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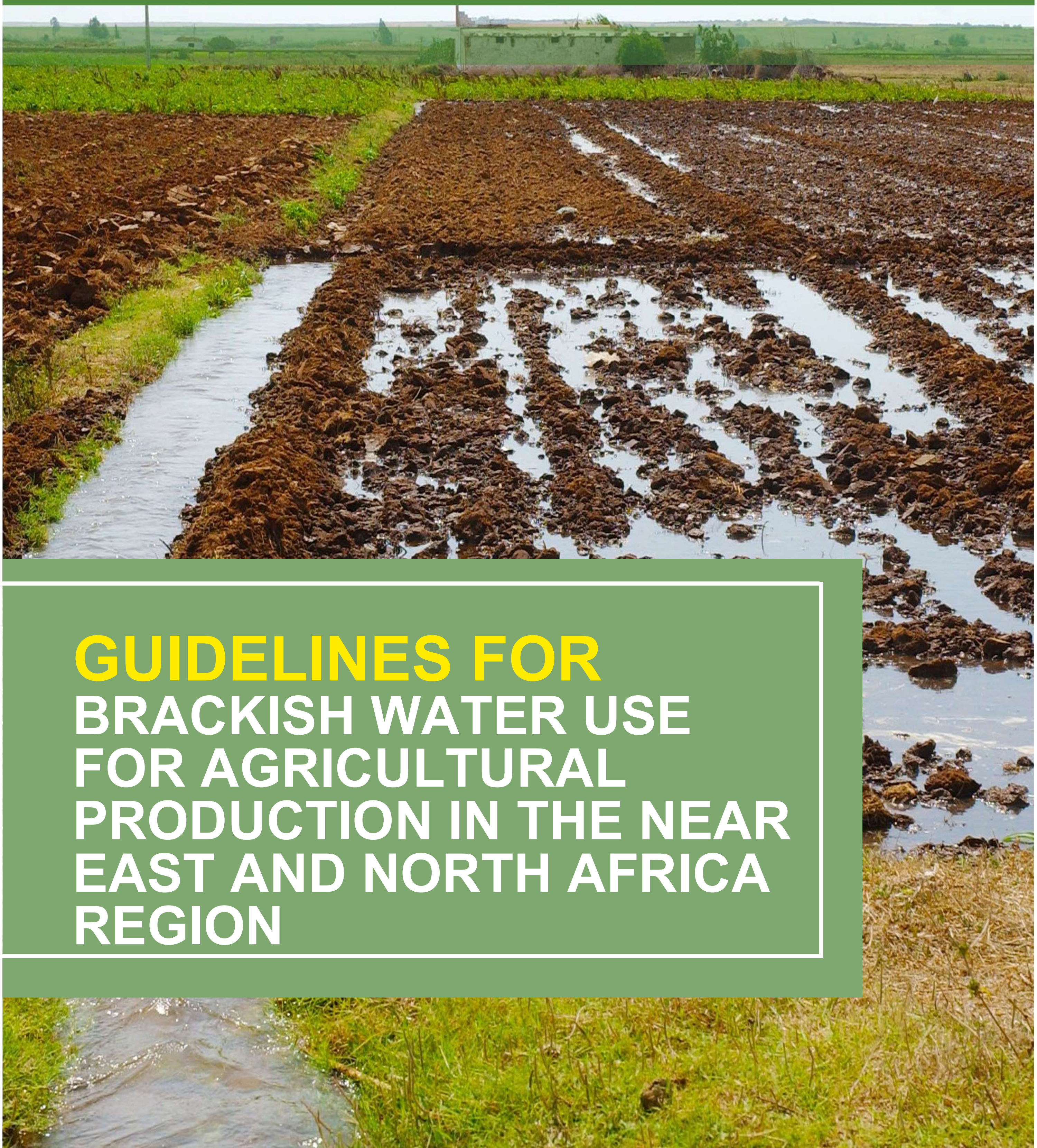

GUIDELINES FOR BRACKISH WATER USE FOR AGRICULTURAL PRODUCTION IN THE NEAR EAST AND NORTH AFRICA REGION

المجلس العربي للمياه
Arab Water Council

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS / ARAB WATER COUNCIL

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Front cover photograph: Irrigation systems in the targeted area supported by FAO
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Acronyms

Organizations

ACSAD	Arab Center for the Studies of Arid Zones and Dry Lands
AWC	Arab Water Council
CEDARE	Centre for Environment and Development for the Arab Region and Europe
DRI/NWRC	Drainage Research Institute/National Water Research Center
DWIP	Drainage Water Irrigation Project
ESCWA	United Nations Economic and Social Commission for Western Asia
FAO	Food and Agriculture Organization of the United Nations
GRDC	Grains Research and Development Center
ICBA	International Center for Biosaline Agriculture
JVA	Jordan Valley Authority
LAS	League of Arab States
MARHP	Ministry of Agriculture, Hydraulic Resources and Fisheries, Tunisia
MWRI	Ministry of Water Resources and Irrigation, Egypt
NAWQAM	National Water Quality and Availability Management
NENA	Near East and North Africa
NRCS	National Resource Conservation Service (United States of America)
NWRC	National Water Research Center
USDA-ARS	United States Department of Agriculture – Agricultural Research Service
USSL	United States Salinity Laboratory

Parameters

B	boron in irrigation water
BCM	billion cubic meters
BR	blending ratio
Ca^2+	calcium ion
Ca_x	adjusted calcium concentration in soil water
CI-	chloride ion
CROSS	cation ratio of soil structural stability
DOC	dissolved organic carbon
DW	Dry weight
dS/m	decisiemens per metre (unit of electrical conductance, synonymous with mmhos/cm)
EC	electric conductivity
ECa	apparent or electrical conductivity of the bulk soil
ECb	electrical conductivity of the blended water
ECd	electrical conductivity of the water draining directly below the root zone
ECe	electrical conductivity of the saturated soil paste
ECp	electrical conductivity of the pore water (synonymous with ECss)
ECss	electrical conductivity of the soil solution (or soil water) (synonymous with ECp)
ECw	electrical conductivity of water
ECiw	electrical conductivity of the irrigation water
EM38	electromagnetic soil conductivity metre
ESP	exchangeable sodium percentage
EPS	exo-polysaccharides
ET	evapotranspiration
ETc	crop evapotranspiration
ETo	reference evapotranspiration
FW	Fresh weight
GAP	good agricultural practices
GIS	geographical information system

HC	hydraulic conductivity of the soil
HCO_3	bicarbonate ion
IR	infiltration rate
LF	leaching fraction
LR	leaching requirement
MCM	million cubic metres
Mg^{2+}	magnesium ion
meq/l	milliequivalents per litre (concentration unit, synonymous with mmolc/l)
mg/l	milligrams per litre (concentration unit, numerically equivalent to ppm)
mmol/l	millimoles per litre (concentration unit)
mmolc/l	millimoles of charge per litre (concentration unit, synonymous with meq/l)
mmolar	millimolar
mmhos/cm	millimhos per centimetre (unit of electrical conductivity, synonymous with dS/m)
Na^+	sodium ion
OM	organic matter
OP (ψπ)	osmotic potential
pH	negative log of the hydrogen ion activity (index of water acidity)
ppm	parts per million (numerically equivalent to mg/l or mg/kg)
RSC	residual sodium carbonate
SAR	sodium adsorption ratio
SO_4^{2}	sulphate ion
TDS	total dissolved solids
TSA	total concentration of soluble anions
TSC	total concentration of soluble cations

Acknowledgements

The Arab Water Council (AWC) and the Food and Agriculture Organization of the United Nations (FAO) have recently embarked on a collaborative program, "Sustainable Management of Brackish Water Agriculture Use", within the framework of the FAO Regional Water Scarcity Initiative and the Arab Water Security Strategy (2010–2030) of the League of Arab States. The development of the present document, "Guidelines for Brackish Water Use for Agricultural Production in the Near East and North Africa (NENA) Region", which aims to contribute to addressing food security under conditions of water scarcity, is part of this program.

The guidelines were formulated by a team of professionals from the AWC, in close collaboration and coordination with experts from the FAO Regional Office for the Near East and North Africa (RNE). Assistance in compiling and reviewing information was provided by several national consultants and experts from nine selected countries in the NENA region and by international consultants, whose knowledge and experience in irrigation with brackish water is the core of this report. The steering committee and local consultants who participated in preparing the outline of this report are also to be commended. To be highlighted as well are the efforts of AWC technical and administrative staff who took the lead in organizing the regional workshops for presenting and discussing the guidelines.

In appreciation of their distinguished efforts, the contributors are listed individually below:

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The present document was reviewed and approved by the following national and international consultants, whose contributions are gratefully acknowledged:

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Executive summary

Water scarcity is one of the major challenges in the 19 countries of the Near East and North Africa (NENA) region. The lack of water is affecting important irrigated areas, limiting the increase of food production needed to address the growing demand due to population growth. In most countries of NENA region, the need to use non-conventional water resources, including brackish water, is well recognized. Brackish water is loosely defined as water that is more saline than fresh water, but less saline than seawater. It covers a large range of salinity levels, from 500 to 30 000 mg/l total dissolved solids (TDS). Despite the presence of large amounts of brackish water and its potential for use in growing a number of crops, it is only used in limited amounts for irrigation.

The successful use of brackish water for irrigation requires a basic understanding of scientific principles affecting the interactions among the climate, the applied water, the soil, the crop and the environment. Equally important is the application of suitable technology and management practices that will facilitate the optional use of this poor quality water. The successful use of brackish water requires a higher level of management and likely the adoption of new irrigation management practices. Because climate, water quality, soil type and crop tolerance to salinity vary from location to location, guidelines, with some degree of site-specific flexibility, must be developed.

Rationale: Due to the limited freshwater resources in the NENA region and need to meet the expanding demand for food and animal feed, it is critical that brackish water be used in agricultural production in the region. However, this requires proper management in order to minimize the negative impact of salinity on soil, plants and the environment. The scientific principles detailed in this report provide the foundations by which guidelines, appropriate for the NENA region, are developed.

Different types of brackish water – agriculture drainage water, groundwater and treated waste water – are widely used nowadays. However, it is necessary to bear in mind its potential negative impacts, such as increased soil salinity, yield reduction and deterioration of soil quality, as well as the costs associated with these impacts. Brackish water can be used directly for irrigation, mixed or blended with good quality water, used cyclically, or desalinated prior to irrigation. But to do so effectively, good agricultural practices (GAPs) are needed and care must be exercised to monitor the water, soil and crop to prevent long-term deterioration. The present brackish water use guidelines for the NENA region were developed by applying scientific principles and GAPs. These guidelines can be adjusted based on site-specific conditions (climate, soil type, water quality, crop tolerance, etc.), local research results and grower experiences. The guidelines will be very important for stakeholders and farmers to successfully use brackish water for irrigation, while safeguarding the environment, conserving natural resources, increasing crop productivity and quality and enhancing farm income.

Scope: In accordance with the FAO Regional Water Scarcity Initiative, and within the framework of the Arab Water Security Strategy (2010–2030) of the League of Arab States (LAS) and the FAO/AWC cooperation on "Sustainable Management of Brackish Water Agriculture Use," it was agreed that the AWC and FAO would develop the present "Guidelines for brackish water use for agricultural production in the NENA region." Work on the technical guidelines began in January 2014 and ended in June 2018.

This joint activity aims to support the NENA countries in adapting their national programs and policies to turning low-quality water into resources, and to help develop the capacities of member countries to successfully use brackish water. The proposed guidelines are intended also to provide information for NENA region planners and operators of irrigation systems in the use of a wide range of water sources.

Objectives: The main objectives of this report are:

- to provide guidelines to use of brackish water for irrigation in NENA region countries;
- to provide science-based good agricultural practices for soil, water and crops for NENA region conditions;
- to propose alternative non-conventional crops that are better adapted to areas with high soil and water salinity problems with the goal to achieve better economic returns to farmers;
- to develop a vision and roadmap for the region and its future need for water resources.

To that end, the AWC, FAO and nine selected countries from the NENA region (Algeria, Egypt, Iraq, Iran [Islamic Republic of], Jordan, Morocco, Saudi Arabia, Tunisia and Yemen) participated in the preparation of the proposed guidelines through the following activities:

1. identifying focal points (national experts) from each of the nine countries;
2. collecting information and knowledge from regional and international organizations;
3. collecting data and information about the use of brackish water in each of the countries involved (through questionnaires, field data templates, personal communications and email correspondence);
4. organizing three regional workshops to present and discuss the basis for the guidelines;
5. developing scientifically sound guidelines after consulting international experts from FAO, AWC, ACSAD, and ICBA as well as experts from United Kingdom of Great Britain and Northern Ireland, United States of America, India and Italy, among others;
6. Reviewing and adjusting scientifically-based guidelines for local, site-specific conditions is recommended as a second stage.

This report consists of nine chapters that define the problem of water scarcity in the NENA region, provide scientific information regarding the effects of brackish water on soils and crops and the tolerance of crops to salts and specific ions, review good agricultural practices for using brackish water and finally, synthesize this information into crop-specific guidelines for the NENA region. The content of each chapter is described below:

Chapter 1 discusses water scarcity in the NENA region and the need to use non-conventional water resources for irrigation, with special focus on brackish water. It also presents the status of brackish water use in selected countries in the region and provides the rationale and need for developing guidelines for the safe use of brackish water.

Chapter 2 defines and describes the chemical characteristics of brackish water and its sources of salts. It details how salinity in irrigation water and soils is expressed. Distinctions are made between concentration and electrical conductance (EC) as well as EC of the soil solution, the saturated soil extract and apparent EC of the bulk soil. The chapter concludes defining the difference between salinity and sodicity.

Chapter 3 focuses on the mechanisms by which saline and sodic waters affect the physical conditions of the soil and the infiltration rate. Distinction is made between the sodium adsorption ratio (SAR), the adjusted SAR and the exchangeable sodium percentage (ESP). The chapter also discusses the role of the anion, residual sodium carbonate (RSC), pH and the free calcium ion (Ca2+) concentration on maintaining soil structure. Finally, a new expression called the “cation ratio of soil structural stability” (CROSS) is introduced as a more scientifically-sound replacement for SAR in predicting the infiltration hazard of the irrigation water.

Chapter 4 reviews the various ways brackish water impacts crops. It focuses on the general mechanisms of salinity tolerance and sensitivity, including osmotic and specific- ion effects and how they interact with one another. Specific ions adversely affect the crop by influencing the mineral nutrition of the crop or by causing direct toxicity. These are primarily chloride (Cl-), sodium (Na+) and boron (B). The importance of the rootstock in reducing Cl- and Na+ transport to the scions and reducing toxicity in trees and vines is discussed. Tables in the chapter provide tolerance rankings for many crops in regards to B and Cl- toxicity. Finally, the chapter concludes setting forth the distinction between glycophytes (most crops) and halophytes than can thrive in highly saline environments.

Chapter 5 expands on the theme of Chapter 4 by defining crop salt tolerance and provides the bases for plant selection. Soil salinity–yield response functions are provided (both the ‘slope-intercept’ and ‘non-linear’ models) as are the most complete tables to date on crop salinity tolerance. The chapter also discusses crop sensitivity to different growth stages and concludes with a description of halophytes or other non-conventional crops that can be used in certain cases.

Chapter 6 focuses on water management using brackish water with an emphasis on following good agricultural practices (GAPs). The chapter addresses the importance of irrigation scheduling, leaching for salinity control and drainage, and describes relationships between the salinity of the irrigation water (ECw), the salinity of the soil (ECe) and leaching fraction (LF) and how irrigation management (convention vs high frequency irrigation) influences this relationship. The distinction between steady-state vs transient models is made, including the advantages and disadvantages of each. The chapter also addresses soil physical properties and management options that can improve those properties. Reclamation leaching is discussed as an important option for reducing salinity in the off season. The chapter then discusses irrigation methods, how they affect salt distribution in the profile, how they can be managed to optimize crop performance, and annual planting strategies taking salt distribution into account. The chapter concludes with a discussion of various irrigation methods using saline water including blending, cyclic and sequential reuse strategies.

Chapter 7 addresses the potential for using brackish water specifically in the NENA region. The chapter focuses on success stories across the globe and reviews the potential opportunities and limitations of brackish water use in the participating NENA countries. Country reports and data from surveys conducted by the AWC were used in this chapter to assess the perceived upper limits for brackish water irrigation. The chapter concludes with a consensus of generalized guidelines that provides the minimum and maximum ECw, SAR, chloride and boron concentration in relation to general salt tolerant categories (These generalized guidelines are based on crop protection, not on the protection of soil physical conditions).

Chapter 8 combines the science-based information described in chapters 3 through 5 and the best management practices presented in Chapter 6, including the ECw–Ece–LF relations based on irrigation management, to develop the crop-specific guidelines to address the salinity hazard (ECw) and the hazard imposed by specific ion toxicity (boron, sodium [and SAR] and chloride). The guidelines provide a range of maximum limits depending upon certain assumptions related to irrigation management, attainable leaching fractions and expected yield potential. Because each country has a range of site-specific conditions related to climate, soil quality, crop type, management options and water quality, the crop-specific guidelines may require slight adjustment for each set of conditions. This is particularly important because each country has its own experience in producing crops that is specific to its local conditions. Each country also has its own crop varieties developed through research and farmer experience. Therefore, Chapter 8 includes a table that indicates the direction of adjustment (increase, decrease or none), but does not specify the degree of adjustment. Finally, the chapter addresses infiltration hazard by accounting for the combined salinity (ECw) and sodicity (CROSS, substituted for SAR) of the irrigation water.

Chapter 9 provides conclusions, recommendations and a future outlook regarding the use of brackish water for agricultural production in the NENA region. The content reflects the contributions and feedback from all national and international consultants involved, provided during the three regional workshops organized throughout the span of the project. The chapter also includes additional input and conclusions by international experts who reviewed and edited the initial May 2015 report.

Recommendations and future outlook: The following are the main recommendations and future vision derived from the deliberations of the three brackish water regional workshops and consultants' comments throughout the lifespan of the project:

- Irrigation with brackish water requires a higher level of management. It is important to monitor the irrigation water, soil and plant tissue to determine whether salinity levels are problematic. Specific ions (Cl, Na and B) and sodicity also need to be monitored and corrective measures must be instituted if needed.

- Brackish water use requires suitable and effective irrigation and drainage systems. Flood or surface irrigation could promote excessive drainage and aggravate water logging. Well-designed and managed drip systems allow higher salinity water to be used as frequent irrigation allows higher root water extraction in the upper, less saline portion of the root zone. In addition, there are ongoing new developments for drippers suitable for brackish water that will potentially reduce the problems with emitter clogging. Overhead sprinkler irrigation systems that wet the foliage should be avoided as the salt could accumulate in leaves via foliar absorption, causing leaf burn. New technologies, such as low elevation sprayers, allow irrigation water to be sprayed below the canopy level and therefore do not wet the leaves.

Brackish water use requires a suitable irrigation management strategy. Keeping the root zone at a higher moisture content prevents the plant from experiencing water stress in addition to salt stress. This does not necessarily suggest irrigation should be more frequent but rather, irrigation should be scheduled when the roots deplete only a fraction of the available water. Avoid prolonged soil wetting as this can induce disease.

• Use of brackish water requires an integrated approach to soil, water and crop management. In terms of soil management, minimum or zero tillage, as well as mulching, can help increase organic matter in the soil which improves its physical condition and nutrient status, while reducing soil evaporation. In terms of crop management, only crops with adequate salt tolerance should be selected.

• Typically, brackish water guidelines are based on crops achieving a leaching fraction during each irrigation. In field conditions, it is often better to implement ‘reclamation leaching’ when salinity levels exceed tolerable levels. Usually this is best done at the end of the season.

