successful webinars in 2020; one on "Saline agriculture: scaling-up opportunities and challenges"[b] and another on "Water and soil management in salt-affected areas".[c]

The SA working group further developed practical guidelines for farmers implementing agriculture in salt-affected areas to assist them in their decision-making processes in dealing with salinity/sodicity issues in their lands. The guidelines were split into two thematic volumes. thematic 1 focuses on "Soil and Water management in salt-affected areas" and thematic 2 on "Saline farming in salt-affected areas".

The current document refers to thematic 1, whereas thematic 2 is being finalized. The experts (scientists, researchers from eminent organizations) who prepared these documents have made considerable effort to simplify the technical language and deliver it in more simplified, laypeople, handy terms that allow farmers to follow and deal with salinity/sodicity effectively, while keeping the scientific essence to its core.

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[a] Get more information about WASAG at www.fao.org/wasag

[b] Watch the full recording of the webinar here: www.fao.org/wasag/resources/webinars/saline-agriculture-opportunities-and-challenges

[c] Watch the full recording of the webinar here: www.fao.org/wasag/resources/webinars/soil-water-management-salt-affected-areas

The document has been developed in a collaborative and voluntary way, in the spirit of WASAG, that is working together to turn challenges posed by climate change and water scarcity into opportunities for sustainable agriculture development, with socio-economic benefits for affected countries and communities. The International Center for Biosaline Agriculture (ICBA) has coordinated this work on behalf of the SA working group.

The next step is to facilitate the adoption of these guidelines by the farmers in order to accelerate the achievement of the relevant Sustainable Development Goals. One such opportunity on the future work related to the guidelines will be undertaken in collaboration with the FAO's Value Adding Impact Area (VAIA) of the FAO Strategic Framework for 2022–2031 on Addressing Water Scarcity in Agriculture and the environment (AWSAMe). FAO and ICBA, together with other WASAG partners and stakeholders, are ready for this next step and look forward to the support of development partners.

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Executive summary for thematic 1

The threats posed by salt-affected soils to global food security are dire. According to FAO's recent Global salt-affected soils map, over 424 million hectares of topsoil (0–30 cm) and 833 million hectares of subsoil (30–100 cm) are currently salt-affected. This practical guide to soil and water management in salt-affected areas provides vital information to farmers dealing with salinity and sodicity issues on their farms and assists them in following suggested practices to mitigate or/and to adapt to these unfavourable conditions without compromising further losses in yields. Thematic 1 is split into five key sections as presented briefly below.

A. Introduction: Why is the management of salt-affected soils and water so important?

This section introduces the user to the global challenge of salinity and sodicity and highlights why much effort ought to be dedicated for their management to improve livelihoods and welfare of marginal resource-poor farmers.

B. Definitions of phenomena

Uniting the understanding of salinity and sodicity, including their appropriate terminology, under one common definition is paramount. This section explains how primary and secondary salinization occur along with other related phenomena. In addition, it sheds light on the effects of salinity and sodicity on plants.

C. Assessment methods, soil and water sampling, and measurement interpretation of salinity and sodicity

Simple guidelines for infield observational (field and crop inspection) and measurement-based assessment methods for soil and crop are presented in this section including elaborate laboratory-based measurements. This section also describes handheld devices and tools for on-site and off-site testing. Further, recommendations are provided for representative and reliable soil and water sampling for salinity/sodicity assessment. Finally, guidance on interpreting salinity and sodicity measurement results is provided.

D. Water resources management in salt affected areas

Irrigation recommendations for salt-affected soils and/or with water high in salts are provided. The different types of irrigation are discussed, and they include drip, sprinkler, subsurface, etc. Strategies and methods for successful management of water resources under salinity constraints are thoroughly explained. These include leaching (requirement, frequency), drainage (system, depth, spacing), irrigation (system, scheduling), and use of multiple water sources (alternating, blending).

E. Soil management in salt affected areas

Recommendations on soil-related management strategies under saline/sodic conditions are presented. These include land levelling, tillage and subsoiling, seedbed shaping, and salt scraping. Salt affected soils can be improved for crops via the application of soil amendments (green manures, compost, fertilizers, etc.). Other strategies and methods such as selection of suitable crops for managing salt-affected soils are also highlighted. The latter approach will be elucidated in thematic 2.


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Introduction: Why is the management of salt-affected soils and water so important?

Lack of good quality of surface waters to meet the increasing water demands due to persistent population growth and urbanization drives the world population to access groundwater sources. Many groundwater sources around the world are not suitable for direct use. These sources can be highly saline, which require additional treatment for removing salts to produce potable water or water suitable for other non-potable uses (Gude, 2017). For example, approximately 30 percent of the groundwater resources in the Near East and North Africa (NENA) region are saline and more than 70 percent are such in the Gulf Cooperation Council (GCC) countries. The existing paradigm for irrigated agriculture has contributed to widespread salinization of groundwater resources (Pulido-Bosch *et al*., 2018).

The recently launched Global Map of salt-affected soils (SAS) Version 1.0 developed from 118 countries covering 85 percent of the global land area showed that more than 424 million hectares of topsoil (0–30 cm) and 833 million hectares of subsoil (30–100 cm) are salt-affected. In particular:

- 85 percent of salt-affected topsoils are saline, 10 percent are sodic and 5 percent are saline-sodic.
- 62 percent of salt-affected subsoils are saline, 24 percent are sodic and 14 percent are saline-sodic.

These estimates based on the submitted data show that more than 3 percent of global topsoils and more than 6 percent of global subsoils are affected by salinity or sodicity. More than two thirds of global SAS are found in arid and semi-arid climatic zones:

- 37 percent of SAS are located in arid deserts.
- 27 percent of SAS are distributed in arid steppe (half in cold arid steppe and half in hot arid steppe).[1]

To this end, the world is pressed to identify proper mitigation and adaptation strategies that support farming communities – especially those struggling to practice agriculture in salt-affected areas – against the impact of soil and water salinization (Hopmans *et al.*, 2021). Initiatives that bring the farmers closer to finding the right information and tools for understanding the salinity/sodicity phenomena and their impacts on soil, water and crops are vital for making appropriate decisions. The current document serves such purposes by offering an informative reference for farmers in salt-affected areas on relevant management strategies.

[1] More information can be found here: www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/global-map-of-salt-affected-soils

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Definitions of phenomena

WHAT IS SALINITY?

Salinity is the excessive quantity of salts in soil or water. It is informally known as "white saltiness".

Salinity is an excessive quantity of water-soluble salts in the soil, soil solution or water. Salts can include sodium, potassium, magnesium, calcium, chloride, sulphate, carbonate and bicarbonate, but the dominant cation in saline conditions is sodium, while the dominant anions are typically soluble chloride and sulphate. While some of these salts are essential nutrients, when found in high concentrations, they can limit the ability of plants to absorb water, have toxic effects on plants and can adversely impact soil health by affecting physical, chemical and biological properties.

WHAT CAUSES SALINITY IN INLAND REGIONS?

In inland regions, salinity is the result of two salinization processes. **Primary salinization** involves accumulation of salts through natural processes due to high salt contents in parent materials or groundwater. **Secondary salinization** is caused by human interventions such as irrigation practices, e.g. with salt-rich irrigation water and/or insufficient drainage.

WHAT CAUSES SALINITY IN COASTAL REGIONS?

In coastal regions, salinity is the result of **primary salinization, secondary salinization** and three additional processes:

- **Seepage salinization** occurs when saline groundwater rises to the root zone as the overlying freshwater body is depleted.
- **Flood salinization** is another process where the sea floods the land thereby depositing salts on the land. Seepage and flood salinization are particularly common in low lying coastal regions.
- **Aerosol salinization** occurs when blowing wind picks up small droplets of sea water which are then deposited on the land, especially those closest to the sea.

WHAT IS SODICITY/ALKALINITY?

Sodicity is the excessive quantity of sodium salts relative to the other salts. It is informally known as "black saltiness".

Sodicity (also known as alkalinity) is the presence of excess sodium ions (Na+) relative to other cations, and excess concentrations of free carbonate (CO_3^{--}) and bicarbonate (HCO_3^{-}) relative to other anions. In soils, sodicity causes degradation of soil structure so that roots, water and air cannot penetrate. Specifically, Na+ ions displace Ca^{2+} and Mg^{2+} ions that normally bind clay particles in the soil together, causing the clay to disperse. These soils are sticky when wet and hard when dry. From a fertility standpoint, they are deficient in nitrogen, phosphorus and zinc. Though naturally sodic soils exist, irrigation with sodic water, waterlogging, clearing natural vegetation, and poor land management can also lead to sodification.

WHAT DOES THE TERM "SALT-AFFECTED" REFER TO?

In general, the term "**salt-affected**" encompasses all the problems due to salts present in the soil, while in strict terms, these soils are categorized into three types: saline, sodic (or alkali) and saline-sodic.

WHAT ARE THE CHARACTERISTICS OF SALINE, SODIC AND SALINE-SODIC SOILS?

Sodium is the dominant cation in most salt-affected soils, while the dominant anion determines the kind of soil and consequential change in **electrical conductivity** (EC), **exchangeable sodium percent** (ESP), pH, **sodium adsorption ratio** (SAR) and the soils appearance (Table 1).

For example, the dominant anions in saline soils are usually soluble chloride (Cl^-) and sulphate (SO_4^{--}), resulting in EC more than 4 dSm^{-1}, ESP less than 15 and relatively low pH values (<4). These soils appear white in color and therefore informally termed "white saltiness".

Contrastingly, the dominant anions in sodic soils are typically carbonate (HCO_3^-) and bicarbonate (CO_3^{--}), resulting in high pH values, ESP more than 15 and EC less than 4 dSm^{-1}. These soils appear dark in color and therefore informally termed "black saltiness".

Saline sodic soils have anions of both groups and have both high ESP and EC.

Table 1. Diagnostic characteristics of salt-affected soils

Type of Salt-affected soil	Electrical conductivity ECe (dSm-1)	ESP (%)	SAR	Dominant Anion	Presence of cation (Na+) in soil	$pH_{1:2}$ (pH of 1 part soil and 2 part water)
Saline	>4	<15	<13	Cl^-, SO_4^{--}	Ionic phase in solution	<8.8
Sodic	<4	>15	>13	HCO_3^-, CO_3^{--}	Colloidal phase on clay exchange site	8.5–10.5
Saline-sodic	>4	>15	variable	Anions of both kind of soils	Both ionic and colloidal	>8.8

Source: Authors' own elaboration.

WHAT ARE THE MAIN EFFECTS OF SALINITY ON PLANTS?

Salinity decreases yields, as it reduces the amount of available water for plant use even in soils with abundant water content. This characteristic is known as the **osmotic effect**, by which salts inhibit the taking-up of water by plants. For a plant to take up water in a saline environment, its own osmotic potential needs to be lower than that of the environment it is in.

Salinity also has an **ionic effect** by which a high concentration of a particular salt can be toxic to plants or compete with other plant-essential nutrients, thereby causing deficiencies. While many of the salt ions are essential nutrients for maintaining healthy plant growth and a healthy soil ecosystem (e.g. magnesium, calcium, potassium and sulphur), if their concentration becomes too high, particularly of sodium in clay rich soils, the soil structure may collapse, resulting in dense soils with poor water infiltration. When this occurs, nutrient availability and crop yields decrease.