• It is recommended that the guidelines be implemented in some experimental areas in the region and adjusted for site-specific conditions.

• As soil salinity increases over time, with little chance for leaching by rainfall or fresh water application, a change in crop type should be considered.

• When using high saline groundwater, non-conventional crops should be considered. Quinoa and amaranth, rather than the classical cereals (wheat, barley, maize), may be an attractive alternative in highly saline areas. These are drought- and salt-tolerant cereals, native to South America, are currently grown in Europe and North Africa.

• There is an ongoing need to develop salt-tolerant varieties using biotechnology.

• As salt-stressed crops use less water than non-stressed crops, it is important to determine the evapotranspiration of the crop in the field. Monitoring the soil for water content and salinity will also help with management decisions.

• The scale of brackish water use must be evaluated on a country by country and region by region basis. Because brackish water resources are limited, the scale or extent (hectares) of brackish water use must be continuously evaluated.

• To facilitate the use of these brackish water guidelines, a farmers’ manual should be written in easy-to-understand language suitable for farmers. The manual should include appropriate crop types/varieties in relation to brackish water source(s), appropriate irrigation management practices, irrigation dates and scheduling and all other important information that could be useful to farmers. The manual can be used by extension service officers who, in turn, can train farmers in its use.

• Regional and national capacity building and institutional development programs should be organized as well as stakeholder and end user level training.

• A training manual should be developed on the use of non–conventional water resources

• Carefully calibrated and validated, user-friendly transient models should be developed as a second phase of the project to help predict the long-term impact of using saline water on soil and on yield. Such models may help improve site-specific guidelines, providing a less expensive alternative to field experiments.

• Friendly and easy-to-use digital guidelines should be developed in the form of a decision-support system (DSS) during the proposed next phase.

• As groundwater in most of the NENA countries is considered a non-renewable water resource, attention should be given to the use of treated domestic waste water which is renewable and has a guaranteed steady supply. However, waste water is typically saline and may contain potentially hazardous pathogens. Thus, supplemental guidelines that address these microbial concerns should be developed.

• Mapping saline brackish water in the NENA region using EM38 sensors, innovative GIS

• and remote sensing techniques could be beneficial to the region, especially for water

• authorities, planners and policymakers at national and regional levels.

• Establishing a digital database hosted by the Arab Water Council (AWC) would be of great interest and benefit to the NENA region in disseminating information and promoting knowledge sharing.

• As an application of these guidelines, brackish water use within the "Water-Food-Energy Nexus" would be of a great importance to the NENA region. Details can be worked out in the future as a joint research activity between AWC and FAO.

• Alternative uses of saline water, in addition to irrigation, such as in agro-forestry, aquaculture (see Box 9.1) of fish/shrimps, rice or multiple cropping systems, should be carefully considered. The least saline-tolerant element in the system is the determinant factor.

• Finally, as with all water management endeavours, understanding the overall impacts and interactions with the environment is critical. Therefore, an ecosystem approach considering off-site brackish water irrigation must be adopted.

CHAPTER 1

Introduction

1.1 WATER SCARCITY IN THE NENA REGION

The Near East and North Africa (NENA) region, covering 19 countries, is one of the most water-scarce regions in the world. The annual fresh water availability is less than 1 000 m^3 per capita. (See Figure 1.1, which illustrates the water vulnerable, water stressed or water scarce environments that characterize the NENA region.) The scarcity of fresh water is affecting important irrigated areas and will likely prevent food production from keeping pace with the increasing demand of the growing population. The average annual precipitation in the region is estimated at 150 mm. Furthermore, due to population growth, the renewable water resources per capita is one of the lowest in the world (690 m^3 per capita/year in the region vs the world average of 6 400 m^3 per capita/year) (Abu-Zeid, 2013). Without a fundamental change in policies and practices, more than 45 million people in the region will lack access to clean water and safe sanitation (FAO, UN, World Resources Institute, 2007), the region's economy and development will suffer and population growth, 90 percent of which is expected to occur in urban areas, will increase political pressure to secure food production and provide an adequate supply of water for domestic and industrial use.

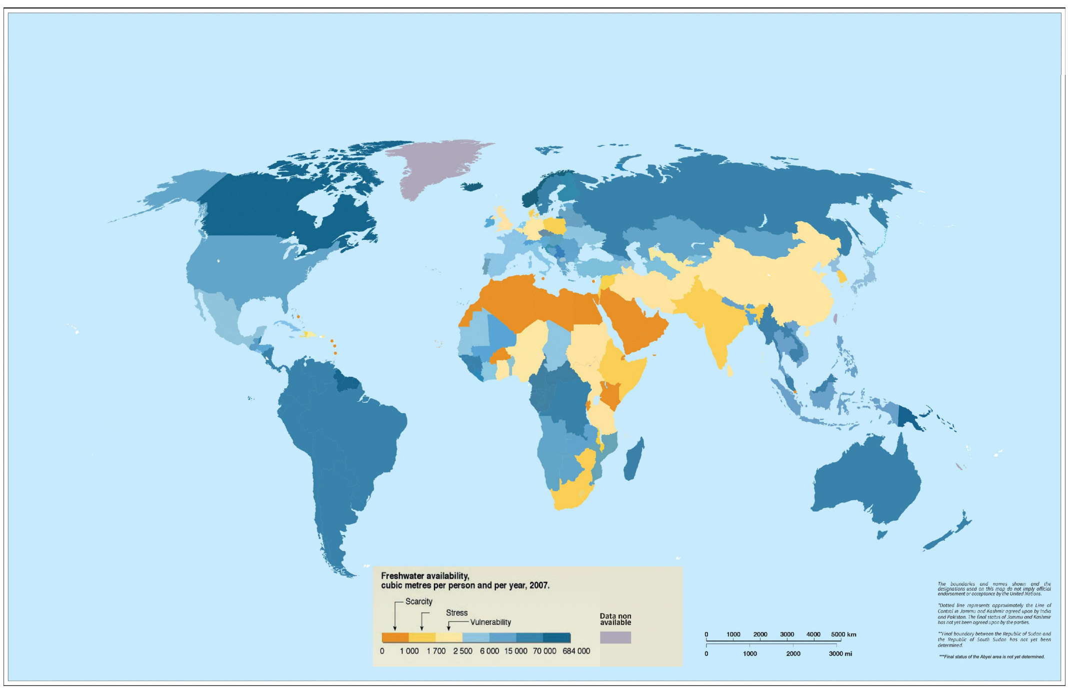

Figure 1.1. Annual fresh water availability (m^3/capita)

Source: Rekacewicz, P. 2006. Global waterstress and scarcity. In: Grid Arendal. Cited 21 December 2022. https://www.grida.no/resources/5596, modified to comply with UN boundaries.

There is already growing concern over the declining availability of freshwater and the ever-increasing demands on the resource (Table 1.1 and Fig. 1.2). Most of the countries in the NENA region already fall below the 'severe water scarcity' annual threshold of 500 m^3 per capita (Fig. 1.2). These include Bahrain, Jordan, Kuwait, Oman, Palestine, Qatar, Saudi Arabia, United Arab Emirates and Yemen. Egypt, Lebanon and Syrian Arab Republic fall below the 'water scarcity' annual threshold of 1 000 m^3 per capita, and only Iraq, for the time being, falls above the 'water stress' annual threshold of 1 500 m^3 per capita. Furthermore, the projected reduction in available freshwater resources per capita per year are remarkable. By 2025, the available fresh water in most NENA countries will decrease by 40 to 72 percent in just 35 years (from 1990) (Table 1.1).

The problem is further aggravated by the deterioration of water quality due to mismanagement and pollution. In many countries, inefficient irrigation distribution systems, poor on-farm water management practices, absence of adequate drainage facilities and uncontrolled discharge of saline drainage waters into non-saline sources have led to extensive water logging and secondary salinization of farm lands (Rhoades *et al.*, 1992).

In general, in arid and semi-arid areas, two realities are recognized. First, for all practical purposes, fresh water resources are finite and most of the economically viable development of these resources has already been implemented. Thus the potential to expand this resource base is marginal. Second, water quality degradation, resulting from pollution, is reducing the volume of freshwater. This is exacerbated by climate change, population growth, fast urbanization and the associated expansion of economic activities, all of which require more water, putting tremendous strain on the already limited and fragile resource.

Table 1.1. Freshwater availability per capita per year (m^3) in different arid and semi-arid countries from 1955 to 2050

Country	1955[b]	1990[b]	2000[a]	2003[c]	2010[a]	2015[c]	2025[a]	2050[d]
Algeria	1 770	689					332	300
Bahrain	672	179	170	153	139	120	89	
Egypt	2 561	1 123	800	770	750	600	550	510
Iraq	18 441	6 029	3 100	2 800	2 400	2 100	1 700	
Jordan	906	327	<500	150	<500	130	121	100
Kuwait				<100	<100	<100	<100	
Lebanon	3 088	1 818	900	900	800	800	867	800

Libya	4 105	1 017					359	250
Morocco	2 763	1 117			780	700	590	600
Oman	4 240	1 266	500	500	450	450	410	
Qatar	1 427	117	<100	<100	<100	<100	68	
Saudi Arabia	1 266	306	<500	400	320	250	113	
Syrian Arab Republic	6 500	2 087	1 250	1 250	900	850	732	600
Tunisia	1 127	540			450		324	400
United Arab Emirates	6 195	308	<500	<400	<300	<200	176	
West Bank and Gaza	1 229	461	<500		<500		264	
Yemen	1 098	445	<500	300	250	200	152	

***Sources**:* Khordagui, H. (2000, 2010); ITT (1955, 1990); ESCWA (2003) & Hamdy, A. (2002).

- Khordagui, H.2000. Policies and institutions for coping with environmental aspects of water scarcity in western Asia, by Ph.D., Lebanon http://www.unwater.org/downloads/ www.Khordagui.pdf
- ITT. 1955, 1990. ITT industries guidebook to global water issues. ITT Inc. https://impeller.net/magazin/itt-industries-releases-guidebook-to-global-water-issues
- ESCWA. 2007. Shared groundwater resources in the ESCWA region: The need, potential benefits and requirements for enhanced cooperation. Paper presented to the Expert Group meeting on Legal Aspects of the Management of Shared Water Resources, 2007, Sharm El-Sheikh, Egypt.
- Hamdy, A. 2002. Water demand management in the Mediterranean, http://www.idrc.org.sg/en/ev-42818-201-1-DO_TOPIC.html

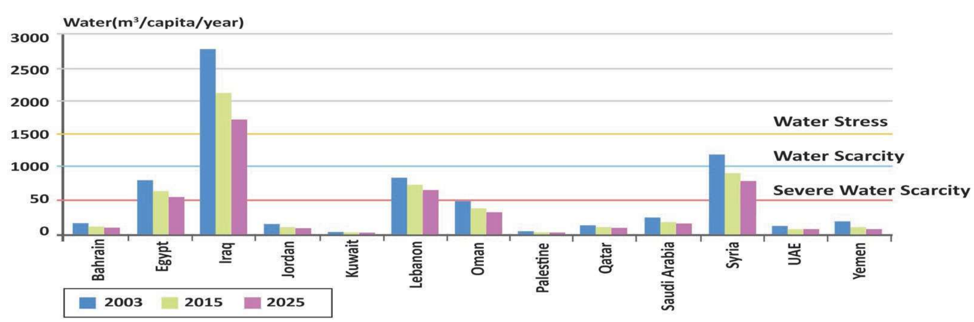

Figure 1.2. Water stress, water scarcity and severe water scarcity in different arid and semi-arid countries in the years 2003, 2015 and 2025.

***Source**:* American University of Beirut. 2004. Proceedings of the symposium on challenges facing water resources management in arid and semi-arid regions. October 7-9. (CD publication).

1.2 IMPACT OF CLIMATE CHANGE ON WATER RESOURCES IN THE NENA REGION

Climate change will have a profound impact in the NENA region. As example, according to the ”Arab Climate Change Assessment Report” (ACCAR) by ESCWA et al., 2017, Regional Climate Modelling (RCM) and Regional Hydrological Modelling (RHM) were applied to generate climate projections for the Arab region until the year 2100, based on climate scenarios adopted by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report (AR5).

The analysis is elaborated based on two representative concentration pathways (RCPs):
- RCP 4.5 – which generally describes a moderate-emissions scenario
- RCP 8.5 – which generally describes a high-emissions or "business as usual" scenario.

The analysis was carried out for three selected time periods for presenting results, namely:
- Reference period (1986-2005)
- Mid-century period (2046-2065)
- End-century period (2081-2100).

Results are shown in Figures 1.3 and 1.4 for the Mean change in annual precipitation (mm/month) and Mean change in annual temperature (°C).

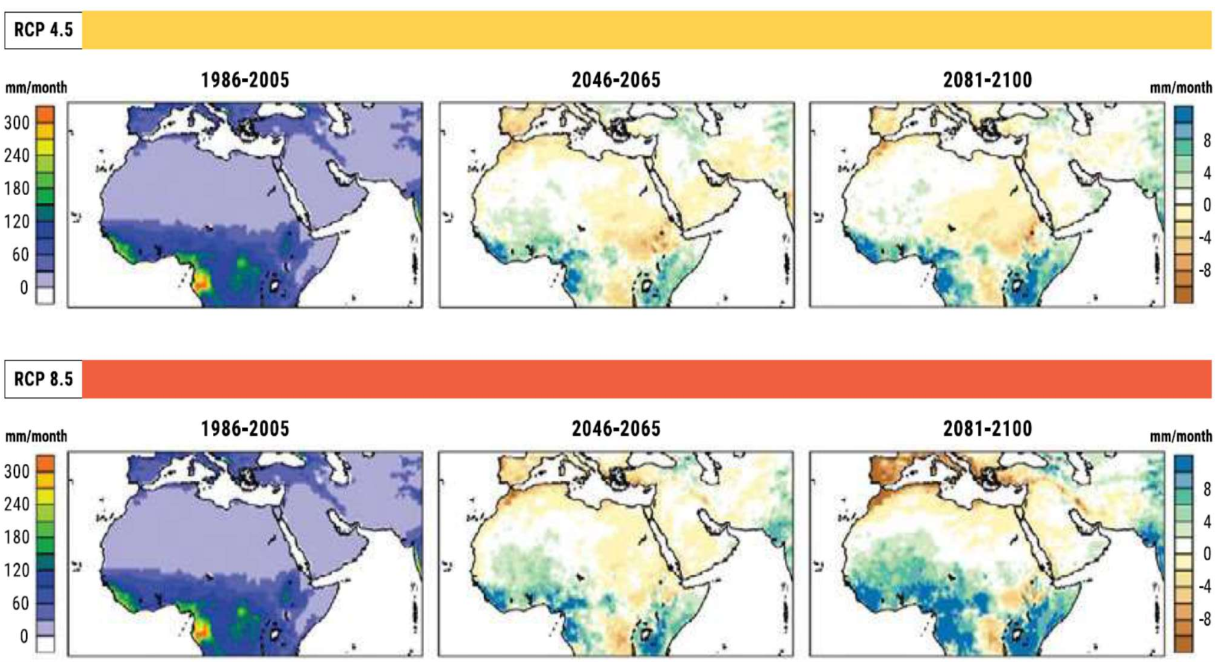

Figure 1.3. Predicted changes in annual precipitation (mm), 2100

Source*: United Nations Economic and Social Commission for Western Asia (ESCWA) et al.* 2017. Arab climate change assessment report – Executive summary. Beirut, E/ESCWA/SPDP/2017/RICCAR/Summary.

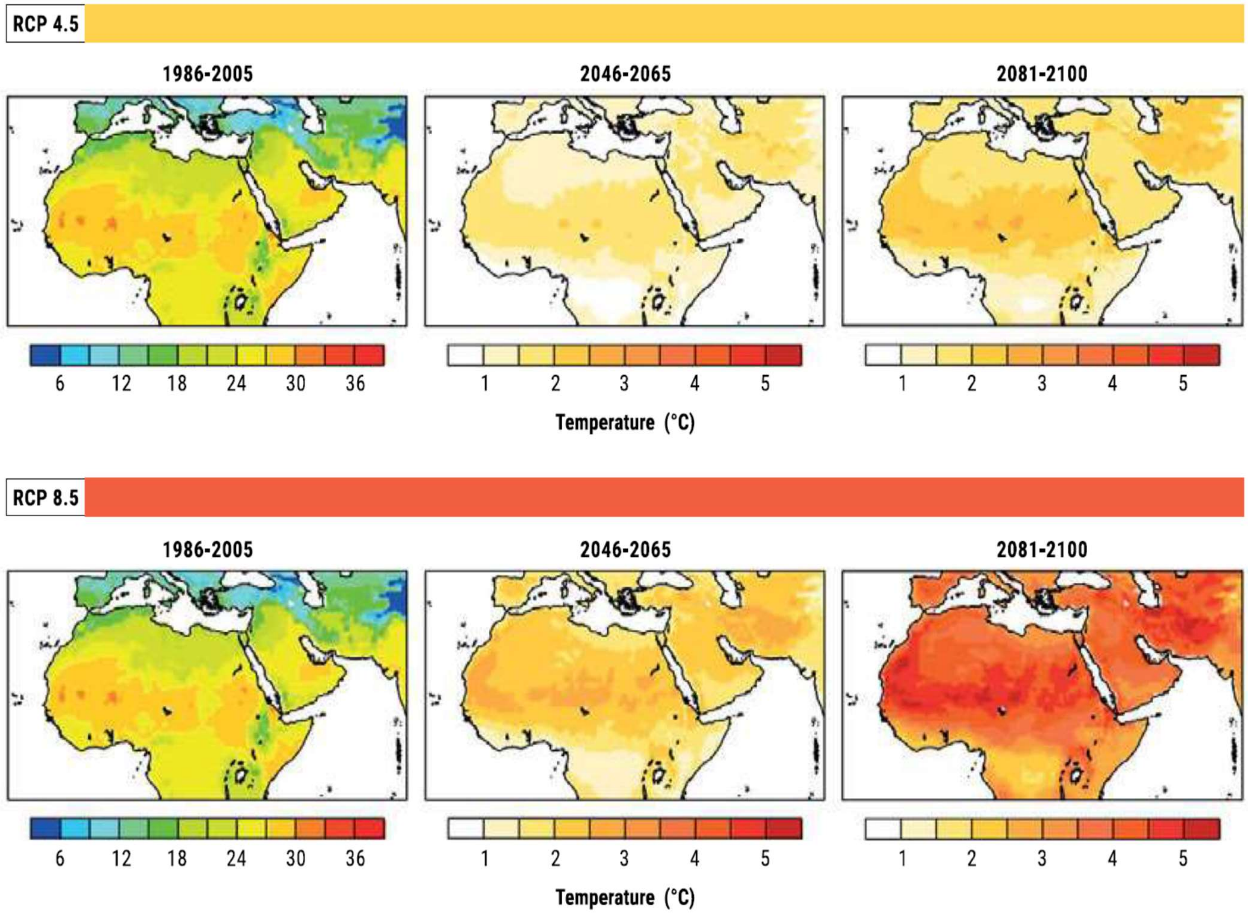

Figure 1.4. Predicted changes in annual temperature, ºC 2100

Source*: United Nations Economic and Social Commission for Western Asia (ESCWA) et al.* 2017. Arab climate change assessment report – Executive summary. Beirut, E/ESCWA/SPDP/2017/RICCAR/Summary.

Furthermore, the irrigation requirement in the region is expected to increase due to increased temperature and evaporation. Increased evaporative demand and lower projected rainfall will produce additional shortages in an already water-stressed region. The temperature in the Arab region is increasing and is expected to continue to increase until the end of the century, where the average mean change in temperature for RCP 4.5 shows a projected increase of 1.2 ºC to 1.9 ºC at mid-century and 1.5 ºC to 2.3 ºC by end-century. For RCP 8.5, temperature increases from 1.7 ºC to 2.6 ºC for mid-century and 3.2 ºC to 4.8 ºC towards end-century. Parts of the Arab region could thus witness a temperature increase of 5 ºC by the end of this century compared to the reference period (1986-2005). Also, precipitation trends are largely decreasing across the Arab region until the end of the century.

Given that rainfall is expected to decrease, the increased water demand is expected to be met by non-conventional water resources, such as brackish water and treated waste water.

There is little doubt that the water demand in arid and semi-arid regions will continue to increase significantly in the years to come in response to predicted warmer and drier climates. The traditional response of increasing fresh water supply to meet higher demands will no longer be adequate in the future. This implies that alternative, non- conventional water sources, although they are of poorer quality, must be identified and used (as well as reused and recycled) in order to meet the demands of a growing population, particularly in the irrigation sector. Coping with water shortage and salinity problems is becoming a top priority for decision-makers and stakeholders in order to ensure the welfare and sustainable development of the NENA region.

1.3 OPPORTUNITIES FOR USING NON-CONVENTIONAL WATER RESOURCES FOR IRRIGATION

The use of non-conventional water resources, such as brackish groundwater and treated waste water, is highly recommended as a supplemental source of irrigation water (Abu-Zeid and Hamdy, 2008). This is particularly important in water scarce areas, such as the NENA region, to meet the increasing water demand for irrigation, expand the irrigated areas and reduce the gap in future needs for food and fibre production. However, despite the possibility of growing many crops with brackish water and the existence of large amounts of brackish water in the region, it is used only to a limited degree for irrigation. This is largely due to the mistaken concept that brackish water, because of its salt content, is unsuitable for irrigation. However, there is sufficient evidence and experiences around the world that demonstrate "that waters of much higher salinities than those customarily classified as unsuitable for irrigation can, in fact, be used effectively for the production of selected crops under the right conditions" (Rhoades *et al*., 1992).

Before discussing the use of brackish water in the NENA region, it is important to inventory the current water resources. Table 1.2 presents water resources in some NENA countries, including renewable conventional water resources, non-renewable fresh water resources, and desalinized and treated waste water.

Table 1.2. Water resources in some NENA countries

	Conventional water resources (million cubic metres)			Non-conventional water resources (million cubic metres)	
Country	Surface water	Groundwater recharge	Groundwater Use	Desalinated water	Waste water and drainage reuse
Bahrain	0.2	100	258	75	17.7 (3)
Egypt	55 500	4 100	4 850	6.6	3 800
Iraq	70 370	2,000	513	7.4	1,500
Jordan	350	277	486	2.5	61
Kuwait	0.1	160	405	388	30
Lebanon	2 500	600	240	n/a	2
Morocco	18 000	4 000	2 000	400	100
Oman	918	550	1 644	51	23
Qatar	1.4	85	185	131	28
Saudi Arabia	n/a	n/a	14,43	795	131 (24)
Syrian Arab Republic	16,375	5,100	3,500	2	1,447
Tunisia*	2700	2165	n/a	18.2	230
United Arab Emirates	185	130	900	455	108
West Bank and Gaza	30	185	200	0.5	2
Yemen	2 250	1 400	2 200	9	52

(Values in brackets are drainage water reuse)

***Sources**: ESCWA, 2007; CEDARE/AWC, 2012; and MARH, 2007:*

- ESCWA. 2007. Shared groundwater resources in the ESCWA region: The need, potential benefits and requirements for enhanced cooperation. Paper presented to the Expert Group meeting on Legal Aspects of the Management of Shared Water Resources, 2007, Sharm El-Sheikh, Egypt.
- CEDARE/AWC. 2012. Arab State of the Water Report. Second edition. Cairo.
- MARHP, 2007. Ministère de l'Agriculture, des Ressources Hydrauliques et de la Pêche. Direction Generale des Ressources en Eau.

This overall inventory suggests that conventional water resources (i.e. surface and groundwater) far exceeds the non-conventional resources (i.e. desalinated water and reuse of drainage and other waste waters). Therefore, the expansion of water to meet the needs of a growing population will need to rely on saline groundwater and other waste waters that is not listed in this inventor.

1.4 CURRENT STATUS OF BRACKISH WATER USE AND IMPACTS IN SELECTED COUNTRIES OF THE NENA REGION

The following is a brief assessment of brackish water use and soil salinization in different NENA countries, reported by El-Bahrawy and Halim (2012):

In Algeria, lands irrigated with brackish water are exhibiting salinity problems that differ under different bioclimatic conditions. Meanwhile, soil degradation advances due to the combined action of water salinity and poor drainage. An inventory of irrigated land in the west and south of the country reveals that much of the agricultural land is suffering from salinity problems. Other lands with high agricultural potential, especially in the eastern and central parts of the country, are likely to become more saline as current irrigation practices continue. It is estimated that salinity has caused the loss of thousands of tonnes of production in the country.

In Egypt, salinity problems are widespread. Thirty to forty percent of the irrigated farmlands are salt-affected. It is estimated that 60 percent of the cultivated land in the north, and 20 percent of the cultivated land in the central and southern delta regions, are salt-affected. Meanwhile, in the Nile Valley (Upper Egypt), about 25 percent of the cultivated areas are salt-affected. In addition, many areas of the reclaimed desert land adjacent to the Nile Valley and Delta, as well as Sinai and Oases, suffer from waterlogging and high salinity.

In Iraq, studies show that the salt concentration in the country's main rivers has increased threefold over the past half century, with salinity levels the highest as the rivers flow into Southern Iraq. In the coming years, brackish water is expected to account for about half of Iraq's total surface water supply and almost all of its shallow aquifers, becoming a major problem for the country.

In Iran (Islamic Republic of), the volume of saline and brackish surface water is about 12 percent of the country's potential renewable surface water resources. The total area of brackish groundwater resources is 350 222 km^2 with an annual extraction volume of 13.7 km^3. The use of brackish water for crop production has a long history in Iran (Islamic Republic of) and farmers employ similar management practices whether they are using brackish or non-saline water, generally relying on high inputs of seeds, fertilizer and water. Agronomic practices such as land preparation, irrigation methods and crop rotation are suboptimal.

In Tunisia, the use of brackish water in agricultural production has a negative environmental, social and economic impact. The absence of effective drainage systems in several areas is the largest constraint in using brackish water for agricultural production. Irrigation with brackish water and agricultural development are in fact possible, but proper techniques and management of the irrigation water are needed, including leaching salts via adequate drainage and selection of salt-tolerant plant varieties.

In Morocco, the sustainability of irrigated agriculture is threatened by the salinization of land and water resources. This is the result of seepage from unlined canals, inadequate surface and subsurface drainage systems, poor water management and cultural practices and the improper use of saline water for irrigation. Approximately 30 percent of the irrigated area is salt-affected, with substantial yield losses.

In Saudi Arabia, the excessive use of groundwater has depleted aquifers and deteriorated groundwater quality, with fresh groundwater becoming brackish. Furthermore, the uncontrolled use of brackish water for irrigation, without applying good irrigation management practices, has increased soil salinity.

In Yemen, brackish water is available as surface water and groundwater. It is mainly used for the rock-cutting industry in the highlands, as well as for irrigating some salt-tolerant crops in coastal plains. However, the extensive withdrawal of groundwater has increased salinity in many locations, particularly in the coastal areas. The brackish water resource has not been inventoried or quantified across the country. The use of brackish water for agriculture in Yemen is about 300 MCM/year, mostly in the Tehama region.

As indicated above, salinity threatens the entire NENA region. But the severity of salinization differs from one country to another and from region to region within each country. In most of the NENA countries, future projections suggest that salt-affected lands will need to be used for agricultural production in order to meet the food and fibre needs of expanding populations. This, coupled with the projected reduction in precipitation and increased use of brackish water in all countries, indicates a dire need for brackish water use guidelines and management strategies to optimize and sustain crop production in this water-scarce region.

1.5 THE NEED FOR GUIDELINES FOR BRACKISH WATER USE IN AGRICULTURAL PRODUCTION IN THE NENA REGION

Rationale: Due to the growing scarcity of fresh water in the NENA region, the need to use brackish water to meet the demand for food, fibre and feed is critical. However, the use of brackish water requires proper management in order to minimize the negative impact of salinity on the soil, plants and the environment. The guidelines proposed in this report are a step ahead in that direction.

Different types of brackish waters (such as agricultural drainage water, saline groundwater and treated waste water) are now widely used in agriculture. However, it is important to bear in mind the negative impacts of the use of brackish water, such as increased soil salinity, the deterioration of soil physical conditions, yield reduction and costs associated with production losses and increased management. Brackish water, mixed with other water supplies to obtain suitable quality or desalinized water, can be used directly for irrigation.

. These guidelines for the use of brackish water in the NENA region are based on sound scientific principles, good agricultural practices (GAPs), and experiences and research results from brackish water studies in the NENA region. They will assist stakeholders and farmers in using brackish water for irrigation, while safeguarding the environment, conserving natural resources, increasing crop productivity and quality, and enhancing farm income.

Scope: In accordance with the FAO Regional Water Scarcity Initiative, and within the framework of the Arab Water Security Strategy (2010–2030) of the LAS and the FAO/AWC cooperation on "Sustainable Management of Brackish Water Agriculture Use," it was agreed that the AWC and FAO, would develop guidelines for the use of brackish water for agricultural production in the NENA region. Work on producing the technical guidelines (Phase 1) began in January 2014 and ended in May 2015.

This joint activity aims to support NENA countries in adapting their national programs and policies to turn low-quality water into resources, and to contribute to developing the capacities of member countries in the use of brackish water. The proposed guidelines are intended also to provide information for NENA region planners and operators of irrigation systems in the use of a wide range of water sources. The guidelines are educational and advisory and provide technical information on the best management practices for irrigation with brackish water. This information can also be useful for meeting environmental requirements.

Objectives: The main objectives of this report are:

- To provide guidelines to use brackish water for irrigation in NENA region countries;
- To recommend appropriate integrated soil, water and crop management strategies for NENA region conditions;
- To propose alternative non-conventional crops that are better adapted to soil and water salinity and will provide better economic returns for farmers.
- To develop a vision and roadmap that participate in responding to the projected water demand in the region.

To that end, the AWC, FAO, nine selected countries from NENA region (Algeria, Egypt, Iraq, Iran (Islamic Republic of), Jordan, Saudi Arabia, Morocco, Tunisia and Yemen) and consultant and water experts participated in the development and refining of the proposed guidelines through the following activities:

1. identifying focal points (national experts) from each of the nine countries;
2. collecting information and knowledge from regional and international organizations;
3. collecting data and information about the use of brackish water in each country, through questionnaires, field data templates, personal communications and e-mail correspondence;
4. organizing two regional workshops to present these guidelines, the first in May 2014 in Doha, Qatar (on the occasion of the Second Arab Water Conference), and the second in Cairo, Egypt, in December 2014 (on the occasion of the Third Arab Water Forum);
5. discussing and approving a general outline of the guidelines, generalized guidelines for irrigation water and good agricultural practices (GAPs) for brackish water use (see AWC/FAO project brief 2014-2015 on www.arabwatercouncil.org);
6. preparing and submitting a draft report (on May, 2015) and consulting international experts from FAO, AWC, ACSAD, and ICBA as well as experts from India, Italy, Spain, United Kingdom of Great Britain and Northern Ireland, United States of America among others to review and revise the report and develop a more crop-specific set of brackish water guidelines.

The final step will be the presentation of the revised report to the AWC to determine if the crop-specific guidelines are appropriate or require more site-specific adjustment.

First Regional Workshop on Brackish Water Use for Agricultural Production in the NENA Region, Doha, Qatar, May 2014. ©AWC.

CHAPTER 2

Brackish water, salinity and sodicity

2.1 CHEMICAL CHARACTERISTICS OF BRACKISH WATER

All soils and irrigation water sources contain mineral salts, but the concentration and composition of these salts vary from one location to another (Ayers & Westcot, 1985 and Wallender & Tanji, 2012). In solution, these salts dissolve and form positively charged cations and negatively charged anions. The most common cations are calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}), while the most abundant anions are chloride (Cl^{-}), sulphate (SO_4^{2-}) and bicarbonate (HCO_3^{-}). Potassium (K^{+}), carbonate (CO_3^{2-}), nitrate (NO_3^{-}), phosphate (H_2PO4^{-}) and trace elements also exist in water supplies and soil solutions, but most often concentrations of these constituents are comparatively low except in certain waste waters such as those from animal feed lots, canneries, olive oil mills and food processing plants where concentrations of K^{+} can be high and where the pH in the effluent can be altered. Some treated waste waters also have a considerable amounts of dissolved organic carbon. Others contain boron (B) at concentrations that may be injurious to certain crops. Brackish water can be characterized in different ways, but, because increased salt concentration is directly related to increased ion concentration, electrical conductivity (EC) is the unit most often used (see Box 2.1).

Box 2.1 How is irrigation water salinity expressed?

The salinity of the irrigation water is usually expressed by its electrical conductivity (ECw) because the salts dissolved in the water form ions (Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2}) that conduct electrical current (USSL Staff, 1954). The standard unit of ECw is decisiemens per metre (dS/m), which is numerically equivalent to millimhos per centimetre (mmho/cm). The EC of water is easily measured using a variety of reputable electrical conductivity metres available on the market. Because the EC measurement is temperature sensitive, the reading is standardized to its reading at 25 ^{o}C (USSL Staff, 1954).

Salinity is also expressed as total dissolved solids (TDS) with units reported in mg/L, which is numerically equivalent to parts per million (ppm). This term is still reported by many analytical laboratories and represents the mass of salt that remains after a liter of water is evaporated to dryness. The salinity parameters ECw and TDS are, for the most part, linearly related to one another over the concentration range where most crops are impacted. The most common conversion is TDS = 640 EC (dS/m) (USSL Staff, 1954) but this conversion is dependent upon the composition and concentration of the water. For example, Rhoades *et al.* (1992) suggests an approximate relationship between water salinity parameters as ECw of 1 dS/m = 10 mmolc/L = 700 mg/l. For ECw > 5 dS/m, a better conversion is TDS (mg/l) = 800 EC (dS/m) (Hanson *et al.*, 2006).

Box 2.1 (Cont.)

But salinity may also be expressed in a number of other ways, depending upon the method or purpose of the measurements. The ions in a solution, important for predicting injury imposed by specific ions (such as Na^+ and Cl^-) are often expressed in concentrations such as mmol/l or meq/l (as in mmol of charge per litre or mmolc/l). Occasionally, the concentration may be expressed as the total concentration of soluble cations (TSC) or anions (TSA). These parameters are often expressed as meq/l (or mmolc/l) and the two should be equal in order to balance electrical charge (that is, TSC = TSA). When concentrations of individual ions are reported, more information can be discerned regarding the suitability and potential impacts on soils and crops. A good estimate of relating EC to either TSC or TSA is: TSC or TSA (meq/l) equals a little more than 10 times EC (dS/m) (USDA Staff, 1954).

Salinity may also be expressed as osmotic potential ($\Psi\pi$). The van't Hoff equation is described as $\Psi\pi = -iCRT$ where 'I' is the moles of particles in solution per moles of dissolved solutes, 'C' is the molar concentration of the solute, 'R' is the universal gas constant and 'T' is absolute temperature in kelvin. Expressing salinity as a function of osmotic potential has been used in many scientific studies as they can normalize data sets with difference salt compositions (Ben-Gal *et al.*, 2009). However, for this manual, EC will be the standard unit of salinity.

References:

Ben-Gal, A., H. Borochov-Neori, Yermiyahu, U. & Shani, U. 2009. Is osmotic potential a more appropriate property than electrical conductivity for evaluating whole-plant response to salinity? *Environmental and Experimental Botany*, 65(2-3):232-237. file:///C:/Users/Charieg/Downloads/Ben-Galetal2009EEBosmoticpotential.pdf

Hanson, B., Grattan, S.R. & Fulton, A. 2006. *Agricultural Salinity and Drainage*. Davis, Division of Agriculture and Natural Resources (UCANR) Publication 3375. University of California. https://hos.ifas.ufl.edu/media/hosifasufledu/documents/pdf/in-service-training/ist30688/IST30688---24.pdf

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Richards, L.A. ed. 1954. *Diagnosis and Improvement of Saline and Alkali Soils.* US Salinity Laboratory. Washington, D.C., United States Department of Agriculture – Agricultural Research Service. https://www.ars.usda.gov/ARSUserFiles/20360500/hb60_pdf/hb60complete.pdf

2.2 SOURCES OF SALTS

Salt manifests itself in the agricultural environment in a number of ways, such as saline irrigation and groundwater, saline drainage waters, saline and saline-sodic soils, and salts from natural geologic formations of marine origin. While the primary source of salts in soils and irrigation water is from the chemical weathering of earth's minerals, salts can build up in the environment from secondary sources as well (Wallender & Tanji, 2012). Certain human activities can increase salinity. These include irrigating with saline wastewater, seawater intrusion of groundwater due to excessive pumping along coastal areas, adding chemical fertilizers and amendments to the farm, applying animal waste and manure, salinization from brines resulting from desalination processes and oil field production. Therefore, a combination of salts from various primary and secondary sources can contribute to salinization of agricultural lands.

2.3 DEFINITION OF BRACKISH WATER

According to the Commonwealth of Australia (2011), brackish water is defined rather broadly as water that has more salinity than fresh water, but not as much as seawater. The word comes from the Middle Dutch root "brak," meaning "salten" or "salty". Because brackish water can adversely affect the growth and production of most terrestrial plant species, without appropriate management it can have a negative impact on the environment.

The term "brackish water" covers a large range of salinity levels and therefore is often broken down into smaller categories (Table 2.1). In practice, definitions of brackish water are numerous, varied and are often refined to suit the prospective use of the water being described (Rhoades *et al.*, 1992). Non-saline water, often referred to as "fresh water" contains a low concentration (< 500 mg/l) of total dissolved solids (TDS) and its electrical conductivity (ECw) is correspondingly low (i.e. < 0.7 dS/m). This high-quality water is scarce in the NENA region. "Slightly saline" water (ECw 0.7–2.0 dS/m), which can also be categorized as fresh water in this region, is more abundant and is used extensively for irrigation. Water categorized as "moderately saline" to "saline" (ECw 2–10 dS/m) is also abundant but has many more restrictions regarding crop suitability, and full yield potential is not achieved for most crops. Water with an ECw of 10–25 dS/m is classified as "very saline" and its suitability is limited to highly salt-tolerant crops and halophytes. Water classified as "very highly saline" (ECw 25–45 dS/m) is typically unsuitable for irrigation with the exception of a few halophytic species with limited agricultural use.

Table 2.1. Classification and uses of saline water

Water Classification	Electrical conductivity (ECw, dS/m)	Salt concentration, TDS (mg/l)	Type of water
Non-saline	< 0.7	< 500	Drinking and unrestricted irrigation water
Slightly saline	0.7–2.0	500–1 500	Irrigation water, including many treated municipal waste waters
Moderately saline – saline	2–10	1 500–7 000	Primarily groundwater and drainage water; limited irrigation water and livestock water
Highly saline	10–25	7 000–15 000	Secondary drainage water; highly saline groundwater; limited livestock (beef, cattle, sheep); very limited irrigational use
Very highly saline	25–45	15 000–35 000	Very saline groundwater; limited industrial uses; ore processing
Seawater	> 45	> 35 000	Seawater

Source*:* Adapted from Rhoades *et al.*, 1992; and the Australian Water Resources Council, 1998:

- Rhoades, J.D., A. Kandiah & Mashali, A.M. 1992. The use of saline waters for crop production. FAO Irrigation and Drainage Paper 48. Rome, FAO.
- Australian Water Resources Council (Department of Primary Industries and Energy) (1998). Water Management series No. 13, Australian Government Publishing Services. Department of Environment & Conservation NSW (DEC) 2004, Environmental Guidelines: use of effluent by irrigation, DEC. Desal No. 8, 2011.