Usually, plants are most sensitive to salinity during germination or at early growth stages. For annual crops, the osmotic effect of salinity stress is usually the first problem to occur, whereas the accumulation of salts to toxic levels usually takes more time to develop and may be more prominent in perennial crops.

WHAT ARE THE EFFECTS OF SODICITY ON PLANTS?

In sodic soils a high sodium content is accompanied by the presence of carbonate and bicarbonate ions leading to a high soil pH, which in turn can reduce the availability of essential macronutrients such as phosphorus, calcium and magnesium, as well as micronutrients such as iron, manganese and zinc. Imbalance in element availabilities in sodic soils can lead to toxic levels of elements such as sodium, molybdenum or boron in plants. Furthermore, sodicity adversely impacts soil structure, making seed germination and plant growth difficult. The poor soil structure is driven by sodic soils' dispersive properties which can cause crusting and surface sealing and lead to reduced flow of water into and through the soil profile. In such situations, plants with deeper roots can experience water shortages due to insufficient water flowing into deeper horizons, whereas plants with shorter roots can experience low-oxygen stress due to waterlogging.

Assessment methods, soil and water sampling, and measurement interpretation of salinity and sodicity

ASSESSMENT METHODS OF SALINITY AND SODICITY

IN-FIELD ASSESSMENT METHODS

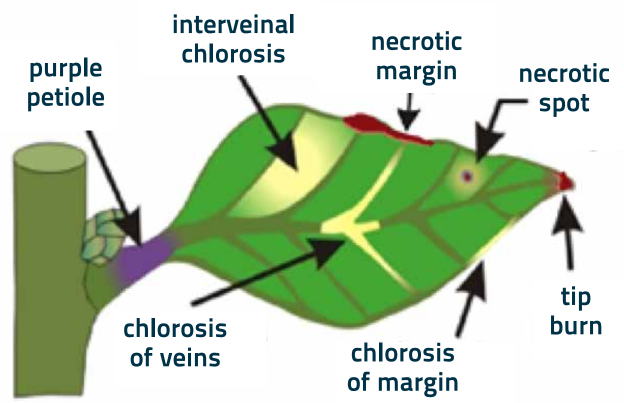
WHAT ARE THE VISUAL SYMPTOMS OF SALINITY AND SODICITY IN THE SOIL?

Soils respond differently to elevated levels of salts depending mainly on the soil's texture and organic carbon content. Accumulation of salts can result in three different soil conditions: saline, saline-sodic and sodic. Each one of these has distinct characteristics that can be observed in the field and are useful for addressing the problem – saline soils tend to be white, sodic soils typically have a brownish-black crust, saline-sodic soils are generally grey.

WHAT ARE THE VISUAL SYMPTOMS OF SALINITY AND SODICITY IN THE CROP?

Crops also respond differently to elevated salt concentrations in the soil, and the exact response depends on crop species and variety. Even though salt-specific crop damage exists (Figure 1) and can be expressed in multiple ways, the visible effects usually reflect an integrated crop response. Often, this is just reduced growth, that is the crop yields are below the yield potential, commonly characterized by patchiness, but in some instances the yield response occurs over the entire field and is therefore hard to visually identify without more detailed knowledge of the soil. In such cases, in-field or laboratory measurements are warranted and typically require sampling. The following physical observations/symptoms may be helpful in visually diagnosing salt-related soil problems (Table 2).

Figure 1. Salt-specific leaf damage



Source: Adapted from /www.floramax.com/nutrient-deficiencies/

Table 2. Signs and symptoms of salinity/ sodicity. Visual indicators of the presence of salinity/sodicity issues.

White salt crust on soil surface

©Antonio Jordán

Salt stains on the dry soil surface

©ICBA

Reduced or no seed germination

©SERC-Carleton

Reduced plant vigour

©WinField United salt breeding nursery

Foliage damage – leaf burn

©NMSU/ L. Peters

Spontaneous growth of halophytic weeds

©Green Deane

Dispersed soil and/or cloudy or turbid water in puddles

©DPIRD

Waterlogging

©CSSRI

Black soil (due to the formation of a Na-humic substances complex)

©Subramanian Dharumarajan

Patchy crop establishment

©DAFWA/ Stephen Davies

Surface sealing and crusting

©FAO

Shallow rooting depth

©UMN extension

Source: Adapted from **Shahid, S. A., Zaman, M., & Heng, L.** 2018. Introduction to soil salinity, sodicity and diagnostics techniques. In *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques* (pp. 1-42). Springer, Cham.

WHAT IS A QUICK AND EASY TEST TO ASSESS THE PRESENCE OF SOIL SODICITY IN THE FIELD?

Soil sodicity can also be diagnosed visually, in relative terms, using a simple field assessment method. Referred to as the soil to water ratio (1:5) suspension turbidity test, this test can give clues on the level of sodicity relative to a reference soil by placing a sample of the soil of interest in a clear container filled with water five times the amount of soil (in weight or volume). Depending on the suspension produced, the soils can be classified non sodic (suspension is clear), somewhat sodic (suspension is partly turbid or cloudy) or highly sodic (suspension is very turbid of cloudy). An object can also be inserted into the suspension to assess the extent of its visibility through the turbidity which may aid in estimating the sodicity class (Shahid *et al*., 2018).

HOW CAN SALINITY/SODICITY BE MEASURED AND QUANTIFIED IN THE FIELD?

Visual assessment only provides a highly subjective qualitative/ categorical indication on the presence of salts in a field and does not satisfy the need for a quantitative measurement of the extent of soil salinity. If laboratory analysis is not available, several handheld devices and tools exist for on-site testing of EC and pH, such as hydrometers, refractometers, and salinometers. Readings from hydrometers are the least accurate, while refractometers require calibration for reference temperature, i.e. 25oC, which if not done may cause misinterpretation of readings. Readings from salinometer (Figure 2), also known as EC meter, a portable inexpensive device costing USD 50 to100, are the most reliable. EC meter units may be in ppt, which can then be converted to ppm or µS/cm using an online tool found here.

HOW CAN A PORTABLE SALINOMETER (EC METER) BE USED TO MEASURE SOIL AND WATER SALINITY IN THE FIELD?

While an EC meter (Figure 2) can be used directly on water bodies and soil samples to determine water and soil salinity respectively, a soil sample must be collected and processed. In the field, extracting the liquid from the water-saturated paste of a soil sample – the more recommended methodology in a laboratory setting – is not possible as it involves laboratory equipment such as a vacuum pump. Therefore, an alternate procedure is used, namely the soil-to-water suspension method (1:1, 1:2.5, 1:5 etc., on a weight or volume basis), which entails adding water to a soil sample since EC meters require an aqueous solution to take measurements. Readings from such suspensions can then be converted to ECe, since ECe is the most appropriate parameter used in salinity management and crop selection.

Less commonly, some EC meters can directly measure salinity in a saturated paste (ECsp). This method can be viewed as a compromise between the measurement of EC from a soil-to-water suspension and the measurement of EC from the extract of a saturated paste. No matter the tool and equipment chosen, they require additional expenses for installation and maintenance in addition to the cost associated with their purchase. Thus, farmers should select the equipment according to their effective needs and financial capabilities. Another important aspect to consider when using equipment is whether technical assistance is available when and if needed to ensure that the tool is always fully operational and properly calibrated. This is very important to avoid wrong measurements which may drive inadequate management, thus putting the farming operation at risk.

Figure 2. An example of salinometer (EC meter).

©Kedida

Several conversion equations have been developed and presented in the literature to convert EC measurement between the soil-to-water suspension method and ECe. Important factors in these conversions are soil texture, organic matter content, temperature, and the measured $EC_{s:w}$ as summarized below (Omuto *et al.*, 2020):

$$EC_e = f(EC_{s:w}, texture, carbon, temperature) + \epsilon$$

where $EC_{s:w}$ is the measured EC from the suspension method. Omuto *et al.* (2020) summarized these equations in Table 3. When salinity has to be determined in the same field over several growing seasons, it is advised to establish one's own specific conversion factor based on the local soil type.

Table 3. Existing EC conversion models

Model Name	Description	Texture Class	Soil-to-water mix*	Reference
USDA	ECe ≈ $EC_{s:w}$*3	All	1:1	Richards (1954)
	Ece ≈ $EC_{s:w}$*5	All	1:2	
Landon	Ece ≈ $EC_{s:w}$*2.2	All	1.1	Landon (1984)
	Ece ≈ $EC_{s:w}$*6.4		1:5	
	Ece ≈ $EC_{s:w}$*3.81		1:3	
Hogg	Ece ≈ $EC_{s:w}$*1.75–0.37	All	1:1	Hogg and Henry (1984)
	Ece ≈ $EC_{s:w}$*1.38–0.14		1:2	

Zhang	Ece ≈ $EC_{s:w}$*1.79+1.46	All	1:1	Zhang *et al.* (2005)
Chi	Ece ≈ $EC_{s:w}$*11.68–5.77	All	1:5	Chi and Wand (2010)
Ozcan	Ece ≈ $EC_{s:w}$*1.93–0.57	All	1:1	Ozkan *et al.* (2006)
	Ece ≈ $EC_{s:w}$*3.3–0.2		1:2.5	
	Ece ≈ $EC_{s:w}$*5.97–1.17		1:5	
Sonmez	Ece ≈ $EC_{s:w}$*2.72–1.27	Coarse Texture	1.1	Sonmez *et al.* (2008)
	Ece ≈ $EC_{s:w}$*4.33+0.17		1:2.5	
	Ece ≈ $EC_{s:w}$*8.22–0.33		1:5	
	Ece ≈ $EC_{s:w}$*2.15–0.44	Medium Texture	1:1	
	Ece ≈ $EC_{s:w}$*3.84+0.35		1:2.5	
	Ece ≈ $EC_{s:w}$*7.58+0.06		1:5	
	Ece ≈ $EC_{s:w}$*2.03–0.41	Fine Texture	1:1	
	Ece ≈ $EC_{s:w}$*3.68+0.22		1:2.5	
	Ece ≈ $EC_{s:w}$*7.58+0.24		1:5	
FAO	Ece = f (texture, clay, carbon, EC)		VARIED	FAO (2006)

*per volume or per weight basis.

Source: **Omuto CT, Vargas RR, El Mobarak, AM, Mohamed N, Viatkin K, Yigini Y.** 2020. *Mapping of salt-affected soils: Technical manual.* Rome, FAO. doi.org/10.4060/ca9215en

LABORATORY ASSESSMENT METHODS

HOW IS SALINITY MEASURED IN THE LAB?

Salinity can be estimated in the lab by measuring either the electrical conductivity (EC) of an aqueous solution derived from the sample or total dissolved solids (TDS) method.

WHAT IS ELECTRICAL CONDUCTIVITY (EC)?

The presence of salts increases electrical conductivity (EC). As such, high EC values indicate high salt levels. The most used units for EC are deciSiemens per meter (dS/m), milliSiemens per centimeter (mS/cm), microSiemens per centimeter (µS/cm), and millimho per centimeter (mmho/cm). ECe refers to the EC of the Saturated Paste Extract. The saturated paste extract is the liquid that is extracted from a water-saturated soil sample and constitutes the recommended methodology by the international scientific community for quantifying concentration of ions as well as EC in soil (Omuto *et al.*, 2020). In fact, most classification values and data about salt sensitivity of crops refer to ECe (FAO, 2006). Its counterpart is the soil-water suspension method (ECs:w) that involve the mixing of soil with water into ratios, the most popular of which are 1:1, 1:2.5 and 1:5.