Soil is considered salt-affected when the salt concentration in the root zone reaches a level that is too high for the plant to achieve optimal growth and yield. Like irrigation water, the salinity of the soil can be measured in various ways (see Box 2.2). Irrigation must be managed in a way that can provide favourable conditions for crop production, even if that means optimal yields cannot be achieved.

2.4 SALINITY VS SODICITY

There is a clear distinction between salinity and sodicity. Salinity is directly related to salt concentration, while sodicity indicates salt composition. "Saline water" indicates that the concentration of salts in the irrigation water or soil water is sufficiently high to adversely affect crop yields or crop quality. These adverse responses are caused by high concentrations of salts in the soil solution (osmotic effects) or by high concentrations of specific ions, such as chloride or sodium, which can cause specific injury to sensitive crops (specific-ion effects) (see Chapter 4 on salinity effects on crops). Sodicity, on the other hand, is related to the proportion of sodium in the water, or adsorbed in the soil surface, relative to calcium and magnesium. Sodic water is synonymous with "soft" water. Sodicity can contribute to the deterioration of soil physical properties, which can indirectly affect plants, resulting in surface crusting, reduced water infiltration and reduced aeration, causing anoxic or hypoxic conditions for roots. Sodic effects on soils are aggravated under low salinity conditions. Traditionally, saline soils were defined as having an ECe > 4 dS/m and sodic soils were defined as having an SAR > 15 (USSL Staff, 1954). Likewise, soil was considered non-saline if the ECe < 4 and non-sodic if the SAR <15. Extrapolating this definition, soils could be saline and/or sodic, or non-saline and non-sodic. However, these are older definitions and categories are too general in order to enable farmers and stakeholders to understand them easily. More detail on the effects of salinity and sodicity on the soil is provided in the next chapter.

Box 2.2 How is soil salinity expressed?

Soil salinity is expressed in a number of ways. It is most commonly expressed as the electrical conductivity of the saturated soil paste (ECe). This is the EC of the filtrate that is extracted from soil samples collected from the root zone in the field, after samples have been carefully saturated with distilled water (Hanson *et al.*, 2006; USSL Staff, 1954). The ECe is the soil salinity parameter used to characterize salt tolerance (see Chapter 5, Crop Salt Tolerance). Others use higher water content extracts such as 1:1, 1:2 and 1:5, which are easier and faster to prepare, but ECe is preferred because it more closely reflects the soil chemistry of the soil solution in field conditions (Suarez & Jurinak, 2012). Other methods that use more water to extract soil salts (such as 1:2 or 1:5) typically dissolve more salt than what would be exposed to the roots in the field environment. It is difficult to then correct the EC of these soil extractions to ECe. The EC of the soil or pore water (ECp) is preferred since it reflects more accurately the EC of the soil solution and, therefore, crop response. However, suction extraction is laborious and is most effective when soils are near or above field capacity.

Sensors to measure soil salinity in situ are available but require calibration to relate the sensor reading to ECp or to ECe (Scudiero *et al.*, 2012). They are valuable for tracking relative soil salinity changes both spatially and temporally. Currently, there are many salinity sensors available that measure the bulk or apparent EC of the soil (i.e. ECa) by:
1) Measuring electrical conductance/resistance either by placing electrodes in the soil or remotely, via electromagnetic effects or 2) indirectly, by measuring dielectric properties of the soil. Newer research is emerging that focuses on multi-spectral properties via remote sensing and geographical information systems (GIS) to map soil salinity (Gorji *et al.*, 2015). Many sensors can be paired with data loggers to record soil salinity on a continuous basis (Photo). When using saline water, salinity should be continuously monitored to ensure that the soil salinity does not reach levels which are harmful to the plant or the environment. Therefore, salinity sensors should be placed in the root zone of the crop (Figure 2.1). Care should be taken to calibrate the EC reading of the senor to either EC of the pore water (ECp) or EC of the saturated soil paste (ECe).

Spectrum SMEC300 and Watch Dog data logger

Salinity sensors (SMEC 300 by Spectrum Technologies, Inc.) for continuous monitoring (Courtesy of Adriano Battilani, CER, Italy. ©CER).

Box 2.2 (Cont.)

Figure 2.1. Soil salinity sensors placed in a field at two root zone depths to monitor soil salinity in rows alternately wet through drip irrigation (illustration based on SMEC 300 sensors by Spectrum Technologies, Courtesy of Adriano Battilani, CER, Italy).

Electromagnetic induction is a popular way to measure the apparent or bulk electrical conductivity of the soil (ECa) and is very useful in developing salinity maps at the field or regional scale (Corwin & Lesch, 2005; 2013; Rhoades *et al.*, 1999). The apparent soil electrical conductivity is influenced by a number of physico-chemical properties such as soluble salts, water content, clay content and mineralogy, temperature, organic matter (OM) and bulk density. The method is non-destructive and can be done with sensors such as the EM38 sensor (see Photo) mounted to non-conducting sleighs towed behind tractors (Photo). The orientation of the sensor probe allows for the measurement of ECa to different soil depths. A dual sensor can be assembled using two sensors – one in a horizontal position to measure ECa from the soil surface down to 0.75 m and the other in a vertical position to measure ECa down to 1.5 m. (see Photo). This method is particularly useful for generating soil salinity maps at two root depths. However, this method requires calibration to relate the ECa reading to ECe. Computer software is available that not only generates the detailed maps but identifies the ideal GPS locations to collect soil samples for relating ECa to ECe. (For more information, see Rhoades *et al.*, 1999; and Corwin & Lesch, 2005, 2013.)

Electromagnetic sensor (EM38 by Geonics Limited) used to remotely measure the apparent or bulk electrical conductivity (ECa) of the soil. Photo by B. Hanson, University of California, Davis, 2000. ©University of California.

Box 2.2 (Cont.)

Close-up of EM38 electromagnetic sensor for non-destructive measurement of bulk or apparent electrical conductivity (ECa) and dual EM38: Above: two EM38 sensors in vertical and horizontal positions. Below: EM38 mounted on PVC sled for field surveys. Photo by D. Corwin & S. Lesch, 2005, US Salinity Laboratory. ©US Salinity laboratory.

CHAPTER 3

Effects of brackish water on soils

Soil tilth and permeability to water and air can be altered by irrigation with saline-sodic water, particularly when followed by irrigation with non-saline water or rainfall. Soil hydraulic conductivity and infiltration rate decrease with decreasing soil salinity and with increasing exchangeable Na^+ (Oster & Schroer, 1979; Rengasamy *et al.*, 1995; Suarez & Jurinak, 2012). Sodicity, as well as irrigation water low in salts, can contribute to the deterioration of soil physical properties (see Box 3.1), which can indirectly affect plants via crusting (Sumner & Stewart, 1992), reduced infiltration, increased soil strength and reduced aeration, resulting in anoxic conditions for roots (Suarez & Jurinak, 2012). With reduced infiltration, salts and specific ions can accumulate in the root zone.

Box 3.1 Impact of brackish water on soil physical properties and clay minerals

Deterioration of soil physical conditions can occur when brackish water is used for irrigation. Soil tilth and permeability to water and air can be reduced by irrigation with saline-sodic water, particularly when followed by irrigation with non-saline water or rainfall. Soil hydraulic conductivities (HCs) (McNeal & Coleman, 1966) and infiltration rates (IRs) (Oster & Schroer 1979; Suarez *et al*. 2006) decrease with decreasing soil salinity and with increasing exchangeable sodium due to the interconnection between salinity and sodicity (Quirk & Schofield, 1955). This occurs because clay swelling increases and aggregate stability decreases, affecting the pore size distribution and network of microstructures in soils. For an electron microscopic view of aggregated clay platelets, see Figure 3.2 (Menzies *et al.*, 2015). Aggregate deterioration, clay swelling into the water-conducting pores, and clay movement and deposition within the macropores are the mechanisms responsible for loss in permeability.

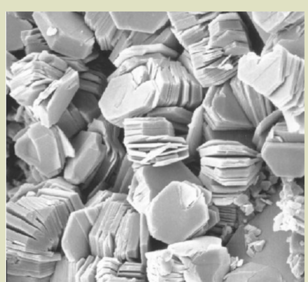

Figure 3.2. Electron microscopic view of well-aggregated clay platelets allowing for large pore spaces between aggregations.

Source*: Menzies, N., M. Bell, P. Kopittke. 2015. Soil sodicity chemistry physics and amelioration. Grains Research and Development Corporation (GRDC), Australian Government. https:// grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc- update-papers/2015/02/soil-sodicity-chemistry-physics-and-amelioration.*

An important aspect of soil management is the recognition of the different responses of surface and subsurface soils to sodicity and salinity (Oster & Shainberg, 2001).

Box 3.1 (Cont.)

Because surface soils have a soil–atmosphere interface and are subjected to tillage, they are affected more than subsoils by water drop impact from rainfall or sprinklers, rapid wetting, irrigation water quality, animal and vehicular traffic, tillage and surface mulches. The bonding mechanisms associated with organic matter (Nelson *et al.*, 1997) and aging are continually changing in surface soils, while subsoils are more stable. Subsoils have lower wetting rates, water content prior to wetting is usually higher, organic matter content is usually lower, and the chemical state of organic matter is more stable than in surface soils.

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3.1. SODIUM ABSORPTION RATIO (SAR) AND EXCHANGEABLE SODIUM PERCENTAGE (ESP)

Sodicity is characterized by the exchangeable sodium percentage (ESP) but has been described in different ways (Suarez & Jurinak, 2012). The ESP is the percentage of the cation exchange capacity occupied by Na^+. The sodicity of the water, on the other hand, is a measure of the sodium adsorption ratio (SAR). SAR is defined as:

$$SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})}} \qquad \textit{Equation 3.1}$$

Where concentrations of all cations are molarities. When concentrations are expressed in meq/l or mmolc/l, the (Ca^{2+} + Mg^{2+}) in the equation above must be divided by 2, since there are two equivalents for every mole of these divalent cations. The ESP and SAR of the soil extract are closely related to one another and, for most practical purposes, are numerically equivalent in the range of 3 to 30 (USDA, 1954).

Therefore, SAR is typically used as a substitute for ESP as the index to characterize the sodium hazard of soils and waters (Rhoades *et al.*, 1992).

3.1.1. Role of accompanying anions

The definition of SAR does not provide any reference to the accompanying anions. Therefore, there is little distinction between an SAR of 10 that is dominated by chloride or by sulphate. In many areas, bicarbonate is a major anion. Therefore, arid lands within the NENA region can have quite a range in anion compositions. The anion composition is important as it can influence the SAR resulting from the precipitation of the divalent cations. High carbonate waters are associated with higher pH ranges, particularly in low salinity conditions, and soluble Ca^{2+} and Mg^{2+} are particularly subjected to precipitation. The term residual sodium carbonate (RSC) was introduced by Eaton (1950) where:

$$RSC = (CO_3^{2-} + HCO_3^{-1}) - (Ca^{2+} + Mg^{2+})$$

Where units are mmol/l. Typically, RSC values in excess of 2.5 are unsuitable for irrigation without modification (USSL Staff, 1954).

3.1.2 Free calcium (Ca^{2+}) and pH

The concentration of free calcium in the soil solution (Ca^{2+}), in addition to the SAR and EC, has a great influence on aggregate stability. Therefore, the pH of the soil solution will affect the Ca^{2+} concentration via carbonate chemistry reactions and this, in turn, will affect the saturated hydraulic conductivity and soil dispersion. As the pH increases, the bicarbonate and carbonate concentrations increase and free Ca^{2+} is decreased as it precipitates out of solution as calcite. Indeed, saturated hydraulic conductivity drops in montmorillonitic and kaolinitic soils as pH increases from slightly acidic to alkaline levels (Suarez *et al.*, 1984).

3.2 EFFECTS OF SODICITY ON SOIL PHYSICAL CONDITIONS

Sodic soil conditions affect almost all crops because of the deterioration of soil physical conditions. Dispersion of soil aggregates decreases soil permeability to water and air, thereby reducing plant growth. The deterioration of the physical conditions of the soil depends upon the sodium adsorption ratio (SAR) and the electrical conductivity of the water (ECw) (Rhoades, 2012; Suarez & Jurinak, 2012). Soil solutions with low Na^+/Ca^{2+} ratios and high salt concentrations compress the exchangeable cation envelope (that is, the effective anion exclusion zone or the distance from the clay surface to where the negative clay surface charge is no longer effective). The compression increases flocculation and maintains soil structure. Figure 3.1 shows the relationship between the SAR and ECw of the irrigation water (Hanson *et al.*, 2006). Irrigation water with both low salinity (e.g., low ECw) and high SAR is particularly problematic (see the red zone). On the other hand, water with low SAR and high salinity has better infiltration (see the blue zone), even though the higher salt concentration could damage the crop. Therefore, water infiltration rates decrease with decreasing soil salinity and with increasing exchangeable Na^+, or sodicity (Figure 3.1).

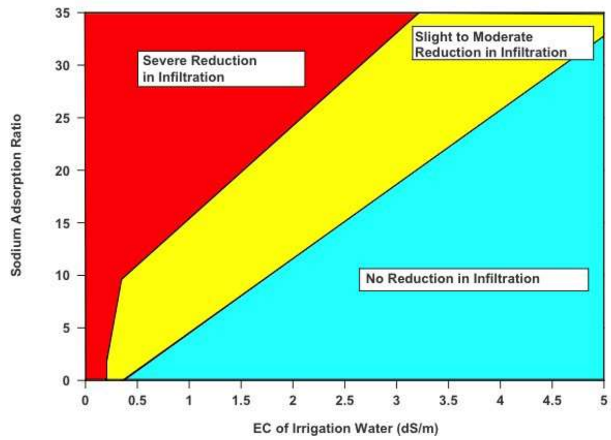

Figure 3.1. Relationship between the salinity (EC) and sodicity (SAR) of the irrigation water and its potential effects on water infiltration in the soil (Adapted from Hanson *et al.*, 2006)

***Source**: Hanson, B.R., S.R. Grattan and A. Fulton. 2006. Agricultural Salinity and Drainage. Division of Agriculture and Natural Resources Publication 3375. University of California. 164pp*

These processes occur due to the combination of clay swelling and instability of soil aggregates (see Box 3.1). The clay fraction in soils is susceptible to long-term damage as it is subject to physico-chemical interactions with sodium in the soil solution, which expands the clay layers (see Figure 3.2) and reduces the soil's hydraulic properties, sometimes irreversibly. Clay dominated soils are therefore most vulnerable to damage from waters rich in sodium and the reduction in hydraulic conductivity and surface infiltration rate caused by clay dispersion (Quirk & Schofield, 1955). Clay soils typically have very low water infiltration rates (e.g. < 2.5 mm/hr) and the infiltration rate increases as the textural class becomes more coarse (see Table 3.1). Regardless of soil textural class, sodicity can reduce water infiltration.

Table 3.1. Classification of soil infiltration rate in relation to soil type.

Infiltration	Classification	Soil Type
< 2.5 mm/hr	Very low	Clays
2.5 – 12.5 mm/hr	Low	Clay loams
– 25 mm/hr	Medium	Loams/silts
>25 mm/hr	High	Sands/silt loams

Source: Abbott C.L. and Hasnip, N.J. 1997. The safe use of marginal quality water in agriculture: A guide for the water resources planner. WR Wallingford, England

Sodicity not only affects aggregate dispersion, but promotes clay migration and deposition into soil pores, thereby reducing the fraction of large pores in the soil (Rengasamy *et al.*, 1995). Large pore-size distribution is important for water movement, adequate drainage and proper aeration. Therefore, a reduction in the large, pore-size fraction reduces the hydraulic conductivity of soils. This reduction in infiltration and aeration will have negative consequences on growth.

3.3. ADJUSTED SAR

The SAR expression was introduced in Handbook 60 (US Salinity Laboratory Staff, 1954) as a means of characterising the sodicity hazard of the irrigation water. The authors understood the need to adjust the SAR to account for dissolution and/or precipitation of Ca^{2+} in the near-surface soil water to obtain a better prediction of Na^{+}'s dispersive effects and introduced an expression to adjust the SAR. However, it was several decades later when a newer, more accurate method of adjusting the SAR was introduced (Ayers & Westcot, 1985; Suarez, 1981). Suarez found that the Ca^{2+} concentration in the soil water near the soil surface could be predicted by knowing the EC and HCO^{-} /Ca^{2+} ratio of the irrigation water (Table 3.2). This adjusted Ca^{2+} concentration (Ca_x) could then be substituted into the SAR expression (equation 3.1) to determine the adjusted SAR (SAR_{adj}). For example, if the ECw is 1.0 dS/m and the HCO_3/Ca ratio is 1.0, then the adjusted calcium concentration (Cax) is 2.09 meq/l. While this improved the estimates of SAR's impact on soil physical conditions, there was still much variability in predicting the sodicity hazard of the irrigation water by SAR and EC alone.

Table 3.2. Predicted calcium concentration (Cax) in the soil water following irrigation with a given ECw (dS/m) and HCO_3/Ca ratio in the irrigation water (after Suarez, 1981). The units for HCO^- and Ca^{2+} are in meq/l.

Salinity of applied water (EC_i) (dS/m)

Ratio of HCO_3/Ca	0.1	0.2	0.3	.05	0.7	1.0	1.5	2.0	3.0	4.0	6.0	8.0
0.5	13.20	13.61	13.92	14.40	14.79	15.26	15.91	16.43	17.28	17.97	19.07	19.94
.10	8.31	8.57	8.77	9.07	9.31	9.62	10.02	10.35	10.89	11.32	12.01	12.56
.15	6.34	6.54	6.69	6.92	7.11	7.34	7.65	7.90	8.31	8.64	9.17	9.58
.20	5.24	5.40	5.52	5.71	5.87	6.06	6.31	6.52	6.86	7.13	7.57	7.91
.25	4.51	4.65	4.76	4.92	5.06	5.22	5.44	5.62	5.91	6.15	6.52	6.82
.30	4.00	4.12	4.21	4.36	4.48	4.62	4.82	4.98	5.24	5.44	5.77	6.04
.35	3.61	3.72	3.80	3.94	4.04	4.17	4.35	4.49	4.72	4.91	5.21	5.45
.40	3.30	3.40	3.48	3.60	3.70	3.82	3.98	4.11	4.32	4.49	4.77	4.98
.45	3.05	3.14	3.22	3.33	3.42	3.53	3.68	3.80	4.00	4.15	4.41	4.61
.50	2.84	2.93	3.00	3.10	3.19	3.29	3.43	3.54	3.72	3.87	4.11	4.30
.75	2.17	2.24	2.29	2.37	2.43	2.51	2.62	2.70	2.84	2.95	3.14	3.28
1.00	1.79	1.85	1.89	1.96	2.01	2.09	2.16	2.23	2.35	2.44	2.59	2.71
1.25	1.54	1.59	1.63	1.68	1.73	1.78	1.86	1.92	2.02	2.10	2.23	2.33
1.50	1.37	1.41	1.44	1.49	1.53	1.58	1.65	1.70	1.79	1.86	1.97	2.07
1.75	1.23	1.27	1.30	1.35	1.38	1.43	1.49	1.54	1.62	1.68	1.78	1.86
2.00	1.13	1.16	1.19	1.23	1.26	1.31	1.36	1.40	1.48	1.54	1.63	1.70
2.25	1.04	1.08	1.10	1.14	1.17	1.21	1.26	1.30	1.37	1.42	1.51	1.58
2.50	0.97	1.00	1.02	1.06	1.09	1.12	1.17	1.21	1.27	1.32	1.40	1.47
3.00	0.85	0.89	0.91	0.94	0.96	1.00	1.04	1.07	1.13	1.17	1.24	1.30
3.50	0.78	0.80	0.82	0.85	0.87	0.90	0.94	0.97	1.02	1.06	1.12	1.17
4.00	0.71	0.73	0.75	0.78	0.80	0.82	0.86	0.88	0.93	0.97	1.03	1.07
4.50	0.66	0.68	0.69	0.72	0.74	0.76	0.79	0.82	0.86	0.90	0.95	0.99
5.00	0.61	0.63	0.65	0.67	0.69	0.71	0.74	0.76	0.80	0.83	0.88	0.93
7.00	0.49	0.50	0.52	0.53	0.55	0.57	0.59	0.61	0.64	0.67	0.71	0.74
10.00	0.39	0.40	0.41	0.42	0.43	0.45	0.47	0.48	0.51	0.53	0.56	0.58
20.00	0.24	0.25	0.26	0.26	0.27	0.28	0.29	0.30	0.32	0.33	0.35	0.37
30.00	0.18	0.19	0.20	0.20	0.21	0.21	0.22	0.23	0.24	0.25	0.27	0.28

Source: Suarez DL. 1981. Relation between pHc and Sodium Adsorption Ratio (SAR) and an alternate method of estimating SAR of soil or drainage waters. Soil Sci. Soc. Am. J 45:469–75.