WHAT ARE TOTAL DISSOLVED SOLIDS (TDS)?

All inorganic and organic substances dissolved in water are considered dissolved solids and measuring their levels can be used as a proxy to estimate salinity given that these substances are not limited to salts. The most used units for TDS are milligrams per litre (mg/L) which is the same as parts per million (ppm).

HOW ARE SALINITY MEASUREMENTS' UNITS CONVERTED?

Table 4. Conversion table for the different units of salinity measurements

1 dS/m = 1 mS/cm = 1000 µS/cm = 1 mmho/cm
1 dS/m = ~ ppm or mg/L × 550
TDS (mmol/L) ≈ ECe (dS/m) × 10
TDS (mg/L or ppm) ≈ ECe × 640 (if 0.1 ≤ ECe < 5 dS/m)
TDS (mg/L or ppm) ≈ ECe × 800 (if ECe ≥ 5 dS/m)
100 mM NaCl = 5844 ppm (1mmol of NaCl = 58.44 mg of NaCl) = 10 dS/m

Source: Authors' own elaboration.

HOW IS SODICITY MEASURED IN THE LAB?

Sodicity is measured in the lab through the **Exchangeable sodium percentage (ESP)**, Sodium adsorption ratio (SAR) and Cation ratio of soil structural stability (CROSS) method.

Exchangeable sodium percentage (ESP) is an estimate of the amount of Na^+ ions occupying the cation exchange sites. Its formula is the proportion of the amount of sodium ions relative to the cation exchange capacity of a soil:

$$ESP = \frac{Na}{CEC} \times 100$$

(Equation 1)

Sodium adsorption ratio (SAR) is the most popular method used to estimate sodicity. It is the ratio of the amount of sodium ions relative to the amount of calcium and magnesium ions, combined:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

(Equation 2)

Cation ratio of soil structural stability (CROSS) is another method, and it estimates sodicity by accounting for the effect of sodium and potassium ions on clay dispersion, and that of calcium and magnesium ions on flocculation (Rengasamy and Marchuk, 2011). It follows the equation:

$$CROSS = \frac{\mathrm{NA} + 0.56\mathrm{K}}{\sqrt{\frac{\mathrm{Ca} + 0.60\mathrm{Mg}}{2}}}$$

(Equation 3)

where the coefficient of K (0.56) is based on the ratio of the dispersive powers of sodium and potassium, and the coefficient of Mg (0.60) is based on the ratio of flocculating powers of calcium and magnesium. This equation addresses a supposed flaw in the SAR equation which treats Mg equal to Ca. In many waters, the Mg concentration is low relative to Ca, although there are well-known exceptions (Oster *et al.*, 2016).

WHAT ARE THE PROS AND CONS OF EACH METHOD?

Table 5. Summary of advantages and disadvantages of the various assessment methods

Method	Pros	Cons
In-field visual	**Simple, cost effective, quick diagnosis, no materials needed**	**Low accuracy, subjective, requires expertise, involves high uncertainty, indicators/ clues may be absent**
In-field measurements	**Quick results**	**Equipment cost, medium accuracy, salt speciation is unknown**
EC_{SP}*	Specialized EC meters can be put directly in a saturated paste made in the field; convenient; relatively quick.	Medium accuracy; a calibration based on more commonly used methods has to be created; mostly suitable for coarse soils.
$EC_{s:w}$	Easy to prepare; quick; various methods for soil-to-water ratios exist; variation exists on quantities based on either volume or (dry) weight.	Medium accuracy; requires dry soil and a mortar; requires calibration factors for correct interpretation.
Laboratory measurements	**Highly accurate**	**Equipment cost, lengthy, costly**
ECe	The EC of an extract of a saturated paste is the internationally recognized method that allows comparisons between soils all over the world.	Experience and training is required, as well as access to equipment for the extraction of the soil moisture; a consistent temperature of 25 °C is needed for accurate readings.
TDS	Accurate, and allows you to assess the soil macro- and micro-nutrient status	Needs expertise to interpret accurately.

*Note: This assumes an EC meter that can directly measure in a saturated paste. More commonly, EC meters need an aqueous solution to determine EC such as the extract of a saturated paste or a soil-to-water suspension.

Source: Authors' own elaboration.

SOIL AND WATER SAMPLING TO MEASURE SALINITY AND SODICITY

HOW SHOULD A SOIL BE SAMPLED TO MEASURE SALINITY OR/AND SODICITY?

Sampling is essential to determine the salinity levels in the soil. It is recommended for the sample to be representative and collected in a way that reflects the spatial heterogeneity of soil within land parcels and vertical distribution of salts in the soil. To get a representative result, one sample is recommended to be composed of a minimum of ten sub-samples. The ten sub-samples should be taken from a maximum area of 0.5 hectares. When high spatial heterogeneity exists in a field, one should increase the 'resolution' of the sampling scheme. In irrigated fields, attention must be given to the locality of the subsample collection as it can lead to misleading results. For example, in drip irrigated fields, sampling from the middle zone (between two drip irrigation lines) will misleadingly present high salinity values. Therefore, samples from within the root-zone can provide a better estimate of the soil's salinity status (Shahid *et al.*, 2018).

Sampling is important for both field and laboratory measurements. In order to have a full understanding of the nature of soil salinity, laboratory testing for pH, total soluble salt content, Na+ content, $CaCO_3$ content, clay ratio (%), organic carbon content and exchangeable cations are necessary. For an initial understanding of the salinity problem, in situ field measurements are available.

Link for soil sampling tools (ppt)[2]: Soil sampling_FG.pptx

Links for videos[3]:

On-farm soil sampling (English) YouTube

On-farm soil sampling (Arabic) - YouTube

On-farm soil sampling (Arabic) - YouTube

HOW SHOULD WATER BE SAMPLED TO MEASURE SALINITY OR/ AND SODICITY?

When collecting a water sample, run the water at full for few minutes (5 to 10 minutes) before saving a sample in a tightly sealed plastic bottle. The sample is then delivered to a laboratory for analysis of EC, pH, nitrate nitrogen, ammonium nitrogen, calcium, magnesium, sodium, potassium, phosphorus, zinc, copper and aluminium.

Link for water sampling (ppt) [4]

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[2] https://www.fao.org/fileadmin/user_upload/faowater/docs/WASAG/Soil_sampling_FG.pdf

[3] https://www.youtube.com/watch%3Fv%3DOMAZR-JJ-EI%26list%3DPL7Cx6PxnScmyV3plcebdZ2DIvvbw-0B4N%26index%3D13

https://www.youtube.com/watch%3Fv%3D3FJ6gmOGUGs%26list%3DPL7Cx6PxnScmyV3plcebdZ2DIvvbw-0B4N%26index%3D14

https://www.youtube.com/watch%3Fv%3DZ0b3y-EBM4o%26list%3DPL7Cx6PxnScmyV3plcebdZ2DIvvbw-0B4N%26index%3D15

[4] https://www.fao.org/fileadmin/user_upload/faowater/docs/WASAG/Water_sampling_FG.pdf

HOW OFTEN SHOULD WATER SAMPLES BE COLLECTED TO MEASURE SALINITY OR/AND SODICITY?

The source of irrigation water should be tested regularly:

1) on a monthly basis for new water sources; and

2) at least twice a year for existing sources, to determine the quality of water.

This is important to aid in the choice of fertilizers for optimum plant growth and to minimize the risk of discharging pollutants to surface and ground water.

SALINITY AND SODICITY MEASUREMENT INTERPRETATION

HOW ARE SALINITY AND SODICITY MEASUREMENTS OF SOIL SAMPLES INTERPRETED?

Saline and sodic soils are classified based on their diagnostic measurements and/or estimates. Established thresholds (Table 6) help farmers, extensionists and researchers interpret salinity and sodicity values. A general interpretation of data based on ECe values can be considered according to Lamond and Whitney (1992):

- from 0 to 2 dS/m there is very little chance of injury for all plants;
- from 2 to 4 dS/m sensitive plants and seedlings of others may show injury;
- from 4 to 8 dS/m most non-salt tolerant plants will show injury; salt-sensitive plants will show severe injury;
- from 4 to 8 dS/m salt-tolerant plants will grow; most others show injury;
- from 8 to 16 dS/m very few plants will tolerate and grow;
- From 6 – 20 dS/m salt-tolerant crops will grow, whereas from 20 dS/m and above halophytic plants will grow

Table 6. Classification of soil according to EC and pH

Classification	Electrical Conductivity (EC) (dS/m)	Soil pH	*Sodium Adsorption Ratio (SAR)	*Exchangeable Sodium Percentage (ESP)
Optimal	< 4.0	6.5 – 7.0	< 13	< 15
High pH	< 4.0	> 7.8	< 13	< 15
Saline	> 4.0	< 8.5	< 13	< 15
Saline-Sodic	> 4.0	< 8.5	≥ 13	≥ 15
Sodic	> 4.0	> 8.5	≥ 13	≥ 15

*Action to remediate sodium problems is recommended before SAR or ESP levels reach 9.0.

Source: Authors' own elaboration.

HOW ARE THE MEASUREMENTS OF THE COMBINED EFFECT OF SALINITY AND SODICITY IN SOIL SAMPLES INTERPRETED?

The following guidelines (Table 7) refer to the combined effect of salinity and sodicity as measured by EC and SAR or CROSS on the risk of soil water infiltration problems due to clay swelling, the breakdown of macroaggregates into microaggregates upon wetting, and/or crusting. All these processes result in a reduction in the number and size of large pores at the soil surface, thereby reducing infiltration of rainfall or irrigation water.

Table 7. Guidelines for interpretation of the combined effects of electrical conductivity (EC) and sodium adsorption ratio (SAR) or cation ratio of structural stability (CROSS) of irrigation water on soil physical properties, particularly infiltration rate.