More than half a century ago, researchers assigned numerical values to soils, classifying them as either saline and/or sodic (USDA Handbook 60, 1954). As indicated in the previous chapter, soils were considered "saline" when the electrical conductivity (EC) of the saturated soil extract exceeded 4 dS/m at 25 °C. They were classified as "sodic" when the ESP exceeded 15 (USSL Staff, 1954). Since that time, much has been learned about the many factors affecting crop response to salinity and differences in sensitivity to salinity among crop species (Läuchli & Grattan, 2012). Similarly, much has been learned about the complexities of soil mineralogy, clay content, organic matter and ionic strength and composition of irrigation waters on aggregate stability and soil physical conditions (Suarez & Jurinak, 2012; Oster *et al.*, 2016; Sposito *et al.* 2016; Smith *et al.*, 2015). As such, those historical values for classifying soils are no longer valid because many other factors must be considered to assess whether irrigation water can have negative impacts on crops or soils.

3.4. MOVING FROM SAR TO CROSSopt

The heightened interest in waste waters as a supplemental source of irrigation water has inspired scientists to re-examine the appropriateness of SAR (as defined above) as the best expression for characterising the sodic effects on aggregate stability. Many waste waters are being considered for irrigation, including municipal waste waters, agricultural drainage waters and waste waters from agricultural processing plants and dairies. The concentration and composition of waste waters can vary quite dramatically.

Some waste waters may have high concentrations of K^+, Mg^{2+} and/or organic carbon. But while Mg^{2+} was traditionally thought to be a cation that promoted good soil structure, in a manner similar to Ca^{2+}, research over the past six decades has recognized magnesium's dispersive properties (Smith *et al.*, 2015; Sposito *et al.*, 2016). Addressing magnesium's dispersive effect, FAO has since defined sodic soil as one with "15 percent or more exchangeable Na^+ plus Mg^{2+} on the exchange complex within 50 cm of the soil surface throughout" (Micheli *et al.*, 2006). However, quantifying magnesium's dispersive influence is complicated by the clay mineralogy and can be masked by the effects of Na^+ (Sposito *et al.*, 2016). Similarly, K^+ is ignored in the SAR equation even though many waste water effluents, such as those from fruit and olive oil processing plants, wineries and animal production facilities, have elevated levels. Potassium has dispersive influences on soil aggregates stronger than Mg^{2+} but less than Na^+. Investigators found that in soils irrigated with waters high in K^+, the relationship between SAR and ESP is moderated such that the ESP of the soil will be less than predicted according to that using USDA's Handbook 60 (Laurenson, 2011). To more accurately describe the dispersive effect of the poor-quality water composition, K^+ should be taken into account as well. Therefore, SAR, as it has been described above and by Ayers and Westcot (1985), is not the best expression for characterising the stability of soil aggregates.

A new water quality parameter, the cation ratio of soil structural stability (CROSS), has recently been proposed as a better predictor of potential soil permeability hazards as it accounts for the dispersive contribution of K^+ and lesser flocculation power of Mg^{2+} relative to Ca^{2+} (Rengasamy & Marchuk, 2011). This new expression modifies the traditional SAR formula by incorporating a numerical coefficient for K^+ that reflects a lower dispersing effect than Na^+ and a numerical coefficient for Mg^{2+} that diminishes its flocculating power relative to Ca^{2+}. As a result, CROSS > SAR for all irrigation waters having significant amounts of K^+ and/or Mg^{2+}, and this revised expression (i.e. CROSS) was found to be far superior at predicting the dispersive power of an irrigation water than SAR (see Box 3.2).

Box 3.2 Cation ratio of soil structural stability (CROSS)

For decades, the sodium adsorption ratio (SAR) has been the standard for predicting the potential permeability hazard of irrigation water of a given quality on soil structure (Ayers / Westcot, 1985; US Salinity Laboratory Staff, 1954). The SAR is equal to the Na^+ concentration divided by the square root of the Ca^{2+} + Mg^{2+} concentrations when units are represented as mmolar. The Ca^{2+} + Mg^{2+} concentration would need to be divided by 2 if units are expressed in meq/l or mmolc/l.

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

More recently, a new expression – the cation ratio of soil structural stability ($CROSS_f$), was introduced. This expression includes the dispersive contribution of K^+ and the much weaker flocculation power of Mg^{2+} (Rengasamy & Marchuk, 2011). Using the different flocculating powers for the various cations (Na^+ = 1.0, K^+ = 1.8, Mg^{2+} = 27 and Ca^{2+} = 45), coefficients could be applied to the expression. For example, the flocculating power of K^+ relative to Na^+ was 1.0/1.8 (or 0.56), and the flocculating power of Mg^{2+} relative to Ca^{2+} was 27/45 (or 0.60). Rengasamy & Marchuk concluded that this $CROSS_f$ expression was much better than SAR as a predictive measure of clay dispersion and flocculation.

$$CROSSf = \frac{Na + 0.56K}{\sqrt{(Ca + 0.60Mg)}}$$

This new expression has since been refined by others to optimize the coefficients for practical application. For instance, investigators modified the coefficients for K^+ and Mg^{2+} by equating CROSS as the weighted sum of SAR and PAR (potassium adsorption ratio). Their goal was to replace the SAR parameter with this new $CROSS_{opt}$ parameter, which was found to better predict soil stability and permeability over a wide range of waste water compositions (Oster *et. al.*, 2016; Smith *et al.* 2015; Sposito *et al.* 2016). While this expression is valuable regardless of water quality, it was introduced to provide more confidence in potential soil structural problems when using waste waters that contained considerable quantities of K^+ and Mg^{2+}. The $CROSS_{opt}$ expression below is a modification of the SAR expression to include coefficients that were optimal using the soils tested by Smith *et al.* (2011).

$$CROSSopt = \frac{Na + 0.335K}{\sqrt{(Ca + 0.758Mg)}}$$

Note that K^+ is added to the numerator where it has about an additional 1/3 of the dispersive effects as Na^+. Similarly, the flocculating power of Mg^{2+} is diminished by over an order of magnitude relative to Ca^{2+}. The result is that CROSS > SAR for most irrigation waters. This more conservative CROSS expression can be substituted in Fig 3.1 to provide a better predictor of the effect of an irrigation water on soil structure and subsequent effect on water infiltration. This will improve the prediction regardless of the water composition and should be used for all irrigation waters.

It is important to note that while this expression is likely better that the SAR expression, factors such as soil texture, dissolved organic carbon (DOC), clay composition, pH, calcite, and Al and Fe oxide content affect soil response to sodic conditions, so there is still room for improving this expression (Sposito *et. al.*, 2016.)

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Box 3.2 (Cont.)

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CHAPTER 4

Effects of brackish water on crops

Unlike halophytes that thrive under highly saline conditions, most crop plants are glycophytes and are unable to tolerate stresses imposed by saline or saline–sodic conditions. Plant stress refers to a condition where the crop is unable to express its full potential for growth, development and reproduction (Läuchli & Grattan, 2012).

Salinity stress is not absolute. Rather, there is a continuum from the absence of stress to severe stress (Läuchli & Epstein, 1990). Individually, crop plants (as well as genotypes within a species) vary widely in their tolerance to saline conditions and as such have been placed into tolerant, moderately salt-tolerant, moderately salt-sensitive and sensitive categories (Ayers & Westcot, 1985; Grieve *et al.*, 2012; Maas & Hoffman, 1977) (see Chapter 5, Crop Salt Tolerance). Salt sensitivity of a given crop is the point at which the plant shows quantitative signs of being adversely affected (i.e. growth and yield reduction) or, in some cases, develops visual injury. This depends not only on the intensity of the salt stress but on the crop species in question, the chemical composition of the medium and other abiotic and biotic stresses that affect the plant, such as drought, temperature extremes, excessive flooding, poor soil physical conditions, nutrient deficiencies, pests and pathogens (Mittler, 2006). Thus, under field conditions, crops are affected to varying degrees by multiple stresses that collectively affect the crop through multiple interactions (Läuchli & Grattan, 2007). Therefore, reports on crop performance under field conditions in NENA countries can only be used as brackish water use success stories and should not be used as actual guidelines.

4.1. INTERACTIVE EFFECTS OF BRACKISH WATER ON CROPS

Brackish water can affect the crop in many ways, as illustrated in Figure 4.1. The effects of salinity on plants are due to two separate properties of saline media that can impact the crop individually but more often collectively. Salinity increases the electrical conductivity and thus reduces the osmotic potential of the soil solution (osmotic effect), and some ions in the solution may have specific ion effects. While salinity effects are, in most cases, injurious or growth-limiting, the far left and right text boxes in Figure 4.1 suggest that some effects of salinity on plants are not always detrimental and can, in fact, bring about plant growth and composition. For example, salinity can promote the growth of halophytes (Flowers *et al.*, 1977) or improve the quality of some crops, such as increased sugar content in carrots, increased soluble solids in tomatoes and melons, and improved grain quality in durum wheat (Maas & Grattan, 1999). Salinity has also been found to improve freezing tolerance of citrus (Syvertsen & Yelenosky, 1988). Despite these beneficial effects (see detailed discussion by Grieve *et al.*, 2012), they rarely counteract the detrimental effects of salinity. Overall, salt tolerance varies considerably among plants and is determined by three distinct components: 1) osmotic adjustment and tolerance, 2) the ability of the plant to exclude Na^+ or Cl^-, and 3) the ability of the tissue to tolerate high concentrations of Na^+ or Cl^- inside the cells (Munns & Tester, 2008).

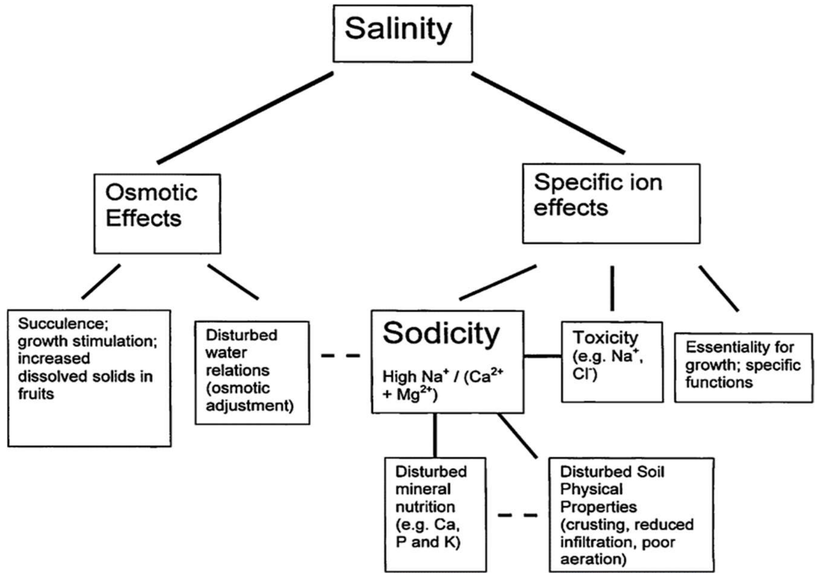


Figure 4.1. Schematic diagram of the various ways brackish water affects crops

***Source**: Läuchli, A. and S.R. Grattan. 2012. Plant responses to saline sodic conditions. In. (W.W. Wallender and K.K. Tanji, eds). Agricultural Salinity Assessment and Management (second edition). ASCE pp 169-205.*

An abrupt increase in the salt concentration of the soil solution outside the root reduces the difference in osmotic potential between inside and outside the root. This reduces the water availability to the plant, at least initially. The reduction in the osmotic potential of the medium is one of the primary causes of the adverse effects of salinity on plant growth (i.e. osmotic effects) (Maas & Nieman, 1978). According to Munns (2005), plants show a "two-phase growth response to salinity". The first phase of growth reduction is due to an osmotic effect which occurs rapidly, within minutes after exposure to salinity. The second phase is much slower, taking days, weeks or months, and is considered a specific ion effect which can result in salt toxicity that is expressed as injury or salt-burn to older leaves. The photo below illustrates both osmotic and specific ion effects on celery in a controlled sand tank study. With up to 8 dS/m in the soil water, growth is reduced by osmotic effects. At very high salinity (i.e. 12 dS/m), the plant suffers from both osmotic and specific ion toxicity.

Osmotic and specific ion effects on celery in a controlled sand tank study where added salinity (ECw) increases from 0 to 12 dS/m. Only at ECw 12 do both osmotic and specific ion toxicity contribute to growth reduction (L. Francois, US Salinity Laboratory. ©US Salinity Laboratory).

4.2. OSMOTIC EFFECTS

Osmotic effects occur because the concentration of salt in the soil solution, regardless of the type of salt, is excessive for crop growth. Thus, both fertilizer salts and table salt (NaCl) can suppress crop growth. Salts reduce the osmotic potential of the soil solution, which reduces water availability to the crop. To prevent this, the plant must adjust osmotically. That is, it must accumulate higher concentrations of solutes in its root cells so that the water potential difference between inside and outside the root cells is restored. Osmotic adjustment can be achieved by either the absorption of ions from the medium, or synthesis and/or accumulation of organic solutes within the cell. The synthesis of compatible organic solutes allows the plant to adjust osmotically and survive, but at the expense of plant growth (Munns & Tester, 2008; Yeo, 1983). The synthesis of organic solutes requires a considerable amount of metabolic energy (i.e. ATP) for cell maintenance and osmotic adjustment. This is energy that would otherwise be used for growth. As a result, salt-stressed plants are stunted, even though they may appear healthy in all other respects. Both processes of adjustment (accumulation of ions and synthesis of organic solutes) occur, but the extent to which one process predominates is dependent upon the type of plant and the level of salinity (Läuchli & Grattan, 2012). Within the cell, compartmentalisation is critical to keep toxic ions away from sensitive metabolic processes in the cytoplasm (Hasegawa *et al.*, 2000). Such compartimentalisation is controlled by transport processes within the plasma membrane and tonoplast (i.e. vacuolar membrane). The efficiency of the ion transport processes, as well as metabolic costs for organic–solute synthesis, differ from crop to crop and even within a species, giving rise to different tolerances to salinity. (For more detailed information, see Flowers *et al.* 1977, Greenway & Munns, 1980; Hasegawa *et al.*, 2000; Munns & Tester, 2008; Rhodes *et al.*, 2002; and Wyn Jones & Gorham, 1983.)

4.3. SPECIFIC ION EFFECTS

Specific ion effects may be categorized under three headings, as illustrated in Figure 4.1. First, high concentrations of a given ion may cause mineral–nutrition disorders in the crop. For example, high sodium concentrations may cause deficiencies of other elements, such as potassium or calcium. Second, certain ions, such as sodium or chloride, may have toxic effects when they accumulate in tissues to lethal levels. Third, there may be specific ion effects that promote the growth or qualitative features of the plant. This manual will address the first two effects.

4.3.1. Specific ion effects: nutritional

Salinity causes extreme ion ratios in the soil solution (e.g. Na^+/Ca^{2+}, Na^+/K^+ Cl^-/NO_3^-) and thus can induce nutritional imbalances in crops. But salinity-induced nutritional disorders can vary among species and even among varieties within a species. Nutrient imbalances in the plant may result from the effect of salinity on 1) nutrient availability, 2) the uptake and/or distribution of a nutrient within the plant, and/or 3) an increase in the internal plant requirement for a nutrient element resulting from physiological inactivation (Grattan & Grieve, 1999).

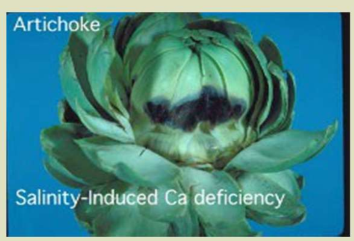
Nutrient uptake by crops is often reduced in saline environments, but this depends on the nutrient element in question and the composition and concentration of the salinizing solution (Grieve *et al.*, 2012). The activity of a nutrient element in the soil solution decreases as salinity increases, unless, of course, the nutrient in question is part of the salinizing salts (e.g. Ca^{2+}, Mg^{2+}, or SO_4^{2-}). For example, phosphate availability is typically reduced in saline soils by two processes: a reduction in the activity of phosphate in the solution and a reduction in concentration due to sorption processes and by precipitation of Ca-P minerals. As a result, phosphate uptake and accumulation in crops is reduced in most saline environments. Regardless of the effect of salinity on mineral nutrition, adding fertilizers to salt-stressed plants is not always beneficial (see Box 4.1).

Box 4.1 Fertilizing under saline conditions

Regardless of whether a field is salt-affected or not, soil fertility is important to optimize crop growth and yield. Many field studies have been conducted over the years focusing on whether the application of fertilizers increases the salt tolerance of the crop. However, many of these studies were conducted in soil conditions where both salinity and nutrient deficiency were limiting growth. Therefore, investigators found an increase in yield when the fertilizers were applied to these salt-affected lands. Basically, application of fertilizers does not improve salt tolerance, but it can increase productivity (Grattan & Grieve, 1999). The degree of positive response to fertilizer application depends upon which stress, salinity or nutrient deficiency, is more growth-limiting. Generally, growth will be promoted more if the most limiting factor is relieved, rather than the least limiting factor. There is little evidence that adding fertilizer to salt-affected soil, above the levels that would achieved optimal yields in non-saline conditions, benefits growth.

However, as mentioned previously, saline/sodic-induced calcium deficiencies have been found in field conditions. Calcium deficiency may appear as physiological disorders of young developing tissue enclosed with older leaves – such as “blackheart” in celery or internal browning of Brussels sprouts, cabbage and cauliflower. In artichoke, calcium deficiency appears in the inner bracts of the developing flower (see photo).

Therefore, maintaining an adequate supply of calcium to plants in saline/sodic environments helps minimize calcium disorders.



Sodium-induced calcium deficiency syndrome affecting the developing flower in artichoke grown in the desert using saline irrigation water. Photo courtesy of L. Francois, USDA/ARS Salinity Laboratory. ©US Salinity Laboratory

Reference:

Grattan, S.R. and C.M. Grieve. 1999. Mineral nutrient acquisition and response by plants grown in saline environments. In (M. Pessarakli, editor). Handbook of Plant and Crop Stress. Marcel Dekker, New York, Second edition Ch. 9, pp 203-230. https://doi.org/10.1201/9780824746728.ch9

Salinity can also cause some physiological inactivation of phosphate. Investigators found that when salt concentrations were increased, P concentration in the youngest mature tomato leaf, necessary to achieve 50 percent yield, almost doubled (Awad *et al.,* 1990). In addition, they found that at any given P concentration in leaves, foliar symptoms of P deficiency increased with increased NaCl salinity. This study suggests that salinity can increase the plant's internal requirement for phosphate.

"Nutrient uptake and accumulation by plants is often reduced under saline conditions by competitive processes between the nutrient and a major salt species. Although plants selectively absorb K^+ over Na^+, Na^+-induced K deficiencies can develop in crops under salinity stress by Na-salts" (Janzen & Chang, 1987). In addition, Cl^- salts have been found to reduce NO_3^- uptake and accumulation in crops, even though this effect may not be growth-limiting (Munns & Termaat, 1986). The opposite effect has also been found. Nitrate can reduce Cl^- uptake to the point where Cl^- toxicity is reduced in citrus and avocado (Bar *et al.*, 1997).

Economic losses of horticultural crops have been linked to inadequate calcium nutrition (Olle & Bender, 2009). Factors that affect the amount of plant-available calcium include:

1) The total supply of calcium, 2) the pH of the substrate, and 3) the ratio of calcium to other cations in the irrigation water (Grattan & Grieve, 1999). Calcium-related disorders may even occur in plants grown on substrates where the calcium concentration appears to be adequate. Deficiency symptoms are generally caused by differences in calcium partitioning to the growing regions of the plant. Because all plant organs (e.g. leaves, stems, flowers, fruits) actively compete for the pool of available calcium, each organ influences calcium movement independently. Organs that are most actively transpiring (i.e. leaves) are those most apt to have the highest calcium concentrations.

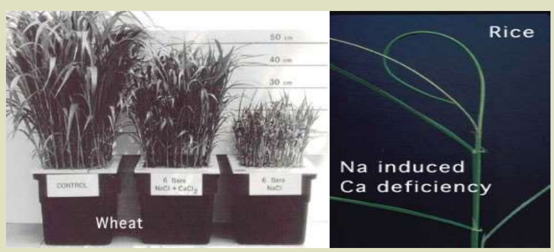
2) Conversely, those not actively transpiring (such as younger, developing tissue) have lower calcium concentrations (see Box 4.1). For example, calcium deficiency appears in younger tissues as internal browning in heads of cabbage and lettuce and blackheart in celery (Grieve et al., 2012). Calcium deficiency disorders also manifest in reproductive tissues, thereby reducing market quality (e.g. blossom-end rot in tomato, melon and pepper, "soft-nose" in mango and avocado, cracking and "bitter pit" in apple) (Grieve et al., 2012).

Sodium-induced calcium deficiencies have been observed in many crops within the grass family (e.g. corn, sorghum, rice, wheat and barley) where striking differences have been observed among species and cultivars (see Box 4.2). Calcium deficiency is related, to some extent, to the effect of sodium on calcium distribution within the plant. For example, Na^+ inhibits the radial movement of Ca^{2+} from the root epidermis to the root xylem vessels (Lynch & Läuchli, 1985), and high Na^+ affects Ca^{2+} transport to meristematic regions and developing leaves (Maas & Grieve, 1987; Grieve & Maas, 1988). Therefore, sodium, by some mechanism, reduces calcium's mobility in the plant.

Box 4.2 Cereal crops sensitive to sodium-induced calcium disorders

Studies conducted at the USDA/ARS Salinity Laboratory in Riverside, California have shown that many cereal crops (e.g. wheat, barley, rice and sorghum) are susceptible to sodium-induced calcium deficiency (Ehret *et al.*, 1990; Grieve & Fujiyama, 1987; Maas & Grieve, 1987). Calcium is a nutrient that is fairly immobile in plants and deficiency symptoms manifest themselves in the growing tips, affecting meristematic tissue. However, in saline-sodic environments (such as those salinized with $NaCl_2$ salts alone), the excess Na+ can immobilize Ca even more. The photos below show two such symptoms in wheat and rice. Both cereal crops were grown in controlled, salinized solution cultures, in modified half-strength nutrient solution. With regards to the wheat crop, the bucket in the center and the bucket on the right have equal salinities (6 bars OP or about 17 dS/m). The bucket in the center shows classical stunting due to salinity as the salts were composed of equal equivalents of NaCl and $CaCl_2$. The bucket on the far right was salinized with NaCl alone. Note that the growth suppression is due to the combined effects of osmotic growth reduction and sodium-induced calcium deficiency. The other photo shows the deformed growth of rice. Note that the young, emerging leaves take on a characteristic whip like appearance. It is also important to emphasize that the effect is cultivar-dependent. Some cultivars are much more susceptible to Na^{+}induced Ca^{2+}deficiency than others.

References:
Ehret, D.L., Redmann, R.E., Harvey, B.L. and A Cipywnyk. 1990. Salinity-induced calcium deficiencies in wheat and barley. Plant Soil 128:143-151. DOI: https://doi.org/10.1007/BF00011103
Grieve C M and Fujiyama H. 1987. The response of two rice cultivars to external Na/Ca ratio. Plant Soil 103:245–250. https://www.ars.usda.gov/arsuserfiles/20361500/pdf_pubs/P963.pdf
Maas E V and Grieve C M. 1987. Sodium-induced calcium deficiency in salt-stressed corn. Plant Cell Environ. 10:559–564. https://www.ars.usda.gov/arsuserfiles/20361500/pdf_pubs/P959.pdf



Sodium induced calcium deficiency in wheat (left) and rice (right) grown in solution cultures at the USDA/ARS Salinity Laboratory. The wheat is grown under non- saline control conditions and where the osmotic potential (OP) of the solution is 6 bars with either NaCl or combined NaCl and CaCl2. Photo courtesy of C. Grieve, US Salinity Laboratory. © US Salinity Laboratory.

4.3.2. Specific ion effects: toxicity

In addition to the effect of salinity on mineral nutrition, specific ions (i.e. Na^+, Cl^- and B) can cause direct injury to the crops, causing further crop damage. Typically, toxic ion effects are most commonly found on woody perennials, such as tree and vine crops, while most annual, row crops remain injury-free unless salinity stress is severe. Toxic ion effects are best illustrated by Bernstein (1965) in colour photographs of severe leaf injury symptoms due to sodium or chloride salts in several fruit and nut crops. These crops are long-lived and have little ability to eliminate sodium or chloride from their leaves; hence, they often suffer toxicities at even moderate soil salinities (see Photo).

Sodium and chloride toxicity on almond leaves

Photo by D. Doll, UC Davis, 2015. ©University of California

Chloride and sodium toxicity can damage the tree physically, biochemically and physiologically. As sodium and chloride move in the transpiration stream, they are deposited in the leaves. Older leaves have had more water transpire from them and, consequently, have higher concentrations of chloride and sodium. Once accumulated in the leaf, Na^+ and Cl^- typically do not remobilize to other tissues. As the concentration in the leaf increases, the salts can physically desiccate cells causing injury in the form of leaf burn.

Necrotic leaves no longer photosynthesize and produce carbohydrates for the tree, which impacts growth and production. However, even before salts accumulate in leaves at levels that cause physical injury, the salts can reduce the chlorophyll content in leaves (Dejampour *et al.*, 2012) and interfere with enzymatic activities, affecting key metabolic pathways in both respiration and photosynthesis (Greenway & Osmond, 1972; Munns & Tester, 2008).

Although not a main salinizing constituent in irrigation water, boron can also injure the crop. The effects of sodium, chloride and boron are detailed below.

4.3.2.1. Sodium

Sodium can have both direct and indirect detrimental effects on plants. Direct effects are caused by the accumulation of toxic levels of Na^+ in the leaves of woody species (i.e. tree crops and vines). The ability of a plant to tolerate excessive amounts of Na^+ varies widely among species and rootstocks. Na^+ injury on avocado, citrus, stone-fruit and some nut crops is rather widespread but can occur at Na^+ concentrations as low as 5 mmol/l (115 mg/l) in soil water (Maas & Grattan, 1999). However, injury may not develop until years after the trees have been exposed to brackish water. Initially, Na^+ is retained in the roots and lower trunk, but after several years the Na^+ entrapped in the sapwood is apparently released to the shoot after it converts to heartwood. Once the Na^+ is in the transpiration stream, it can accumulate in leaves, causing burn (see Figure 4.2).

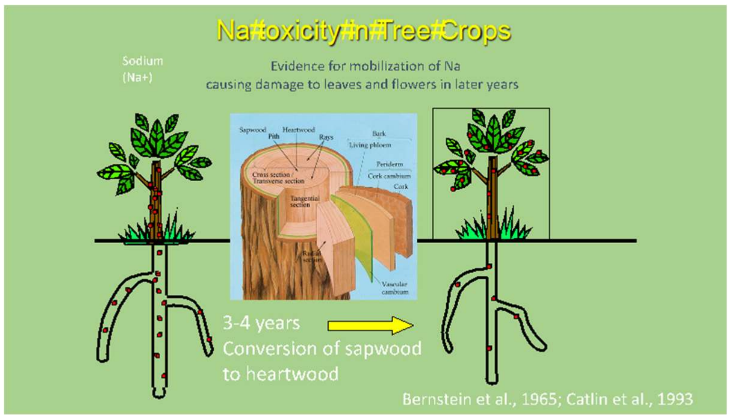


Figure 4.2. Representation of Na^+ accumulation in sapwood and its release to scion after it is converted to heartwood.

Sources:

- *Bernstein, L. 1965. Salt tolerance of fruit crops. United States Department of Agriculture, Agriculture Information Bulletin No. 292.*
- *Catlin, P.B., G.J. Hoffman, R.M. Mead and R.S. Johnson. 1993. Long-term response to mature plum trees to salinity. Irrigation Science 13:171-176.*

The rootstock plays an important role in Na^+ tolerance and sensitivity as well. Some rootstocks are better able to retain Na^+ in the roots, trunks and branches than others, allowing greater tolerance (Brown *et al.*, 2015). In non-saline, sodic conditions where soluble Ca^{2+} is inadequate, Na^+ toxicity would likely occur earlier.

In most annual and row crops, sodium toxicity *per se* is rarely observed. This of course implies that the soil solution has an adequate supply of soluble Ca^{2+}. Adequate Ca^{2+} stabilizes root membranes allowing them to retain their integrity and selectivity (Läuchli & Epstein, 1990). Since Na^+ uptake by plants is strongly regulated by Ca^{2+} in the soil solution, the presence of sufficient Ca^{2+} is essential to prevent the accumulation of Na^+ to toxic levels. For annual crops, the plants are grown and harvested before any Na^+ toxicity can play a significant role, unlike perennial treecrops.

As discussed previously, the indirect effects of Na^+ include both nutritional imbalance and the deterioration of soil physical conditions (Grieve *et al.*, 2012). The nutritional effects of Na^+ are not simply related to the SAR or the exchangeable Na^+ percentage of soils, but depend upon the concentrations of Na^+, Ca^{2+}, and Mg^{2+} in the soil solution. In non-saline, sodic soils, total soluble salt concentrations are low. Consequently, Ca^{2+} and/or Mg^{2+} concentrations can be inadequate, causing poor plant growth. As a general guide, Ca^{2+} and Mg^{2+} concentrations in the soil solution above 1 mmol/l each are nutritionally adequate in most non-saline, sodic soils (Carter *et al.* 1979; Hanson, 1983).

Sodicity indirectly affects almost all crops because the deterioration of soil aggregates affects the overall soil structure (see Chapter 3). Dispersion of aggregates affects pore size distribution in soils, thereby reducing the water infiltration rate and aeration, which negatively affect plant growth. Additionally, poorly structured soils are prone to waterlogging, which promotes root disease. Therefore, yield reductions in crops in sodic soils, that are not specifically sensitive to Na^+, generally reflect both nutritional- imbalance problems and stresses associated with poor soil conditions.

4.3.2.2. Chloride

Like Na^+, most annual, non-woody crops are not specifically sensitive to Cl^- even at higher concentrations (Grieve *et al.*, 2012). However, most woody species, as well as strawberry, bean and onion, are susceptible to Cl^- toxicity, but such sensitivities are largely variety- and rootstock-dependent. Chloride ions move readily with soil water, are taken up by the crop via the roots, and then move within the transpiration stream where they accumulate in leaves. And like Na^+, susceptibility to Cl^- toxicity is dependent upon the plant's ability to restrict Cl^- translocation from roots to the scion. In studies conducted over a half-century ago with avocado, grapefruit and orange, investigators found that salt tolerance of those trees is closely related to the Cl^- accumulation properties of the rootstocks (Cooper, 1951 & 1961). Large differences in the salt tolerance of grape varieties have also been linked to the Cl^- accumulating characteristics of different rootstocks (Bernstein *et al.*, 1969; Ehlig, 1960; Groot Obink & Alexander, 1973; Sauer, 1968). Similar effects of rootstocks on salt accumulation and tolerance have been reported for stone-fruit (Bernstein *et al.*, 1956) and pistachio (Ferguson *et al.*, 2002c). Recent research has shown that almonds grafted on Nemaguard rootstock are very sensitive to both chloride and sodium toxicity while those grafted on Hansen are considerably more tolerant (Brown *et al.*, 2015). Research findings also show that almonds on peach-almond rootstocks were generally more tolerant than those on peach rootstocks because they restricted the uptake and translocation of these toxic ions to the scion. By selecting rootstocks that restrict Cl^- from the scions, Cl^- toxicity can be avoided or at least delayed.

The maximum Cl^- concentrations permissible in soil water that do not cause leaf injury in selected fruit-crop cultivars and rootstocks have been reported elsewhere (Grieve *et al.*, 2012) and are included here in Table 4.1. While the list includes only some crops and rootstocks, it is still a valuable guide since it provides concentration ranges that are problematic to common trees and vines. Note that Cl^- sensitivity, the maximum concentration of Cl^- in the soil water above which injury occurs, covers an eightfold concentration range (from 10 to 80 mmol/l).

Table 4.1. Chloride-tolerance limits of some fruit-crop rootstocks and cultivars. Adapted from Grieve *et al.*, 2012.

Maximum permissible Cl- in soil water without leaf injury†		
Crop	Rootstock or cultivar	(mmol/l)
Cultivars		
Avocado (Persea americana)	West Indian Guatemalan Mexican	15 12 10
Citrus (Citrus sp.)	Sunki mandarin, grapefruit Cleopatra mandarin, Rangpur lime Sampson tangelo, rough lemon sour orange, Ponkan mandarin Citrumelo 4475, trifoliate orange Cuban shaddock, calamondin sweet orange, Savage citrange Rusk citrange, Troyercitrange	50 50 30 30 20 20 20 20
Grape (Vitis sp.)	Salt Creek, 1613-3 Dog ridge	80 60
Cultivars		
Berries ‡ (Rubus sp.)	boysenberry Olallie blackberry Indian Summer raspberry	20 20 10
Grape (Vitis sp.)	Thompson seedless, Perlette Cardinal, black rose	40 20
Strawberry (Fragaria sp.)	Lassen Shasta	15 10

† For some crops, these concentrations may exceed the osmotic threshold and cause some yield reduction.
‡ Data available for one variety of each species only.

Source: Grieve, C.M., S.R. Grattan and E.V. Maas. 2012. Plant salt tolerance. In. (W.W. Wallender and K.K. Tanji, eds). Agricultural Salinity Assessment and Management (second edition). ASCE pp 405-459.

While the rootstock mainly controls the tolerance of crops to ion toxicity, research has shown that the scion (the variety grafted on the rootstock) can also have a significant role in reducing or increasing the rate of ion accumulation (Brown *et al.*, 2015; Grattan, unpublished data, 2017).

4.3.2.3. Boron

Boron (B) is an essential micronutrient for plants, but the concentration range of plant available-B in the soil solution that is optimal for growth for most crops is very narrow. Toxicity occurs above this narrow range. Criteria have been proposed to define levels that are potentially toxic and those necessary for adequate B nutrition yet low enough to avoid B toxicity symptoms, plant injury and subsequent yield reduction (Ayers & Westcot, 1985; Grieve *et al.,* 2012; Gupta *et al.*,1985; Keren & Bingham, 1985).

Boron toxicity, including how and where it is expressed in the plant, is related to the mobility of boron in the plant. Boron is thought to be immobile in most species where it accumulates within the margins and tips of the oldest leaves, where injury occurs. However, boron can be re-mobilized by some species due to high concentrations of sugar alcohols (polyols) where they bind with boron and can carry it to younger tissue (Brown & Shelp, 1997). These boron-mobile plants include almond, apple, grape and most stone fruits. For these crops, boron concentrations are higher in younger tissue than in older tissue and injury is expressed in the young, developing tissue as twig dieback, gum exudation and reduced bud formation. Boron immobile plants, such as pistachio, tomato, walnut, and fig, do not have high concentrations of polyols and boron concentrates in the margins of older leaf tissue (see Photo). Injury in these crops is expressed as the classical necrosis on leaf tips and margins.

Boron injury on the margins of Kerman pistachio leaves
(B-immobile species)

Photo by S.R. Grattan, UC Davis. ©University of California

Many of the guidelines that were developed that identify boron sufficient and excessive ranges for crops are based on data from experiments conducted during 1930-34 by Eaton (1944). While useful, this experimental data cannot be used to develop any reliable growth response function with increasing solution boron. Nevertheless, his results provide the majority of the threshold limits above which injury occurs (see Table 4.2). In several cases, plant response to excess B was fitted to the two-piece linear response model that was used for crop salt tolerance (see Crop Salt Tolerance section and Grieve *et al.*, 2012). Therefore, Table 4.2 does provide the threshold and slope parameters for these limited crops where the threshold is the maximum concentration in soil water before yields are reduced (see Chapter 5, 'Crop Salt Tolerance').

Like salt tolerance, B tolerance varies with climate, soil conditions and crop cultivars. Therefore, the data presented in Table 4.2 may not apply to all cultural conditions.

Table 4.2. Boron tolerance limits for agricultural crops. Threshold based on boron concentration in soil water. Adapted from Grieve *et al.*, 2012.