	Degree of impact of SAR according to EC		
	None	Slight to moderate	Severe
SAR or CROSS*	-------------- EC (dS/m) -----------------		
0-3	> 0.7	0.2–0.7	< 0.2
3–6	> 1.2	0.3–1.2	< 0.3
6–12	> 1.9	0.5–1.9	< 0.5
12–20	> 2.9	1.3–2.9	< 1.3
20–40	> 5.0	2.9–5.0	< 2.9

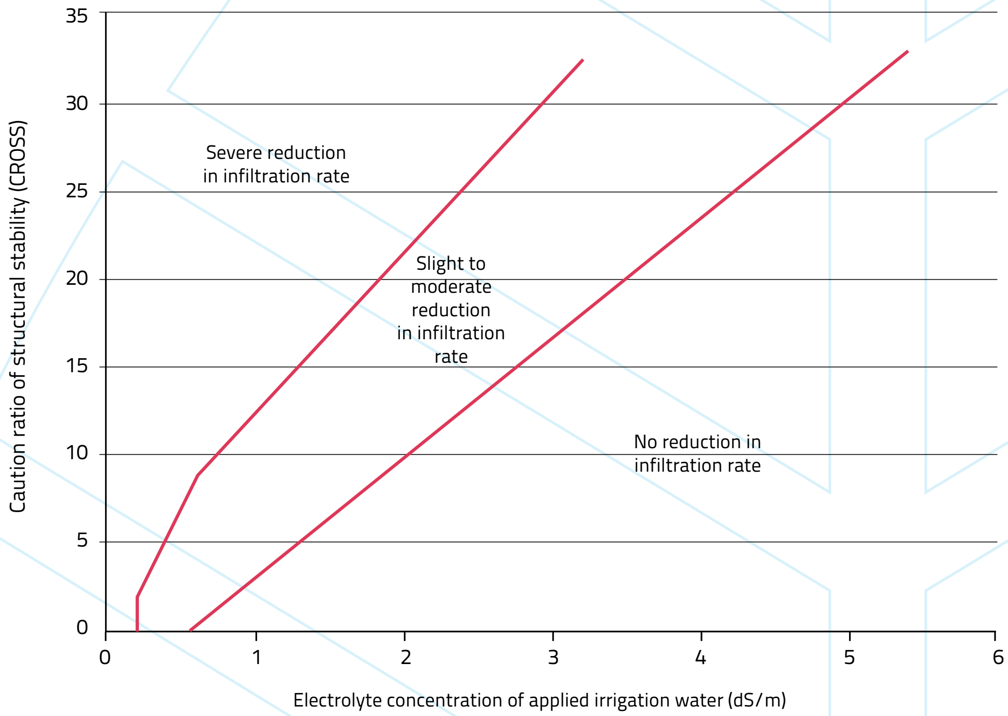
*As the phenomenon underlying the validity of either SAR or CROSS is similar, the values of CROSS, if available, can be used to replace SAR.

Source: Modified from **Ayers R.S. & Westcot D.W.** 1985. *Water quality for agriculture.* Irrigation and drainage paper 29 Rev 1. FAO, Rome.

HOW DOES SALINITY AND SODICITY AFFECT THE INFILTRATION OF THE APPLIED WATER IN THE SURFACE SOIL?

Figure 3 shows in graphic form that both salinity and sodicity of the applied water affect the rate of infiltration of water into surface soil.

Figure 3. Relative rate of water infiltration as affected by salinity and sodicity of irrigation water. The sodicity on the y-axis can be described by SAR or CROSS.



Source: Modified from **Rhoades J.D.** 1977. Potential for using saline agricultural drainage waters for irrigation. Proc. *Water Management for Irrigation and Drainage*. ASCE, Reno, Nevada. 20–22 July 1977. pp. 85-116, **Oster J.D. and Schroer, F.W.** 1979. Infiltration as influenced by irrigation water quality. *Soil Sci. Soc. Amer. J*. 43:444–447 and **Ayers R.S. & Westcot D.W.** 1985. *Water quality for agriculture.* Irrigation and drainage paper 29 Rev 1. FAO, Rome.

HOW ARE ELECTRICAL CONDUCTIVITY (EC) VALUES OF WATER SAMPLES INTERPRETED?

On a typical EC scale, freshwater can have electrical conductivity values between 0 and 0.7 dS/m whilst sea water can have more than 50 dS/m. Table 8 outlines the range of characteristics of different sources of water while Table 9 reports the general target and acceptable range of nutrients and other components in irrigation water.

Table 8. Classification of water quality corresponding to salt concentration

Water category	Hazard classification	EC (dS/m)	Salt concentration (total dissolved salts)(mg/L)	Typical water source
Non-saline	Water for which no detrimental effects will usually be noticed	< 0.7	< 450	Drinking and irrigation water
Slightly saline	Water that may have detrimental effects on sensitive crops	0.7–2.0	450–1500	Irrigation water; treated wastewater

Moderately saline	Water that may have adverse effects on many crops and requiring careful management practices (only for salt tolerant plants)	2–10	1500–6500	Primary drainage water and groundwater
Highly saline	Water that can be used for halophytes plants on permeable soils	10–25	6500–16,000	Secondary drainage water and groundwater
Very highly saline	Unsuitable for growing plants	25–50	16,000–35,000	Very saline groundwater; seawater2
Brine		> 50	> 35,000 (or 3.5%)	Hypersaline seawater

Source: Authors' own elaboration.

Table 9. Target range and acceptable range of nutrients and other components of irrigation water. Interpretation of results depends on the soil and crop, but the following values should be generally considered.

	Target range in ppm expect for pH and EC	Acceptable range
pH	5.5–7.0	4 to 10
EC	0.2–0.8 dS/m	0–1.5 dS/m
Nitrate N	NA	< 75
Iron	< 1.0	< 4.0
Chloride	0–20	< 140
Magnesium	10–30	< 50
Calcium	25–75	< 150
Sulfate	0–40	< 100
Sodium		< 50
Bicarbonate		< 120

Source: Authors' own elaboration.

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Water management in salt-affected areas

WHAT FACTORS NEED TO BE CONSIDERED WHEN MANAGING IRRIGATION IN SALT-AFFECTED AREAS?

The ideal practice for managing irrigation under salinity conditions is to provide the right volume of water at the right time, according to the local meteorological conditions, crop needs, and soil type. The volume of water required depends on the available soil moisture content (Figure 4).

Figure 4. Key soil moisture levels and terminology

Soil moisture level	Potential (cb=centibars)	Volumetric water content (VWC) sand	VWC clay	Physical meaning
Too full	-10 CB	25%	60%	Saturation
		Excess		Field capacity
Full	-20 CB	15%	50%	
		Optimal		Management allowable depletion
Refill	-50 CB	10%	40%	
		Stress		Permanent wilting point
Stress	-1500 CB	5%	30%	
		Extreme stress		

Source: Authors' own elaboration.

WHAT ARE THE THREE SOIL WATER CONTENT LEVELS TO CONSIDER FOR IRRIGATION MANAGEMENT IN SALT-AFFECTED AREAS?

Plants extract water from the soil through cohesive forces corresponding to the soil water tension. Soil water tension reflects soil water status, e.g., the higher the tension, the drier the soil. To this end, there are three soil water content (or tension) levels that are important when planning irrigation: Soil saturation; Field Capacity and Permanent Wilting Point. These can be understood by examining how much water is retained in the soil and also relates to the dynamics of water movement through the soil after a watering event.

WHAT IS "SOIL SATURATION"?

When water enters the soil more quickly, then it is moved downward by gravity, so the soil becomes saturated. Saturation is formally defined as the condition where all soil pores/voids are filled with water. Saturated soil contains little air and can be thought of as mud. Conditions in a saturated soil are anaerobic and are not conducive to healthy growth of most plants. Tension in saturated soil is very low, generally less than 10 centibar, i.e., matric potential -10 centibar. Volumetric water content (VWC) at saturation can range between 25 percent and 60 percent depending on soil type.

WHAT IS "FIELD CAPACITY"?

With time (the amount of time depends on soil type), substantially all the water that will be transported downward due to gravity has drained. The soil solution is now in balance, containing all the water that can be held by surface tension. This condition is referred to as field capacity. At field capacity, water is easily available to plants, and the soil solution contains ample oxygen. Optimal growing conditions for most plants occur at field capacity or slightly drier. Tension at field capacity is between 10 and 20 centibar. VWC can range from 15 percent to 50 percent depending on soil type.

WHAT IS "PERMANENT WILTING POINT (PWP)"?

As soil is subject to evaporation and withdrawal by plants, water content decreases and tension increases to a point where plants can no longer extract water. Maintaining soil at this level for any length of time can cause permanent damage to plants. Matric potential at PWP can be as low as -15 bar (-1,500 centibar), i.e., tension of 15 bar. VWC ranges from 5 percent for sandy soils to 30 percent for soils high in clay.

WHAT IS "MANAGEMENT ALLOWABLE DEPLETION (MAD)"?

On a management level, the management allowable depletion (MAD) is the lowest moisture level which can sustain plants without adverse stress effects. This is the moisture point, above Permanent Wilting Point (PWP) at which irrigation should be initiated to avoid having stress affect plant growth. Matric potential at MAD is typically -50 to -70 centibar. Volumetric water content (VWC) at this point can range from 10 percent to 40 percent. Any moisture content below this level is likely to cause stress to plants. It is recommended to use sensors to monitor water content and keep the MAD at desired level. In sandy soils, the MAD level is about 10 percent of VWC and in clay soils is about 40 percent.

WHAT OTHER WATER MANAGEMENT RECOMMENDATIONS FOR SALT-AFFECTED AREAS EXIST?

Generally, there is usually no single bullet methodology to successfully manage water resources in salt affected areas, particularly in arid regions. It is therefore advisable to adopt an integrated approach taking into account several aspects, such as:

- Leaching (Requirement, Frequency)
- Drainage (System, Depth, Spacing)
- Irrigation (System, Scheduling): Proper choice of the irrigation system is a key issue for sustainable use of water in saline areas
- Multiple water resources use (Alternating, Blending)

LEACHING

WHAT IS LEACHING AND WHY IS IT IMPORTANT FOR WATER MANAGEMENT IN SALT-AFFECTED AREAS?

The main causes of soil salinity are high evaporation in the presence of soluble salts in the subsoil, poor irrigation practices, and inadequate drainage. Under irrigated conditions, leaching is generally provided by excess application of water or through rainfall. The Leaching Requirement (LR) is the calculated fraction of amount of water that must pass through the plant root zone to maintain the ECe at or below a desired value. Proper estimation of LR can benefit effective water use, decrease the salt load needing of disposal, and substantially reduce the volume of drainage water. When the LR is met, the salts stop accumulating in the soil (Figure 5).

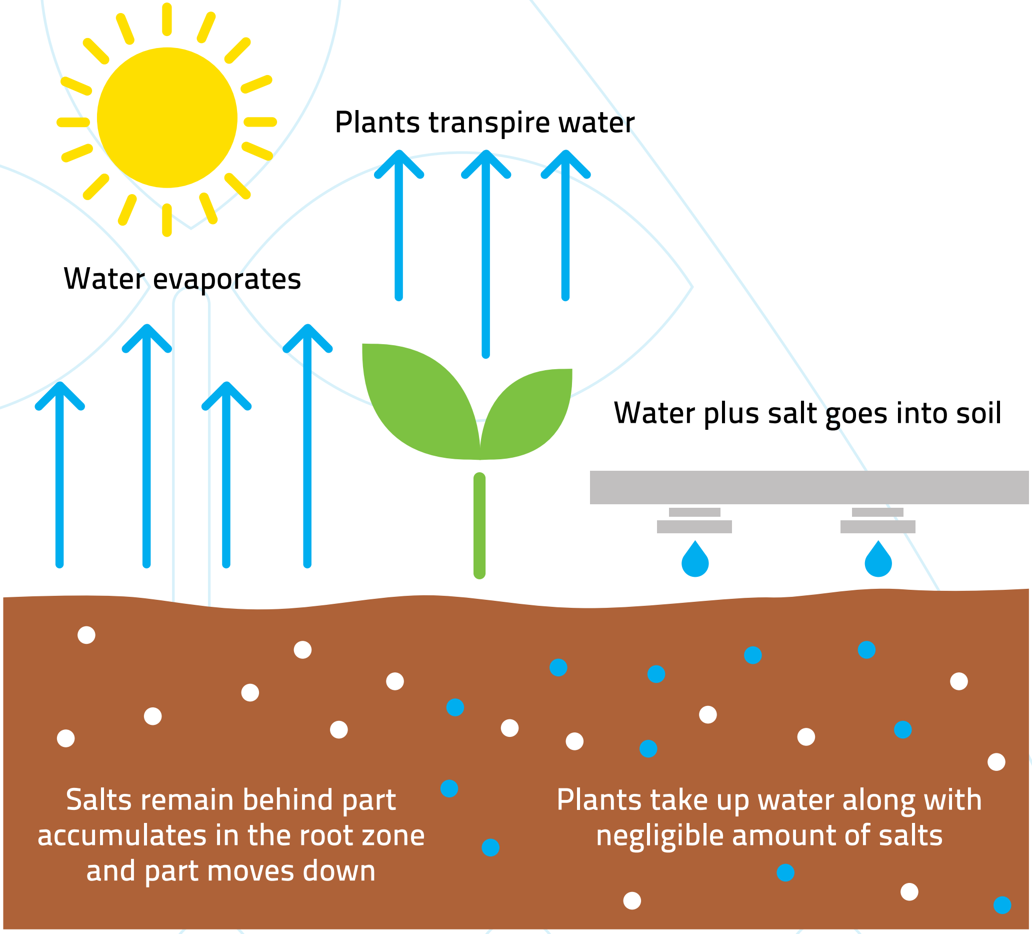
HOW IS A GENERALIZED LEACHING REQUIREMENT (LR) OR FRACTION CALCULATED?

Proper determination of LR is not very easy to assess, since drainage rate is more a function of the soil characteristics, rather than of the water content, and since determination of drainage depends on accurate measurement or estimation of all the other water balance parameters including evapotranspiration.

However, a generalized LR[5] can be calculated based on the EC of irrigation water (EC_w, dS/m) and the target soil ECe (ECe, dS/m) in the root zone (Table 10). The target ECe is crop specific and represents the maximum ECe value that a crop can tolerate without a potential yield decline or an ECe value that leads to a minor, acceptable, decrease in yield. As such, the formula reads as follows:

[5] This generalization does not consider plant response interactions or feedback. If plants are still affected by salinity and take up less water, the actual leaching fraction increases – most likely causing over-estimation of the LR.

Figure 5. Water, salt balance and the control of leaching through irrigation[6]



Source: **Qadir, M.; Noble, A. D.; Karajeh, F.; George, B.** 2015. Potential business opportunities from saline water and salt-affected land resources. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). 29p. (Resource Recovery and Reuse Series 5). doi: 10.5337/2015.20

$$LR = \frac{EC_w}{(5 \times EC_e) - EC_w}$$

(Equation 4)

Example: If ECw is 0.6 dS/m and target ECe as tolerated by the crop is 1.5 dS/m, then:

LR = 0.6 / ((5 × 1.5) –0.6 = 0.087

The Water Requirement (WR) needed to achieve this LR is thus calculated as follows:

$$WR = \frac{total\ water\ use}{1 - LR}$$

(Equation 5)

Example: If the total seasonal water use of the crop is 800 mm, the EC of irrigation water is 0.6 dS/m and the desired ECe in the soil is 1.5 dS/m, then:

WR = 800/ (1–0.087) = 876 mm

[6] This illustration on the water balance needs improvement to include the leaching effect. We suggest to the graphic designer either add arrows down and indicate leaching of salts with draining water or switch to a more appropriate illustration.

Table 10. Leaching requirement (LR) as a function of actual EC of water and target ECe in the soil according to Equation 4

EC_W (dS/m)	EC_E (dS/m)				
	4	8	12	16	20
	%				
1	5.26	2.56	1.69	1.27	1.01
1.5	8.11	3.90	2.56	1.91	1.52
2	11.11	5.26	3.45	2.56	2.04
2.5	14.29	6.67	4.35	3.23	2.56
3	17.65	8.11	5.26	3.90	3.09
4	25.00	11.11	7.14	5.26	4.17
5	33.33	14.29	9.09	6.67	5.26
6	42.86	17.65	11.11	8.11	6.38
7	53.85	21.21	13.21	9.59	7.53
8	66.67	25.00	15.38	11.11	8.70
9	81.82	29.03	17.65	12.68	9.89
10	100.00	33.33	20.00	14.29	11.11
11	122.22	37.93	22.45	15.94	12.36
12	150.00	42.86	25.00	17.65	13.64
13	185.71	48.15	27.66	19.40	14.94
14	233.33	53.85	30.43	21.21	16.28
15	300.00	60.00	33.33	23.08	17.65

Source: Authors' own elaboration.

Today, more robust methods for calculating leaching requirements based on modeling and understanding of interactions and feedback between crops and the water and salute balances they encounter are becoming available and used in irrigation decision making support tools (Minhas *et al.*, 2020). One example is an application that couples crop response environmental conditions and local economics to make decisions regarding irrigation and leaching as a function of water salinity based on costs and benefits in the Israeli agricultural setting. See ANSWERapp: app.agri.gov.il/AnswerApp.

DRAINAGE

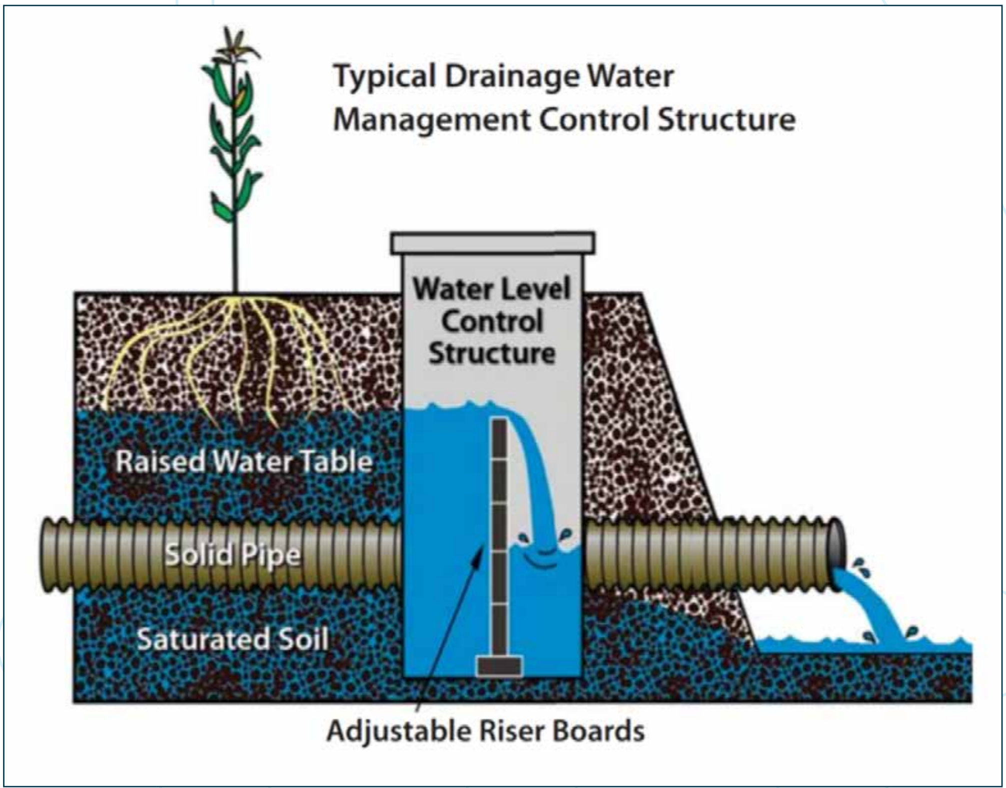
WHAT ARE THE DIFFERENT OPTIONS FOR MANAGING SALINE DRAINAGE WATERS?

The two generic options for local management of saline drainage waters are disposal to evaporation basins for regional storage, and reuse for irrigation of crops that can withstand the levels of salinity and sodicity in the drainage water and its receiving soils.

WHAT IS "OFF-SITE MANAGEMENT OF SALINE DRAINAGE WATERS" AND WHAT ARE THE CONDITIONS FOR ITS APPLICATION?

Such an approach should only be considered where the productive use of the saline drainage waters is economically unsuitable. In such cases, the use of **subsurface drainage or deep channels** may be used (Figure 6). Their setup must consider possible impacts of the drainage water on agricultural fields downstream as well as the environment (loss of wetlands, change of habitat, subsidence, seepage, erosion, leaching of nutrients, and pesticides and toxic element overload). Thus, it is important to evaluate the suitability of the potential disposal site(s) for the drainage water and the salt it contains. This is often referred to as "**Off-site salinity management**"

Figure 6. Example of drainage water management control structure to manage ground water table



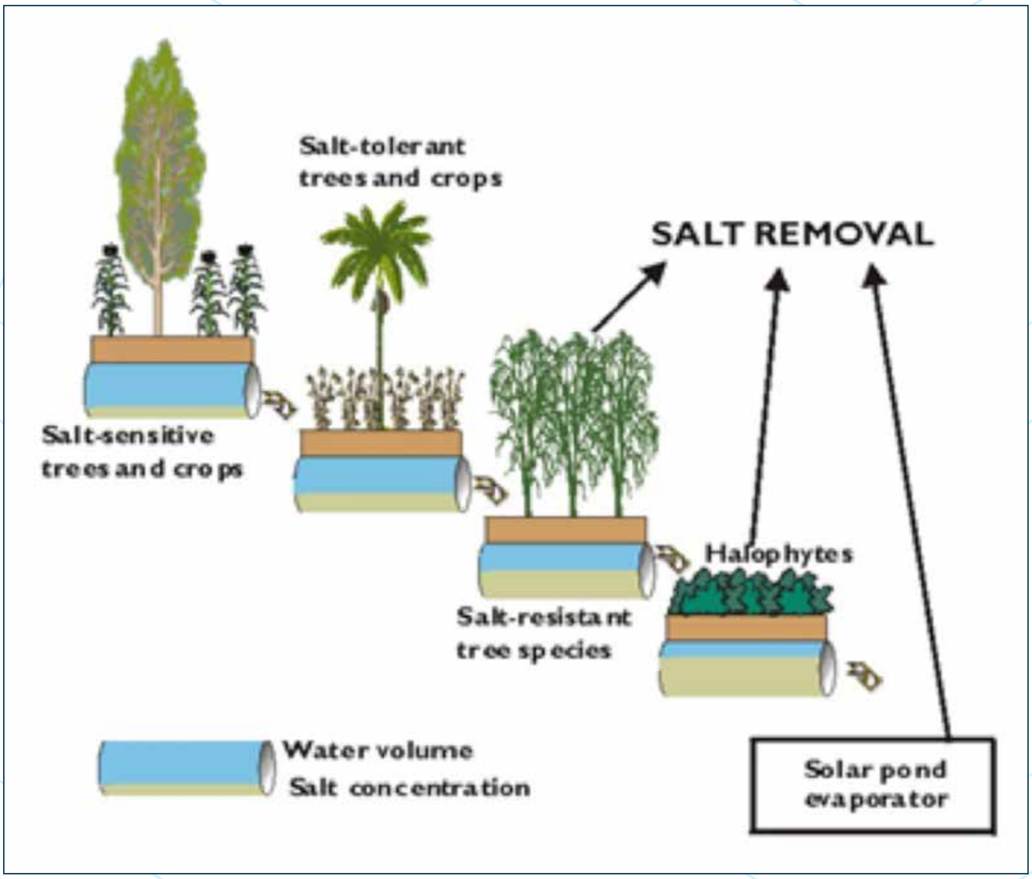
Source: Adapted from USDA-NRCS South Dakota fact sheet. Drainage water management plan, 2012.