Crop			Boron tolerance parameters		
Common name	Botanical name	Tolerance based on:	Threshold† (mg/l)	Slope % per mg/l	Rating‡
Alfalfa	*Medicago sativa* L.	Shoot(DW) Dry weight	4.0-6.0		T
Apricot	*Prunus armeniaca* L.	Leaf & stem injury	0.5-0.75		S
Artichoke, globe	*Cynara scolymus* L.	Laminae DW	2.0-4.0		MT
Artichoke, Jerusalem	*Helianthus tuberosus* L.	Whole plant DW	0.75-1.0		S
Asparagus	*Asparagus officinalis* L.	Shoot DW	10.0-15.0		VT
Avocado	*Persea americana* Mill.	Foliar injury	0.5-0.75		S
Barley	*Hordeum vulgare* L.	Grain yield	3.4	4.4	MT
Bean, kidney	*Phaseolus vulgaris* L.	Whole plant DW	0.75-1.0		S
Bean, lima	*Phaseolus lunatus* L.	Whole plant DW	0.75-1.0		S
Bean, mung	*Vigna radiata* (L.) R. Wilcz.	Shoot length	0.75-1.0		S
Bean, snap	*Phaseolus vulgaris* L.	Pod yield	1.0	12	S
Beet, red	*Beta vulgaris* L.	Root DW	4.0-6.0		T
Blackberry	*Rubus sp.* L.	Whole plant DW	< 0.5		VS
Bluegrass, Kentucky	*Poa pratensis* L.	Leaf DW	2.0-4.0		MT

Broccoli	*Brassica oleracea* L. (Botrytis group).	Head (FW) Fresh weight	1.0	1.8	MS
Cabbage	*Brassica oleracea* L. (capitata group)	Whole plant DW	2.0-4.0		MT
Carrot	*Daucus carota* L.	Root DW	1.0-2.0		MS
Cauliflower	*Brassica oleracea* L. (Botrytis group)	Curd FW	4.0	1.9	MT
Celery	*Apium graveolens* L. var. *dulce* (Mill.) Pers.	Petiole FW	9.8	3.2	VT
Cherry	*Prunus avium* L.	Whole plant DW	0.5-0.75		S
Clover, sweet	*Melilotus indica* All.	Whole plant DW	2.0-4.0		MT
Corn	*Zea mays* L.	Shoot DW	2.0-4.0		MT
Cotton	*Gossypium hirsutum* L.	Boll DW	6.0-10.0		VT
Cowpea	*Vigna unguiculata* (L.) Walp.	Seed yield	2.5	12	MT
Cucumber	*Cucumis sativus* L.	Shoot DW	1.0-2.0		MS
Fig, kadota	*Ficus carica* L.	Whole plant DW	0.5-0.75		S
Garlic	*Allium sativum* L.	Bulb yield	4.3	2.7	T
Grape	*Vitis vinifera* L.	Whole plant DW	0.5-0.75		S
Grapefruit	*Citrus x paradisi* Macfady.	Foliar injury	0.5-0.75		S
Lemon	*Citrus limon* (L.) Burm. f.	Foliar injury, Plant DW	< 0.5		VS
Lettuce	*Lactuca sativa* L.	Head FW	1.3	1.7	MS
Lupine	*Lupinus hartwegii* Lindl.	Whole plant DW	0.75-1.0		S
Muskmelon	*Cucumis melo* L. (Reticulatus group)	Shoot DW	2.0-4.0		MT
Mustard	*Brassica juncea* Coss.	Whole plant DW	2.0-4.0		MT
Oats	*Avena sativa* L.	Grain (immature) DW	2.0-4.0		MT
Onion	*Allium cepa* L.	Bulb yield	8.9	1.9	VT
Orange	*Citrus sinensis* (L.) Osbeck	Foliar injury	0.5-0.75		S

Parsley	*Petroselinum crispum* Nym.	Whole plant DW	4.0-6.0		T
Pea	*Pisum sativa* L.	Whole plant DW	1.0-2.0		MS
Peach	*Prunus persica* (L.) Batsch.	Whole plant DW	0.5-0.75		S
Peanut	*Arachis hypogaea* L.	Seed yield	0.75-1.0		S
Pecan	*Carya illinoinensis* (Wangenh.) C. Koch	Foliar injury	0.5-0.75		S
Pepper, red	*Capsicum annuum* L.	Fruit yield	1.0-2.0		MS
Persimmon	*Diospyros kaki* L. f.	Whole plant DW	0.5-0.75		S
Plum	*Prunus domestica* L.	Leaf & stem injury	0.5-0.75		S
Potato	*Solanum tuberosum* L.	Tuber DW	1.0-2.0		MS
Radish	*Raphanus sativus* L.	Root FW	1.0	1.4	MS
Sesame	*Sesamum indicum* L.	Foliar injury	0.75-1.0		S
Sorghum	*Sorghum bicolor* (L.) Moench	Grain yield	7.4	4.7	VT
Squash, scallop	*Cucurbita pepo* L. var *melopepo* (L.) Alef.	Fruit yield	4.9	9.8	T
Squash, winter	*Cucurbita moschata* Poir	Fruit yield	1.0	4.3	MS
Squash, zucchini	*Cucurbita pepo* L. var *melopepo* (L.) Alef.	Fruit yield	2.7	5.2	MT
Strawberry	*Fragaria sp.* L.	Whole plant DW	0.75-1.0		S
Sugar beet	*Beta vulgaris* L.	Storage root FW	4.9	4.1	T
Sunflower	*Helianthus annuus* L.	Seed yield	0.75-1.0		S
Sweet potato	*Ipomoea batatas* (L.) Lam.	Root DW	0.75-1.0		S
Tobacco	*Nicotiana tabacum* L.	Laminae DW	2.0-4.0		MT
Tomato	*Lycopersicon lycopersicum* (L.) Karst. ex Farw.	Fruit yield	5.7	3.4	T
Turnip	*Brassica rapa* L. (Rapifera group)	Root DW	2.0-4.0		MT

Vetch, purple	*Vicia benghalensis* L.	Whole plant DW	4.0-6.0		T
Walnut	*Juglans regia* L.	Foliar injury	0.5-0.75		S
Wheat	*Triticum aestivum* L.	Grain yield	0.75-1.0	3.3	S

†Maximum permissible concentration in soil water without yield reduction. Boron tolerances may vary depending upon climate, soil conditions and crop varieties.

‡The B tolerance ratings are based on the following threshold concentration ranges: < 0.5 mg/l very sensitive (VS), 0.5-1.0 sensitive (S), 1.0-2.0 moderately sensitive (MS), 2.0-4.0 moderately tolerant (MT), 4.0-6.0 tolerant (T), and > 6.0 very tolerant (VT).

Source: Grieve, C.M., S.R. Grattan and E.V. Maas. 2012. Plant salt tolerance. In. (W.W. Wallender and K.K. Tanji, eds). Agricultural Salinity Assessment and Management (second edition). ASCE pp 405-459.

Different rootstocks of citrus and stone fruits absorb B at different rates, so that tolerance will likely be improved by using rootstocks that restrict B uptake. A number of these rootstocks are listed in Table 4.3, in order of increasing B accumulation.

Table 4.3. Citrus and stone-fruit rootstocks ranked in order of increasing boron accumulation and transport to scions. Adapted from Grieve *et al.*, 2012.

COMMON NAME	BOTANICAL NAME
Citrus	
Alemow	Citrus macrophylla
Gajanimma	C. pennivesiculata or C. moi
Chinese box orange	Severina buxifolia
Sour orange	C. aurantium
Calamondin	x Citrofortunella mitis
Sweet orange	C. sinensis
Yuzu	C. junos
Rough lemon	C. limon
Grapefruit	C. x paradisi

Rangpur lime	C. x limonia
Troyer citrange	x Citroncirus webberi
Savage citrange	x Citroncirus webberi
Cleopatra mandarin	C. areticulata
Rusk citrange	x Citroncirus webberi
Sunki mandarin	C. reticulata
Sweet lemon	C. limon
Trifoliate orange	Poncirus trifoliata
Citrumelo 4475	P. trifoliata x C. paradisi
Ponkan mandarin	C. reticulata
Sampson tangelo	C. x Tangelo
Cuban shaddock	C. maxima
Sweet lime	C. aurantiifolia
Stone fruit	
Almond	Prunus duclis
Myrobalan plum	P. cerasifera
Apricot	P. armeniaca
Marianna plum	P. domestica
Shalil peach	P. persica

Source: Grieve, C.M., S.R. Grattan and E.V. Maas. 2012. Plant salt tolerance. In. (W.W. Wallender and K.K. Tanji, eds). Agricultural Salinity Assessment and Management (second edition). ASCE pp 405-459.

4.4. HALOPHYTIC PLANTS

Halophytes are plants that thrive in saline environments. In fact, unlike glycophytes, which include the vast majority of crop plants, the growth of halophytes is typically stimulated with increased salt concentration (Flowers *et al.*, 1977). These plants have a remarkable ability to utilize salt as an osmoticum to osmotically adjust the high salinity in the soil water.

Salts can readily be absorbed and partitioned inside the vacuole and away from salt-sensitive metabolic pathways that take place in the cytoplasm. Using salt as an osmoticum is energetically cheaper than synthesizing organics (Yeo, 1983).

Not only do halophytes have the ability to partition salt into vacuoles as a mechanism for tolerating salinity, many halophytes have specialized features such as salt glands or bladders that can excrete salt (i.e. NaCl) directly outside the plant.

CHAPTER 5

Crop salt tolerance and crop selection

Crop salt tolerance is based on the crop's ability to maintain yield with increased salinity. As indicated in the previous chapter, the most common whole-plant response to salt stress is a general stunting of growth (an osmotic effect). As salt concentration in the root zone increases above the threshold level, both the growth rate and ultimate yield of the crop progressively decrease. However, the threshold and the rate of growth reduction vary widely among different crop species.

5.1. SOIL SALINITY–YIELD RESPONSE FUNCTIONS

The salt tolerance of crops can be described as a function of yield decline across a range of salt concentrations (Maas & Hoffman, 1977; Grieve *et al.*, 2012). Salt tolerance can be adequately measured on the basis of two parameters: 1) a threshold parameter, which is the maximum root zone salinity (described as electrical conductivity of the saturated soil extract – ECe) that the crop can tolerate above which yields decline, and 2) the slope, which describes the rate by which yields decline with increased soil salinity beyond the threshold (Figure 5.1). Slope is simply the percentage of expected yield reduction per unit increase in salinity above the threshold value.

For soil salinities exceeding the threshold of any given crop, relative yield (Yr) or yield potential can be estimated using the following expression:

$$Yield\ (\text{percent}) = 100 - s(ECe - t)$$

Equation *5.1*

Where t equals the soil salinity threshold value expressed in dS/m; s equals the slope expressed in percent yield decline per dS/m; and ECe equals the average root zone salinity of the saturated soil extract. The most up-to-date listing of specific values for t and s, called "salinity coefficients", are found in a book chapter by Grieve *et al.* (2012), reprinted here in tables 5.1 and 5.2. The greater the threshold value and the lower the slope, the greater the salt tolerance.

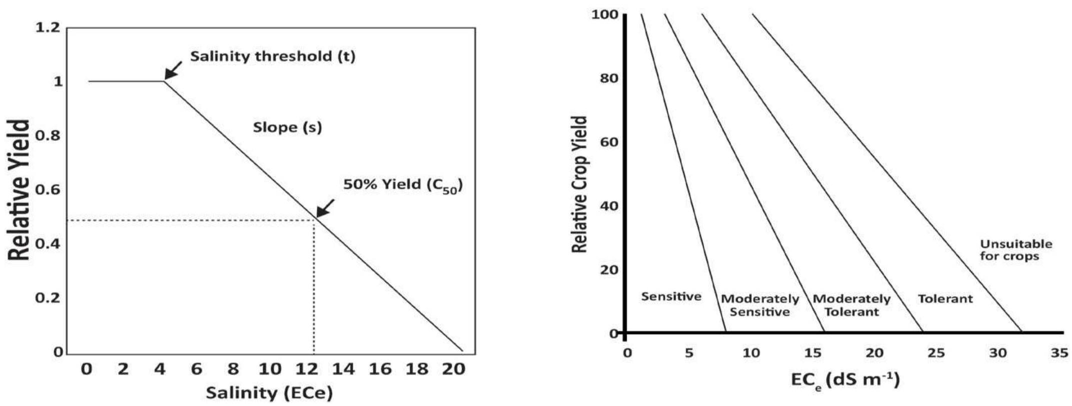


Figure 5.1. Salt tolerance parameters salinity threshold (t) and slope of yield decline (s) for salinity that exceeds the threshold (left) and salt tolerance categories first described by Maas and Hoffman, 1977 (right). (Figures adapted from Shannon & Grieve, 1998)

Source*: Shannon, M.C. and Grieve, C.M. (1998). Tolerance of vegetable crops to salinity. Horticulture 78 (1-4):5-38.*

It is important to understand that there is uncertainty regarding the yield-threshold (t) soil-salinity values and that such threshold values, for the most part, lack physiological justification. In fact, over the past few decades, scientists have developed non-linear expressions that fit the data better and are more scientifically justified. The salinity coefficients (yield threshold [t] and slope values [s]) for the slope-threshold model of the Maas-Hoffman expression (equation 5.1) are determined by non-linear least-squares statistical fitting that determines the slope and threshold values from a particular set of experimental data. Despite investigators controlling salinity and minimizing all other stresses that would affect plant yield in salt tolerance studies, the standard errors associated with the threshold values can be 50 to well over 100 percent (Grieve *et al.*, 2012). Obviously, these are very large percentages of uncertainty and suggest that actual threshold values do not exist (Steppuhn *et al.*, 2004 a, b). Rather, yields of salt- sensitive crops decrease with increased salinity in a non-linear relationship such as that proposed by van Genuchten and Gupta (1993) or by Steppuhn *et al.*, (2004 a, b). The non-linear expression can be seen in Figure 5.2 and is described as follows, where, Yr is relative yield, p is an empirical shape parameter, EC is soil salinity and EC_{50} is the soil salinity where 50 percent yield is predicted:

$$Yr = 1 / [1 + (EC/EC_{50})^p] \qquad \textbf{Equation 5.2}$$

These investigators found that while the curvilinear model fits the salt-tolerance data better than the Maas-Hoffman piecewise model, both fit the data very well.

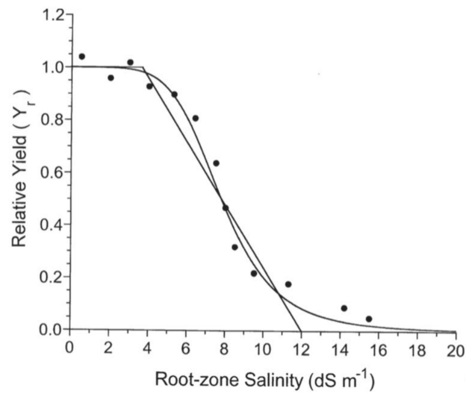


Figure 5.2. Typical non-linear response curve superimposed on the Maas-Hoffman slope-threshold model

Source: Steppuhn, H., M.Th. van Genuchten, and C.M. Grieve. 2004b. Root-zone salinity: II. Indices for tolerance in agricultural crops. Crop Sci. 45:221-232.

In some cases, the response function indicates that yields of salt-tolerant crops may in fact increase slightly with mild increases in salinity and then decrease at higher levels. Despite the slightly better data fit with non-linear expressions, as compared to the Maas- Hoffman threshold and slope model, all expressions fit the data very well and there is little benefit to using non-linear expressions for developing salinity guidelines.

Table 5.1. List of herbaceous crops and corresponding salt tolerance ranking, and salinity coefficients for threshold and slope that can be used to estimate yield potential given average root zone salinity (ECe). Adapted from Grieve *et al.*, 2012.

Crop		Tolerance based on:	Salt tolerance parameters		
Common name	Botanical name‡		Threshold§ (EC_e)dS/m	Slope % per dS/m	Rating¶
Fibre, grain and special crops					
Artichoke, Jerusalem	*Helianthus tuberosus L.*	Tuber yield	0.4	9.6	MS
Barley#	*Hordeum vulgare L.*	Grain yield	8.0	5.0	T
Canola or rapeseed	*Brassica campestris L. [syn. B. rapa L.]*	Seed yield	9.7	14	T
Canola or rapeseed	*B. napus L.*	Seed yield	11.0	13	T
Chickpea	*Cicer arietinum L.*	Seed yield	--	--	MS
Corn‡‡	*Zea mays L.*	Ear FW	1.7	12	MS
Cotton	*Gossypium hirsutum L.*	Seed cotton yield	7.7	5.2	T
Crambe	*Crambe abyssinica Hochst. ex R.E. Fries*	Seed yield	2.0	6.5	MS

Flax	*Linum usitatissimum L.*	Seed yield	1.7	12	MS
Guar	*Cyamopsis tetragonoloba (L). Taub.*	Seed yield	8.8	17	T
Kenaf	*Hibiscus cannabinus L.*	Stem DW	8.1	11.6	T
Lesquerella	*Lesquerella fenderli (Gray) S. Wats.*	Seed yield	6.1	19	MT
Millet, channel	*Echinochloa turnerana (Domin) J.M. Black*	Grain yield	--	--	T
Oats	*Avena sativa L.*	Grain yield	--	--	T
Peanut	*Arachis hypogaea L.*	Seed yield	3.2	29	MS
Rice, paddy	*Oryza sativa L.*	Grain yield	3.0[§§]	12[§§]	S
Roselle	*Hibiscus sabdariffa L.*	Stem DW	--	--	MT
Rye	*Secale cereale L.*	Grain yield	11.4	10.8	T
Safflower	*Carthamus tinctorius L.*	Seed yield	--	--	MT
Sesame[¶¶]	*Sesamum indicum L.*	Pod DW	--	--	S
Sorghum	*Sorghum bicolor (L.) Moench*	Grain yield	6.8	16	MT
Soybean	*Glycine max (L.) Merrrill*	Seed yield	5.0	20	MT
Sugar beet[##]	*Beta vulgaris L.*	Storage root	7.0	5.9	T
Sugarcane	*Saccharum officinarum L.*	Shoot DW	1.7	5.9	MS
Sunflower	*Helianthus annuus L.*	Seed yield	4.8	5.0	MT
Triticale	*X Triticosecale Wittmack*	Grain yield	6.1	2.5	T
Wheat	*Triticum aestivum L.*	Grain yield	6.0	7.1	MT
Wheat (semi-dwarf)[†††]	*T. aestivum L.*	Grain yield	8.6	3.0	T
Wheat, durum	*T. turgidum L. var. durum Desf.*	Grain yield	5.9	3.8	T
Grasses and forage crops					
Alfalfa	*Medicago sativa L.*	Shoot DW	2.0	7.3	MS
Alkaligrass, Nuttall's	*Puccinellia airoides (Nutt.) Wats. & Coult.*	Shoot DW	--	--	T*
Alkali sacaton	*Sporobolus airoides Torr.*	Shoot DW	--	--	T*
Barley (forage)[#]	*Hordeum vulgare L.*	Shoot DW	6.0	7.1	MT
Bentgrass, creeping	*Agrostis stolonifera L.*	Shoot DW	--	--	MS
Bermuda grass[‡‡‡]	*Cynodon dactylon (L.) Pers.*	Shoot DW	6.9	6.4	T

Bluestem, Angleton	*Dichanthium aristatum (Poir.) C.E. Hubb. [syn. Andropogon nodosus (Willem.) Nash]*	Shoot DW	--	--	MS*
Broad bean	*Vicia faba L.*	Shoot DW	1.6	9.6	MS
Brome, mountain	*Bromus marginatus Nees ex Steud.*	Shoot DW	--	--	MT*
Brome, smooth	*B. inermis Leyss*	Shoot DW	--	--	MT
Buffelgrass	*Pennisetum ciliare (L). Link. [syn. Cenchrus ciliaris]*	Shoot DW	--	--	MS*
Burnet	*Poterium sanguisorba L.*	Shoot DW	--	--	MS*
Canary grass, reed	*Phalaris arundinacea L.*	Shoot DW	--	--	MT
Clover, alsike	*Trifolium hybridum L.*	Shoot DW	1.5	12	MS
Clover, berseem	*T. alexandrinum L.*	Shoot DW	1.5	5.7	MS
Clover, hubam	*Melilotus alba Dest. var. annua H.S.Coe*	Shoot DW	--	--	MT*
Clover, ladino	*Trifolium repens L.*	Shoot DW	1.5	12	MS
Clover, Persian	*T. resupinatum L.*	Shoot DW	--	--	MS*
Clover, red	*T. pratense L.*	Shoot DW	1.5	12	MS
Clover, strawberry	*T. fragiferum L.*	Shoot DW	1.5	12	MS
Clover, sweet	*Melilotus sp. Mill.*	Shoot DW	--	--	MT*
Clover, white Dutch	*Trifolium repens L.*	Shoot DW	--	--	MS*
Corn (forage)[††]	*Zea mays L.*	Shoot DW	1.8	7.4	MS
Cowpea (forage)	*Vigna unguiculata (L.) Walp.*	Shoot DW	2.5	11	MS
Dallisgrass	*Paspalum dilatatum Poir.*	Shoot DW	--	--	MS*
Dhaincha	*Sesbania bispinosa (Linn.) W.F. Wight [syn. Sesbania aculeata (Willd.) Poir]*	Shoot DW	--	--	MT
Fescue, tall	*Festuca elatior L.*	Shoot DW	3.9	5.3	MT
Fescue, meadow	*Festuca pratensis Huds.*	Shoot DW	--	--	MT*
Foxtail, meadow	*Alopecurus pratensis L.*	Shoot DW	1.5	9.6	MS
Glycine	*Neonotonia wightii [syn. Glycine wightii or javanica]*	Shoot DW	--	--	MS
Gram, black or urd bean	*Vigna mungo (L.) Hepper [syn.Phaseolus mungo L.]*	Shoot DW	--	--	S