HOW CAN SALINE DRAINAGE WATER BE RE-USED AND WHAT CONDITIONS NEED TO BE CONSIDERED FOR ITS APPLICATION?

The reuse of drainage water to directly irrigate downstream crops (Figure 7) by traditional irrigation methods is less sustainable than the original irrigation water as the drainage water contains higher concentrations of salts. Thus, in an irrigation cascade relying on drainage water, each successive plant must have a higher salt tolerance than the one preceding it with the final plants likely being halophytes (Link halophytes –

Thematic 2). Although **sequential reuse of drainage water** is conceptually attractive, caution is advised for those designing these systems and estimating the rate of salt movement through the sequential system.

Figure 7. Illustration of an example of water reuse from sequential drainage

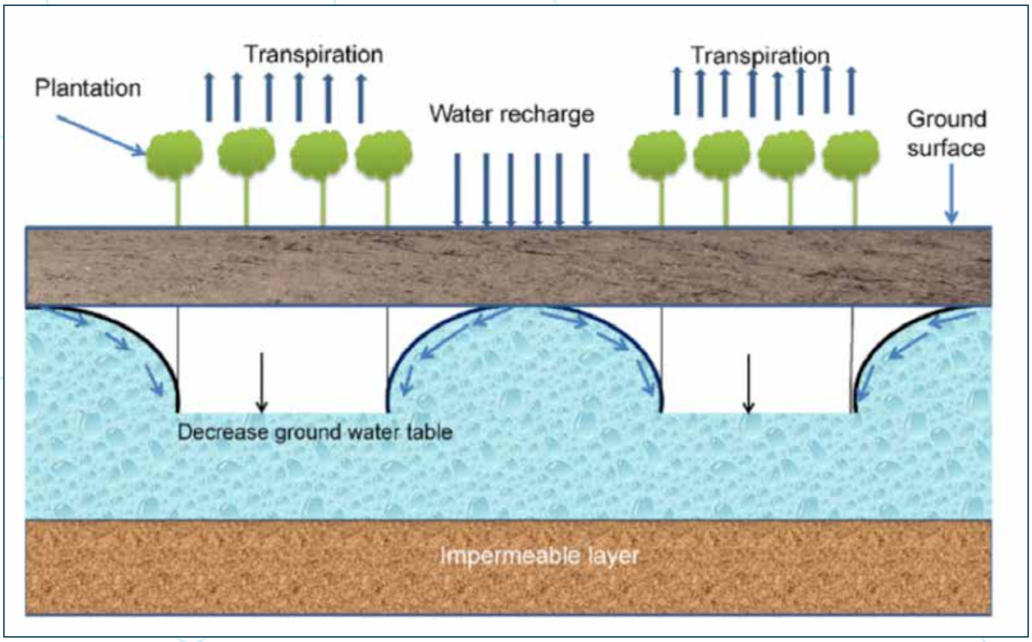


Source: UN-Water, 2020

WHAT IS BIO-DRAINAGE AND HOW CAN IT BE APPLIED?

Bio-drainage is one of the most feasible ways to help control groundwater table rise by planting species that can develop deep root systems to consume groundwater (Figure 8). Bio-drainage is also suitable where engineering approaches to control groundwater are not possible due to economic or technical considerations. This approach may add economic benefits to farmers provided that the crops' produce is of marketable value.

Figure 8. Difference in ground water table depth between areas with planted trees versus areas with bare ground. The trees serve as bio-drainage



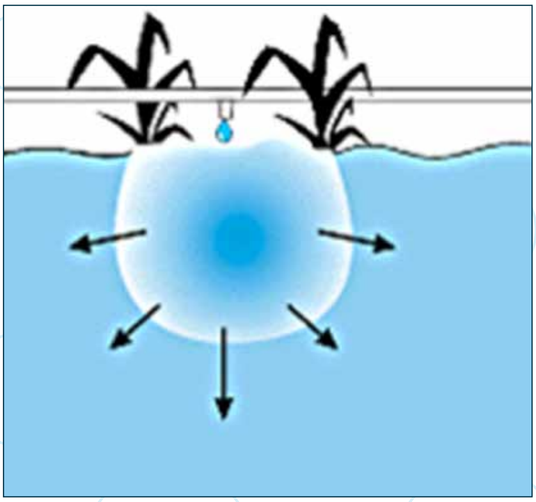
Source: **Manik, S. N., Pengilley, G., Dean, G., Field, B., Shabala, S., & Zhou, M.** 2019. Soil and crop management practices to minimize the impact of waterlogging on crop productivity. *Frontiers in plant science*, 10, 140. https://doi.org/10.3389/fpls.2019.00140

IRRIGATION

WHAT ARE THE KEY FEATURES OF DRIP IRRIGATION?

Drip irrigation generates the best conditions for the plant in terms of soil water potential, avoiding leaf injury and salt accumulation, provided that timing and distribution of water are well scheduled. The frequency rate affects soil moisture and salinity distribution, as well as the anti-clogging performance of the drip irrigation system (Figure 9). Limitations lie in the high initial cost, periodic operation and maintenance requirements, low root zone soil aeration, dense root mass, constant power and water supply needs, besides the high level of know-how needed to operate drip systems.

Figure 9. The pattern of soil wetting under a drip emitter



Source: Small-scale irrigation for arid zones. Principles and options.

Source: FAO, 1997

WHAT ARE THE KEY FEATURES OF SPRINKLER IRRIGATION?

In some environments, sprinkler irrigation can be considered as an alternate option (Figure 10). However, the main problem with sprinklers is that burning of foliage is very likely to occur when using saline water, even though salt-removal efficiency tends to be significantly higher than with furrow or other irrigation systems (drip).

Figure 10. Sprinkler irrigation of horticultural crops with saline water

©FAO

WHAT ARE THE KEY FEATURES OF SUB-SURFACE DRIP IRRIGATION?

Sub surface drip irrigation can be quite effective and worthwhile for perennial crops even when using water high in salts (Figure 11). It however provides no means of leaching the soil above the source. This may not pose a serious problem for perennial crops, however for annual crops, salt levels in the soil will certainly become toxic unless the soil is leached by rainfall or surface irrigation. Thus, this system is not suitable over the long-term for annual crops, especially in dryland areas, but it has shown to be successful for perennial crops.

Figure 11. Sub surface drip irrigation of herbaceous crops with saline water

©Civilseek

WHAT ARE THE PROS AND CONS OF THESE AND OTHER IRRIGATION SYSTEMS?

Table 11. Comparison of different irrigation systems and their effects on plants and the rhizosphere

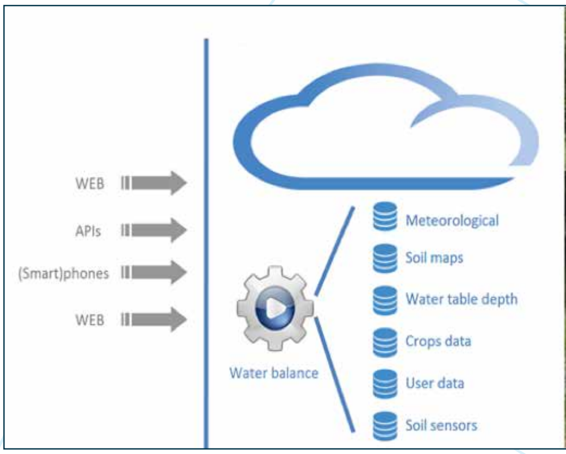
Evaluation parameter	Irrigation method			
	Furrow irrigation	Border irrigation	Sprinkler irrigation	Drip irrigation
	 ©Abby Waldorf/WLE	 ©Rutilo Lopez-Lopez	 ©WikimediaImages	 ©H. Gomez/CIMMYT
Foliar wetting and consequent leaf damage, resulting in poor yield.	No foliar injury as the crop is planted on the ridge.	Some bottom leaves may be affected but the damage is not so serious as to reduce yield.	Severe leaf damage can occur, resulting in significant yield loss.	No foliar injury occurs under this method of irrigation.
Root zone salt accumulation with repeated application.	Salts tend to accumulate in the ridge, which could harm the crop.	Salts move vertically downwards and are not likely to accumulate in the root zone.	Salt movement is downwards, and root zone is not likely to accumulate salts.	Salt movement is radial along the direction of water movement. A salt wedge is formed between drip points.
Ability to maintain high soil water potential (risk of soil moisture stress).	Plants may be subject to stress between irrigations.	Plants may be subject to water stress between irrigations.	Not possible to maintain high soil water potential throughout the growing season.	Possible to maintain high soil water potential throughout the growing season and minimize the effect of salinity.
Suitability to handle brackish wastewater without significant yield loss.	Fair to medium. With good management and drainage acceptable yields are possible.	Fair to medium. Good irrigation and drainage practices ca produce acceptable levels of yield.	Poor to fair. Most crops suffer from leaf damage and yield is low.	Excellent/good. Almost all crops can be grown with very little reduction in yield, unless the pipes clog.

Source: Authors' own elaboration.

DO PRECISION TOOLS EXIST TO SUPPORT IRRIGATION SCHEDULING?

Independently from the irrigation system adopted, precision tools can be useful in aiding in irrigation scheduling in order to optimally manage water resources in saline environments. One example of this innovative system is "IrriWeb", which is intended to help water managers and farmers optimize how often and how much water to apply for irrigation (Figure 12). The model, which is based on a multiple factor water balance, has shown to significantly reduce irrigation volume (25 percent and 35 percent less water, depending on crop and field condition) with no substantial differences in yield quantity and quality.

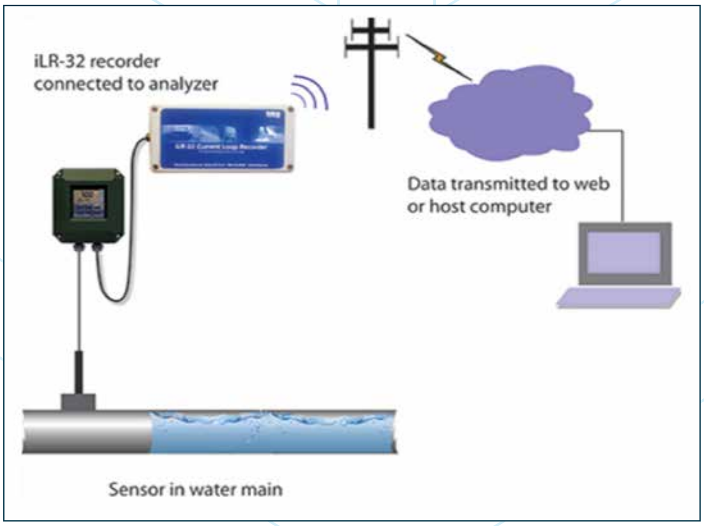
Figure 12. Sustainable water management and irrigation scheduling by means of IRRIWEB Expert System



©ENRD

Source: enrd.ec.europa.eu/projects-practice/irrinate-irriframe-sustainable-irrigation-management-0_en

When technically feasible (depending on the operating networks and delivery service conditions) and economically sustainable, constant and accurate monitoring of water quality is advisable. Monitoring allows control of main parameters and adoption of required measures.



Source: www.beltecno-global.com

WHAT ARE WATER ALTERNATING AND BLENDING TECHNIQUES?

Recycling and alternating techniques are based on alternate application of fresh and brackish water, according to the tolerance of crops at different growth stages. Significant increase in crop production, given the original conditions, can usually be achieved by supplying the same amount of water while separating the two water components. Alternatively, blending water sources with different salinities and diluting saline water to improve irrigation water quality or to reduce the consumption of good quality water is a common practice.

Soviet era irrigation canals in Tajikistan

©Neil Palmer-IWMI

Improving irrigation by means of proper water resources management

©FAO

Blending has been practiced successfully in many projects and under different environmental conditions including in Australia, Egypt, Israel, Pakistan and India. Results of several studies show that this practice is more economic and easier to implement on large farms than other alternative uses of water. However, the appropriateness of blending or diluting low quality waters should be carefully considered prior to its adoption. Its practice requires experience and skillful management in order to avoid damage to crops.

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Soil management in salt-affected areas

WHAT IS LAND LEVELLING AND WHY IS IT IMPORTANT IN SALT-AFFECTED AREAS?

Figure 13. Laser land leveler

©Open source

Land levelling is the process of smoothing the soil surface to eliminate high and low spots in the field, which disturb the uniform distribution of water and waste labor and energy (Figure 13). Levelling is often the first step before deploying more elaborate reclamation and management methods of salt-affected soils. Plowing is not an appropriate method for levelling as it will leave the land uneven and will negate any further reclamation techniques by creating areas of high salt concentration. If the soil is naturally compacted, plowing should occur prior to levelling.

WHAT ARE THE CONSIDERATIONS FOR TILLAGE AND SUBSOILING IN SALT-AFFECTED AREAS?

Figure 14. Moldboard plow that inverts soil

©Dowda Farm equipment

The depth of and equipment used for tillage should be specific to the horizontal and vertical distributions of salts in the soil profile (Figure 14). Deep plowing including turning the soil should be avoided in soils where maximum salt concentration is below the topsoil. In spite of this, loosening of deeper layers can be beneficial via the increase of the water infiltration capacity and improving soil structure in general. Loosening is a relevant management method for all types of salt affected soils and should be complemented by other water management methods.

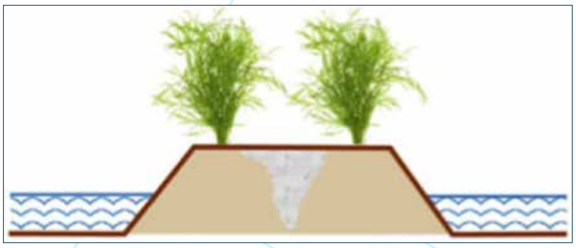
WHAT ARE THE DOS AND DON'TS OF TILLAGE IN SALINE/SODIC CONDITIONS?

Don'ts	Dos
Plow if salts only affect a small portion of the land	Plow if the majority or the entirety of your field is salt affected
Moldbloard plow if subsoil is salt affected	Subsoil plow if subsoil is salt-affected and there is a hardpan preventing proper drainage
Shallow plow if there is subsoil hardpan preventing proper water drainage	Disk/ shallow plow if only topsoil is salt-affected
Chisel plow if a hard pan segregates a saline subsoil from a less saline subsoil	Chisel plow to disrupt capillary action from saline subsoil and improve water infiltration
Plow after watering the field as to not create compaction	Plow after the addition of chemical amendments such as gypsum, but before watering the field.

HOW DOES THE SHAPE OF THE SEEDBED DETERMINE THE SALT ACCUMULATION IN THE SOIL?

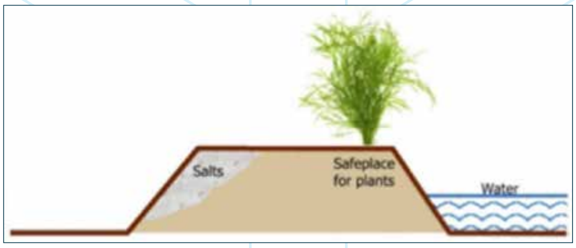
The shape of the seedbed, coupled with the specific irrigation system used, determines the distribution of salt accumulation in the field from which a zone of low salinity can be predicted and leveraged for planting. In furrow irrigation, salts tend to accumulate on the ridges away from the wet zone (Figure 15–18) because this is where the soil dries out quickest, thus concentrating the salts. As such, it is recommended to place the seeds on the off-center slope (i.e., shoulder) of the single row. Under high salinity conditions, an alternate row should be left fallow and un-irrigated to direct maximum accumulation of salts in this area, thereby leaving the planted and irrigated rows with less concentrations of salt. In all the scenarios, the salts concentrate quickest the furthest away from the water source.

Figure 15. Salt accumulation on flat bed with double-sided furrow irrigation system



Source: **Zaman, M., Shahid, S. A., & Heng, L.** 2018. Irrigation systems and zones of salinity development. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*, pp. 91-111. Springer, Cham.

Figure 16. Salt accumulation on flat bed with one-sided furrow irrigation

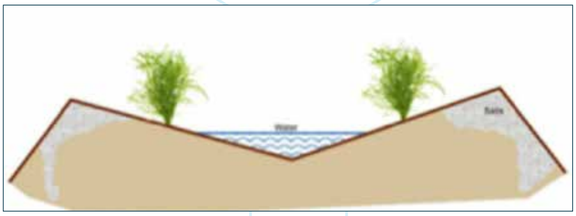


Source: **Zaman, M., Shahid, S. A., & Heng, L.** 2018. Irrigation systems and zones of salinity development. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*, pp. 91-111. Springer, Cham.

Figure 17. Salt accumulation on sloping bed with two-sided furrow irrigation system

Source: **Zaman, M., Shahid, S. A., & Heng, L.** 2018. Irrigation systems and zones of salinity development. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*, pp. 91-111. Springer, Cham.

Figure 18. Salt accumulation on sloping bed with middle furrow irrigation system



Source: **Zaman, M., Shahid, S. A., & Heng, L.** 2018. Irrigation systems and zones of salinity development. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*, pp. 91-111. Springer, Cham.

Useful tip: This feature does not pose a problem in surface drip-irrigated fields if the drippers are placed directly on the seed/plant, thus flushing salt away from the root zone (Figure 19).

Figure 19. Concentration of salts in surface drip-irrigated field

©M. Zaman

HOW CAN SALT SCRAPPING BE APPLIED IN THE FIELD?

Figure 20. Salt build-up in furrow irrigation system prior to scraping

©M. Zaman

Accumulated surface salts can also be removed by scraping off the surface (Figure 20). Scraping is typically practiced with two-sided furrow irrigation to direct the salt to the centre of the ridge where salt crusts accumulate through capillary rise and subsequent evaporation. The salt crusts can then be removed manually or mechanically. Mechanical removal is the simplest and the most economical way of reclaiming saline soils in large fields. This practice is a temporary solution, and if water high in salts is used for irrigation, salt accumulation will continue.

WHAT THE SOIL AMENDMENTS CAN BE APPLIED IN SALT-AFFECTED SOILS?

There are three different types of salt affected soils from the viewpoint of soil improvement needs in inland areas under temperate climate. Those with

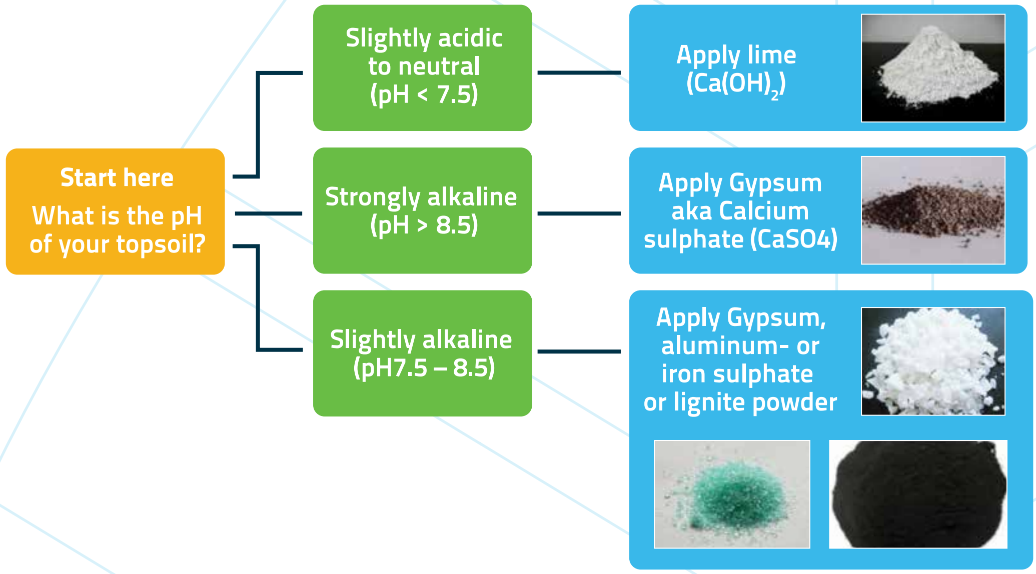
(i) slightly acidic or neutral topsoil (pH<7.5);

(ii) slightly alkaline topsoil (pH 7.5–8.5); and

(iii) strongly alkaline topsoil (pH >8.5).

Soils in group (i) can be improved by liming (products to increase pH of acid soils), while those in group (ii) need gypsum (calcium sulphate), as lime would not dilute in alkaline conditions. Combined application of calcium sulphate (which lowers pH) and lime may be considered. Group (iii) soils, due to their strong alkalinity need acidifying agents, which can be gypsum, aluminum- or iron phosphate or lignite powder (Figure 21).

Figure 21. Decision tree of soil chemical amendments based on topsoil pH



Source: Authors' own elaboration.

HOW IS LIME QUANTITY CALCULATED TO BE ADDED TO SLIGHTLY ACIDIC SOILS?

The simplest method to calculate the amount of lime needed to be added to ameliorate slightly acidic salt affected soils (Filep, 1976) is based on the knowledge of the texture class of soil and data on Exchangeable Acidity (AC), which refers to the combined total of exchangeable aluminium and hydrogen cations. The general equation (Equation 6) reads as follows:

$$LiR\ (tons/ha) = coeff.\ \times Ac$$

(Equation 6)

where LiR is lime requirement in tons per hectare, coeff. is the soil texture-specific coefficient as reported in Table 12, and AC is exchangeable acidity.

Table 12. Lime requirement calculations for different soil textural classes

Soil texture	Coeff.
Coarse sand	0.35
Sand	0.5
Sandy Loam	0.6
Loam	0.7
Clayey Loam	0.8
Clay	0.95
Heavy Clay	1.2

Source: Authors' own elaboration.

Another method to calculate lime requirement is based on the lime buffer capacity (LBC) of soil, which needs to be established through a laboratory test based on the $CaCO_3$ amount needed to raise the soil pH of one kilogram of soil by one unit (UGA 2015).

The formula reads as:

$$LiR = LBCEq \times (Target\ pH - Initial\ pH) \times 4$$

(Equation 7)

where LiR is lime requirement, and the LBCEq is the Equilibrium Lime Buffer Capacity.

HOW IS GYPSUM QUANTITY CALCULATED TO BE ADDED TO ALKALINE SOILS?

In order to quantify the exact amount of gypsum needed for the improvement of alkaline soils, information on some additional soil properties is necessary. Measurement of bulk density, which is the weight of soil per given volume (g/cm^3), cation exchange capacity (CEC) and the amount of sodium in the soil (meq/100 g) are the parameters needed for the calculations.

Gypsum requirement of soils can be calculated based on the amount of exchangeable Na present using the formula:

$$CaSO_4.2\ H2O\,\frac{t}{m^2} = (\mathrm{Na}_x \times \mathrm{A} \times \mathrm{M} \times \rho \times 86.1) \times 100{,}000$$

(Equation 8)

where:

Na_x is the exchangeable sodium content in meq/100g;

A is the extent of area reclaimed in m^2;

M is the soil depth to be improved (m);

ρ is the bulk density of soil (g/c^3);

86.1 is the weight equivalent of gypsum = 86.1.

Useful tip: For large fields (> 1 hectare) a simplified formula can be used:

$$CaSO_4.2\ H2O\,\frac{t}{m^2} = (\mathrm{Na}_x \times \mathrm{A} \times \mathrm{M} \times \rho \times 86.1) \times 100{,}000$$

(Equation 9)

Often it is not necessary to exchange all sodium, but in any case, the sodium concentration should be lowered below 5 percent of the cation exchange capacity of the soil. A practical approach is to target the applied amount of gypsum based on the actual amount of Na and the targeted amount of acceptable Na, using the formula:

$$CaSO_4.2\,H2O\,\frac{t}{m^2} = (\mathrm{Na}_x \times \mathrm{M} \times \rho \times \frac{86.1}{10})$$

(Equation 10)

WHAT SHOULD A FARMER BE CAUTIOUS OF WHEN APPLYING INORGANIC FERTILIZER IN A SALT-AFFECTED SOIL?

Many fertilisers contain soluble salts in high concentrations. Therefore, it is important to consider the fertiliser nutrient source, rate, timing and application. The salt index (commonly referred to as fertiliser salts) is a measurement that indicates the degree that the fertiliser will increase salt concentration (and decrease osmotic potential) of the soil solution. Most commercial fertiliser products have established salt indices (Table 13). For example, KCl has a salt index almost triple that of K2SO4. A farmer must consider the salt index before selecting the fertiliser to be applied to the field.

Table 13. Salt index of different commercial fertilizers

Fertilizer Type	Analysis	Acceptable range
Nitrogen/ Sulphur		
Ammonia	82% N	47.1
Ammonium nitrate	34% N	104.0
Urea	46% N	74.4
UAN	28–0–0–0 (39% AMMONIUM NITRATE, 31% UREA)	63.0
Ammonium sulfate	21% N, 24% S	88.3
Ammonium thiosulfate	12% N, 26% S	90.4
Gypsum	23% Ca, 17% S	8.7
SUL4R-PLUS®	**21% Ca, 17% S**	**8.1**
Phosphorus		
DAP	**10% N, 46% P–05**	29.2
MAP	**11% N, 52% P–05**	26.7
APP	**10% N, 34% P>05**	20
Crystal Green®	**5% N, 28% P›05, 10% Mg**	**7.7**
Potassium		
/ Potassium chloride	62% K20	120.1
Potassium sulfate	50% K20,18% S	42.6
Potassium thiosulfate	25% K20, 17% S	68.0
Miscellaneous		
Manure salts (20%)		112.7

Source: Taurus. Lowering Fertilizer Salts to Prevent Seed Burn. taurus.ag/lowering-fertilizer-salts-to-prevent-seed-burn
taurus.ag/lowering-fertilizer-salts-to-prevent-seed-burn

HOW SHOULD INORGANIC FERTILIZERS BE APPLIED IN SALT-AFFECTED SOILS?

Regarding the application method, band application of fertilisers with high salt indices near seedlings should generally be avoided as it concentrates the salts near the plant. In addition, since nitrogen is soluble and rather mobile in the soil and likely to be lost during the growing season, it needs to be applied in various application events. It is recommended to apply around 40 percent of the total required nitrogen at the start of the growing season as a top dressing, and the remaining 60 percent over three applications of 20 percent each. This is a general rule of thumb; different crops have different N requirements depending on their growth stage.

HOW CAN COMPOST IMPROVE SALT-AFFECTED SOILS?

Figure 22. Compost

©Rodale Institute

Increasing the organic matter of a soil through the application of compost and/or organic and green manures is of fundamental importance for salt affected soils (Figure 22). Compost has several beneficial aspects.

First, the organic matter increases the number of binding sites in a soil, aiding in a more balanced cation exchange complex. This means that, in salt affected soils where sodium (Na+) is the dominant cation, there is a better chance that there are enough binding sites for other important cations, such Calcium (Ca), Magnesium (Mg) and Potassium (K). This also reduces the risk of soil slaking and dispersion in clay soils, which means the loss of aggregates and thereby good soil structure which is integral for the proper management of saline and sodic soils.

Second, organic matter increases the moisture retention capacity of a soil, which reduced peak concentrations of salts that the crops will be exposed to between irrigation events.

Thirdly, a higher organic matter content in the soil usually supports a healthier microbiological community, also benefiting the crops.

HOW CAN GREEN MANURES IMPROVE SALT-AFFECTED SOILS?

Figure 23. Green manuring using buckwheat (Polygonaceae family)

© Open source.

Green manures refer to plants mostly of the family of the Fabaceae or Leguminosae, although species of green manures from other families exist (Figure 23). Around 80 percent of the members of this very large plant family host bacteria in their roots that fix atmospheric nitrogen and supply this in forms that can be assimilated by the host plant (usually in the form of ammonium or nitrate) in return for carbohydrates. These bacteria live in specialized organelles called nodules, produced by the plants. Inside the nodules, the host creates an anoxic environment necessary for the nitrogen fixation process using a molecule called leghemoglobin. This gives (the inside of) active nodules a pinkish appearance. Green manures are thus a free source of nitrogen and are useful to include in crop rotation schemes. Some species can fix high quantities of nitrogen, providing almost all the required nitrogen for the subsequent crop in the rotation scheme. Additionally, there are some deep rooting species which can also help in lowering the groundwater table, which can help when the source of salinity is from secondary salinization where saline ground water gets too close to the surface to the point where it is transported up by capillary rise and thereby affects the root zone. Some species are trees and can be of great value in agroforestry. Finally, green manures help in increasing the organic matter content of the soil when (parts of) the plants are incorporated in the soil.

HOW CAN MULCHING IMPROVE SALT-AFFECTED SOILS?

Figure 24. Mulching with straw in potato fields

©Sanjay Ray

Mulching is beneficial under saline conditions since it covers the soil surface and reduces evaporation from the soil, keeping a more stable moisture content of the topsoil and hence, a more stable salinity level. Without any soil surface coverage, the salinity concentrations increase when soils dry out, and crops may be exposed to high peak concentrations of salinity between irrigation events (Figure 24). As such, surface coverage can dampen those peak concentrations. It can also increase the organic matter content of the soil over time when using organic material, which is also beneficial for salinity management. Straw generally makes for a good mulch, but any carbon rich crop residue can be used as mulch. In hyper arid climates, date palm leaves can be used.

HOW CAN CROP ROTATION AND CROPPING PATTERNS IMPROVE SALT-AFFECTED SOILS?

Salt tolerance is crop specific. Different varieties exist and new ones are being developed that are relatively capable of coping under conditions of salinity. Crop rotation can be an efficient measure to counter soil salinization (Figure 25). Incorporating cover crops into a cropping system can prevent or even reverse salinization. For example, the inclusion of barley and vetch in a cropping system with irrigated maize in a Mediterranean area can help maintain or reduce the salinity of the topsoil compared to the option of a having a fallow period (Gabriel *et al*., 2014). In rainfed cropping systems, a more sustainable approach would be to grow the less salt-tolerant species during the rainy season and more tolerant ones during the dry period. A set-aside period should be maintained at the beginning of the rainy season for the rain to wash out the salts and bring salinity to levels tolerable by the crops.

Figure 25. Crop rotation between bean and wheat. Here, bean plants can be seen emerging among the residue of the previous crop: wheat

©CIMMYT

WHAT KIND OF CROPS CAN BE INTRODUCED IN SALT-AFFECTED AREAS?

If there are constraints and barriers in adopting mitigative approaches to soil salinity and/or sodicity when dealing with higher salinities, one possible solution is to replace the existing crop varieties with salt-tolerant ones or with halophytic (salt-loving) crops. These crops will be presented in the thematic 2: Saline farming in salt-affected areas.

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Glossary

Aerosol salinization occurs when blowing wind picks up small droplets of sea water that are then deposited on the land, especially those closest to the sea.

Alkalinity – see sodicity

Anions – an ion that has more electrons than protons, consequently giving it a net negative charge

Cations – an ion that has more protons than electrons, consequently giving it a net positive charge

Field Capacity – the state of a soil that has drained water due to gravity and retains water held by surface tension typically in micropores

Ionic Effect – the salt's aptitude to cause plant toxicity due to excessiveness of the concentration of a certain ion

Electrical Conductivity – the degree to which a specified solution conducts electricity and is used as an indirect measure of salinity

Exchangeable Sodium Percentage – the relative amount of the sodium ions present on the soil surface, expressed as a percentage of the total cation exchange capacity

Flood salinization is another process where the sea floods the land thereby depositing salts on the land, which may take several years to restore. Seepage and flood salinization are particularly common in low lying coastal regions.

Leaching Requirement – the calculated fraction of amount of water that must pass through the plant root zone to maintain ECe at or below a desired value.

Management Allowable Depletion – the lowest moisture level that can sustain plants without adverse stress effects

Osmotic Effect – the salt's aptitude to reduce the availability of water for plant uptake due to the increased pressure gradient

Permanent Wilting Point – the state of a soil lacking sufficient water for plant uptake due to increase in tension

Primary salinization involves accumulation of salts through natural processes due to high salt contents in parent materials or groundwater.

pH – a measured value that follows a 0–14 scale used to specify the degree of acidity of alkalinity of a solution

Salinity – excessive quantity of salts in soil or water; soil salinity is informally known as "white saltiness"

Salinization – the process of becoming saline

Salt-affected soils – soils that exhibit one of the three kinds of saltiness (saline, sodic, saline-sodic)

Saturation – the state of a soil accumulating more water than it can drain and the soils macropores are filled

Secondary salinization is caused by human interventions such as irrigation practices, e.g., with salt-rich irrigation water and/or insufficient drainage.

Seepage salinization occurs when saline groundwater rises to the root zone as the overlying freshwater body is depleted.

Sequential reuse of drainage water – an irrigation cascade relying on drainage water to irrigate successive plants in increasing order of salt tolerance

Sodicity – excessive quantity of sodium salts relative to the other salts; soil sodicity is informally known as "black saltiness"

Sodification – the process of becoming sodic

Sodium Adsorption Ratio (SAR)– a measure of the amount of sodium (Na) ions relative to calcium (Ca) and magnesium (Mg) ions

Total Dissolves Solids (TDS) – the amount of minerals, metals, organic material and salts that are dissolved in a certain water volume and is associated with the quality and purity of water

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