Grama, blue	*Bouteloua gracilis (HBK) Lag. ex Steud.*	Shoot DW	--	--	MS*
Guinea grass	*Panicum maximum Jacq.*	Shoot DW	--	--	MT
Harding grass	*Phalaris tuberosa L. var. stenoptera (Hack) A. S. Hitchc.*	Shoot DW	4.6	7.6	MT
Kallar grass	*Leptochloa fusca (L.) Kunth [syn. Diplachne fusca Beauv.]*	Shoot DW	--	--	T
Kikuyu grass	*Pennisetum clandestinum L.*	Shoot DW	8.0	--	T
Lablab bean	*Lablab purpureus (L.) Sweet [syn. Dolichos lablab L.]*	Shoot DW	--	--	MS
Love grass[§§§]	*Eragrostis sp. N. M. Wolf*	Shoot DW	2.0	8.4	MS
Milkvetch, cicer	*Astragalus cicer L.*	Shoot DW	--	--	MS*
Millet, foxtail	*Setaria italica (L.) Beauvois*	Dry matter	--	--	MS
Oat grass, tall	*Arrhenatherum elatius (L.) Beauvois ex J. Presl & K. Presl*	Shoot DW	--	--	MS*
Oats (forage)	*Avena sativa L.*	Straw DW	--	--	T
Orchard grass	*Dactylis glomerata L.*	Shoot DW	1.5	6.2	MS
Panicgrass, blue	*Panicum antidotale Retz.*	Shoot DW	--	--	MS*
Pigeon pea	*Cajanus cajan (L.) Huth [syn. C. indicus (K.) Spreng.]*	Shoot DW	--	--	S
Rape (forage)	*Brassica napus L.*	--	--	--	MT*
Rescue grass	*Bromus unioloides HBK*	Shoot DW	--	--	MT*
Rhodes grass	*Chloris Gayana Kunth.*	Shoot DW	--	--	MT
Rye (forage)	*Secale cereale L.*	Shoot DW	7.6	4.9	T
Ryegrass, Italian	*Lolium multiflorum Lam.*	Shoot DW	--	--	MT*
Ryegrass, perennial	*Lolium perenne L.*	Shoot DW	5.6	7.6	MT
Ryegrass, Wimmera	*L. rigidum Gaud.*	--	--	--	MT*
Saltgrass, desert	*Distichlis spicta L. var. stricta (Torr.) Bettle*	Shoot DW	--	--	T*
Sesbania	*Sesbania exaltata (Raf.) V.L. Cory*	Shoot DW	2.3	7.0	MS
Siratro	*Macroptilium atropurpureum (DC.) Urb.*	Shoot DW	--	--	MS

Sphaerophysa	*Sphaerophysa salsula (Pall.) DC*	Shoot DW	2.2	7.0	MS
Sudan grass	*Sorghum sudanense (Piper) Stapf*	Shoot DW	2.8	4.3	MT
Timothy	*Phleum pratense L.*	Shoot DW	--	--	MS*
Trefoil, big	*Lotus pedunculatus Cav.*	Shoot DW	2.3	19	MS
Trefoil, narrowleaf birdsfoot	*L. corniculatus var tenuifolium L.*	Shoot DW	5.0	10	MT
Trefoil, broadleaf birdsfoot	*L. corniculatus L. var arvenis (Schkuhr) Ser. ex DC*	Shoot DW	--	--	MS
Vetch, common	*Vicia angustifolia L.*	Shoot DW	3.0	11	MS
Wheat (forage)[†††]	*Triticum aestivum L.*	Shoot DW	4.5	2.6	MT
Wheat, durum (forage)	*T. turgidum L. var durum Desf.*	Shoot DW	2.1	2.5	MT
Wheatgrass, standard crested	*Agropyron sibiricum (Willd.) Beauvois*	Shoot DW	3.5	4.0	MT
Wheatgrass, fairway crested	*A. cristatum (L.) Gaertn.*	Shoot DW	7.5	6.9	T
Wheatgrass, intermediate	*A. intermedium (Host) Beauvois*	Shoot DW	--	--	MT*
Wheatgrass, slender	*A. trachycaulum (Link) Malte*	Shoot DW	--	--	MT
Wheatgrass, tall	*A. elongatum (Hort) Beauvois*	Shoot DW	7.5	4.2	T
Wheatgrass, western	*A. smithii Rydb.*	Shoot DW	--	--	MT*
Wild rye, Altai	*Elymus angustus Trin.*	Shoot DW	--	--	T
Wild rye, beardless	*E. triticoides Buckl.*	Shoot DW	2.7	6.0	MT
Wild rye, Canadian	*E. canadensis L.*	Shoot DW	--	--	MT*
Wild rye, Russian	*E. junceus Fisch.*	Shoot DW	--	--	T
Vegetable and fruit crops					
Artichoke	*Cynara scolymus L.*	Bud yield	6.1	11.5	MT
Asparagus	*Asparagus officinalis L.*	Spear yield	4.1	2.0	T
Bean, common	*Phaseolus vulgaris L.*	Seed yield	1.0	19	S
Bean, lima	*P. lunatus L.*	Seed yield	--	--	MT*
Bean, mung	*Vigna radiata (L.) R. Wilcz.*	Seed yield	1.8	20.7	S
Cassava	*Manihot esculenta Crantz*	Tuber yield	--	--	MS
Beet, red[##]	*Beta vulgaris L.*	Storage root	4.0	9.0	MT

Broccoli	*Brassica oleracea L. (Botrytis Group)*	Head FW	1.3	15.8	MT
Brussels sprouts	*B. oleracea L. (Gemmifera Group)*	--	--	--	MS*
Cabbage	*B. oleracea L. (Capitata Group)*	Head FW	1.8	9.7	MS
Carrot	*Daucus carota L.*	Storage root	1.0	14	S
Cauliflower	*Brassica oleracea L. (Botrytis Group)*	--	1.5	14.4	MS*
Celery	*Apium graveolens L. var dulce (Mill.) Pers.*	Petiole FW	1.8	6.2	MT
Corn, sweet	*Zea mays L.*	Ear FW	1.7	12	MS
Cowpea	*Vigna unguiculata (L.) Walp.*	Seed yield	4.9	12	MT
Cucumber	*Cucumis sativus L.*	Fruit yield	2.5	13	MS
Eggplant	*Solanum melongena L. var esculentum Nees.*	Fruit yield	1.1	6.9	MS
Fennel	*Foeniculum vulgare Mill.*	Bulb yield	1.4	16	S
Garlic	*Allium sativum L.*	Bulb yield	3.9	14.3	MS
Gram, black or urd bean	*Vigna mungo (L.) Hepper [syn.Phaseolus mungo L.]*	Shoot DW	--	--	S
Kale	*Brassica oleracea L. (Acephala Group)*	--	--	--	MS*
Kohlrabi	*Brassica oleracea L. (Gongylodes Group)*	--	--	--	MS*
Lettuce	*Lactuca sativa L.*	Top FW	1.3	13	MS
Muskmelon	*Cucumis melo L. (Reticulatus Group)*	Fruit yield	1.0	8.4	MS
Okra	*Abelmoschus esculentus (L.) Moench*	Pod yield	--	--	MS
Onion (bulb)	*Allium cepa L.*	Bulb yield	1.2	16	S
Onion (seed)	--	Seed yield	1.0	8.0	MS
Parsnip	*Pastinaca sativa L.*	--	--	--	S*
Pea	*Pisum sativum L.*	Seed FW	3.4	10.6	MS
Pepper	*Capsicum annuum L.*	Fruit yield	1.5	14	MS
Pigeon pea	*Cajanus cajan (L.) Huth [syn. C. indicus (K.) Spreng.]*	Shoot DW	--	--	S
Potato	*Solanum tuberosum L.*	Tuber yield	1.7	12	MS
Pumpkin	*Cucurbita pepo L. var Pepo*	--	--	--	MS*

Purslane	*Portulaca oleracea L.*	Shoot FW	6.3	9.6	MT
Radish	*Raphanus sativus L.*	Storage root	1.2	13	MS
Spinach	*Spinacia oleracea L.*	Top FW	2.0	7.6	MS
Squash, scallop	*Cucurbita pepo L. var melopepo (L.) Alef.*	Fruit yield	3.2	16	MS
Squash, zucchini	*C. pepo L. var melopepo (L.) Alef.*	Fruit yield	4.9	10.5	MT
Strawberry	*Fragaria x Ananassa Duch.*	Fruit yield	1.0	33	S
Sweet potato	*Ipomoea batatas (L.) Lam.*	Fleshy root	1.5	11	MS
Swiss chard	*Beta vulgaris L.*	Top FW	7.0	5.7	T
Tepary bean	*Phaseolus acutifolius Gray*	--	--	--	MS*
Tomato	*Lycopersicon lycopersicum (L.) Karst. ex Farw. [syn. Lycopersicon esculentum Mill.]*	Fruit yield	2.5	9.9	MS
Tomato, cherry	*L. lycopersicum var. Cerasiforme (Dunal) Alef.*	Fruit yield	1.7	9.1	MS
Turnip	*Brassica rapa L. (Rapifera Group)*	Storage root	0.9	9.0	MS
Turnip (greens)		Top FW	3.3	4.3	MT
Watermelon	*Citrullus lanatus (Thunb.) Matsum. & Nakai*	Fruit yield	--	--	MS*
Winged bean	*Psophocarpus tetragonolobus L. DC*	Shoot DW	--	--	MT

† *These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary, depending upon climate, soil conditions and cultural practices.*

‡ *Botanical and common names follow the convention of Hortus Third (Bailey & Bailey, 1976), where possible.*

§ *In gypsiferous soils, plants will tolerate EC_e's about 2 dS/m higher than indicated.*

¶ *The B tolerance ratings are based on the following threshold concentration ranges: < 0.5 mg/L very sensitive (VS), 0.5-1.0 sensitive (S), 1.0-2.0 moderately sensitive (MS), 2.0-4.0 moderately tolerant (MT), 4.0-6.0 tolerant (T), and > 6.0 very tolerant (VT). Ratings with an * are estimates.*

Less tolerant during seedling stage, EC_e at this stage should not exceed 4 or 5 dS/m.

†† *Unpublished U. S. Salinity Laboratory data.*

‡‡ *Grain and forage yields of DeKalb XL-75 grown on organic muck soil decreased about 26 percent per dS/m above a threshold of 1.9 dS/m.*

§§ *Because paddy rice is grown under flooded conditions, values refer to the electrical conductivity of the soil water while the plants are submerged. The rice is less tolerant during seedling stage.*

¶¶ *Sesame cultivars Sesaco 7 and 8 may be more tolerant than indicated by the S rating.*

Sensitive during germination and emergence. EC_e should not exceed 3 dS/m.

††† *Data from one cultivar: Probred.*

‡‡‡ *Average of several varieties. Suwannee and Coastal are about 20 percent more tolerant, and common and Greenfield are about 20 percent less tolerant than the average.*

§§§ *Average for Boer, Wilman, Sand and Weeping cultivars. Lehmann seems about 50 percent more tolerant.*

Source: Grieve, C.M., S.R. Grattan and E.V. Maas. 2012. Plant salt tolerance. In. (W.W. Wallender and K.K. Tanji, eds). Agricultural Salinity Assessment and Management (second edition). ASCE pp 405-459.

Table 5.2 Salt tolerance of tree, vine and woody crops. † Adapted from Grieve *et al.* (2012).

Crop			Salt tolerance parameters		
Common name	Botanical name‡	Tolerance based on:	Threshold§ (*ECe*)	Slope	Rating¶
			dS/m	% per dS/m	
Almond	*Prunus duclis (Mill.) D.A. Webb*	Shoot growth	1.5	19	S
Apple	*Malus sylvestris Mill.*	--	--	--	S
Apricot	*Prunus armeniaca L.*	Shoot growth	1.6	24	S
Avocado	*Persea americana Mill.*	Shoot growth	--	--	S
Banana	*Musa acuminata Colla*	Fruit yield	--	--	S
Blackberry	*Rubus macropetalus Doug. ex Hook*	Fruit yield	1.5	22	S
Boysenberry	*Rubus ursinus Cham. and Schlechtend*	Fruit yield	1.5	22	S
Castorbean	*Ricinus communis L.*	--	--	--	MS*
Cherimoya	*Annona cherimola Mill.*	Foliar injury	--	--	S
Cherry, sweet	*Prunus avium L.*	Foliar injury	--	--	S*
Cherry, sand	*Prunus besseyi L., H. Baley*	Foliar injury, stem growth	--	--	S*
Coconut	*Cocos nucifera L.*	--	--	--	MT*
Currant	*Ribes sp. L.*	Foliar injury, stem growth	--	--	S*
Date palm	*Phoenix dactylifera L.*	Fruit yield	4.0	3.6	T
Fig	*Ficus carica L.*	Plant DW	--	--	MT*
Gooseberry	*Ribes sp. L.*	--	--	--	S*
Grape	*Vitis vinifera L.*	Shoot growth	1.5	9.6	MS
Grapefruit	*Citrus x paradisi Macfady.*	Fruit yield	1.2	13.5	S
Guava	*Psidium guajava L.*	Shoot & root growth	4.7	9.8	MT
Guayule	*Parthenium argentatum A. Gray*	Shoot DW & rubber yield	8.7 7.8	11.6 10.8	T T
Jambolan plum	*Syzygium cumini L.*	Shoot growth	--	--	MT
Jojoba	*Simmondsia chinensis (Link) C. K. Schneid*	Shoot growth	--	--	T
Jujube, Indian	*Ziziphus mauritiana Lam.*	Fruit yield	--	--	MT

Lemon	*Citrus limon (L.) Burm. f.*	Fruit yield	1.5	12.8	S
Lime	*Citrus aurantiifolia (Christm.) Swingle*	--	--	--	S*
Loquat	*Eriobotrya japonica (Thunb). Lindl.*	Foliar injury	--	--	S*
Macadamia	*Macadamia integrifolia Maiden & Betche*	Seedling growth	--	--	MS*
Mandarin orange, tangerine	*Citrus reticulata Blanco*	Shoot growth	--	--	S*
Mango	*Mangifera indica L.*	Foliar injury	--	--	S
Natal plum	*Carissa grandiflora (E.H. Mey.) A. DC.*	Shoot growth	--	--	T
Olive	*Olea europaea L.*	Seedling growth, Fruit yield	--	--	MT
Orange	*Citrus sinensis (L.) Osbeck*	Fruit yield	1.3	13.1	S
Papaya	*Carica papaya L.*	Seedling growth, foliar injury	--	--	MS
Passion fruit	*Passiflora edulis Sims.*	--	--	--	S*
Peach	*Prunus persica (L.) Batsch*	Shoot growth, Fruit yield	1.7	21	S
Pear	*Pyrus communis L.*	--	--	--	S*
Pecan	*Carya illinoinensis (Wangenh.) C. Koch*	Nut yield, trunk growth	--	--	MS
Persimmon	*Diospyros virginiana L.*	--	-	--	S*
Pineapple	*Ananas comosus (L.) Merrill*	Shoot DW	--	--	MT
Pistachio	*Pistacia vera L.*	Shoot growth	--	--	MS
Plum, prune	*Prunus domestica L.*	Fruit yield	2.6	31	MS
Pomegranate	*Punica granatum L.*	Shoot growth	--	--	MS
Popinac, white	*Leucaena leucocephala (Lam.) de Wit [syn. Leucaena glauca Benth.]*	Shoot DW	--	--	MS
Pummelo	*Citrus maxima (Burm.)*	Foliar injury	--	--	S*
Raspberry	*Rubus idaeus L.*	Fruit yield	--	--	S
Rose apple	*Syzygium jambos (L.) Alston*	Foliar injury	--	--	S*
Sapote, white	*Casimiroa edulis Llave*	Foliar injury	--	--	S*
Scarlet wisteria	*Sesbania grandiflora*	Shoot DW	--	--	MT
Tamarugo	*Prosopis tamarugo Phil.*	Observation	--	--	T
Walnut	*Juglans spp.*	Foliar injury	--	--	S*

Source: Grieve, C.M., S.R. Grattan and E.V. Maas. 2012. Plant salt tolerance. In. (W.W. Wallender and K.K. Tanji, eds). Agricultural Salinity Assessment and Management (second edition). ASCE pp 405-459.

† *These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary, depending upon climate, soil conditions, and cultural practices. The data are applicable when rootstocks are used that do not accumulate Na^{+} or Cl^{-} rapidly or when these ions do not predominate in the soil.*

‡ *Botanical and common names follow the convention of Hortus Third (Liberty Hyde Bailey Hortorium Staff, 1976) where possible.*

§ *In gypsiferous soils, plants will tolerate EC_e's about 2 dS/m higher than indicated.*

¶ *The B tolerance ratings are based on the following threshold concentration ranges: < 0.5 mg/L very sensitive (VS), 0.5-1.0 sensitive (S), 1.0-2.0 moderately sensitive (MS), 2.0-4.0 moderately tolerant (MT), 4.0-6.0 tolerant (T), and > 6.0 very tolerant (VT). Ratings with an * are estimates.*

Most of the studies used to develop these crop salt-tolerance coefficients were conducted in controlled plots with high leaching to reduce spatial and temporal changes in salinity and to avoid additional biotic and abiotic stresses (such as water stress, nutrient stress, plant diseases, etc.). In addition, the salts used to characterize salt tolerance in most these studies was combined NaCl and $CaCl_2$ at ratios to produce low SAR values to avoid soil structural problems. As the footnotes in tables 5.1 and 5.2 indicate, in gypsiferous soils, crop salt tolerances listed here should be increased by about 2 dS/m. That is, they tolerate a higher salinity (ECe) than those under chloride-dominated conditions. While these salt-tolerance coefficients are valuable, in field conditions many factors affect salt tolerance such as salt type, climate, soil conditions and plant age. Therefore, this categorization is best used as a first approximation, which should be adjusted to account for climate, soil type and management.

5.2 SALT TOLERANCE AT DIFFERENT GROWTH STAGES

It has been recognized for decades that a crop's sensitivity to salinity varies from one developmental growth stage to the next (Bernstein & Hayward, 1958). While the research on this subject is rather limited, the majority of the research indicates that most annual crops are tolerant at germination but are sensitive during emergence and early vegetative development (Läuchli & Epstein, 1990; Läuchli & Grattan, 2007; Maas & Grattan, 1999). As plants mature, they become progressively more tolerant to salinity, particularly at later stages of development. Since, for many crops, salt tolerance increases as the growing season progresses, it is advisable to start with low salinity irrigation water at the beginning of the season. (Refer to Chapter 6 regarding irrigation strategies using multiple sources of water with different qualities.)

Salinity affects both vegetative and reproductive developmental processes in plants. This is particularly important because the harvested organ of the crop can be a stem, leaf, root, shoot, fruit, fibre or grain (Läuchli & Grattan, 2007). The remaining sections in this chapter provide a short description of how salinity stress affects different growth stages in several annual crops.

5.2.1. Germination and seedling emergence

Most annual crops are tolerant during germination and can germinate under high salinity conditions. This includes many that are rated as sensitive to salinity, such as corn (Maas *et al.*, 1983), kenaf (Curtis & Läuchli, 1985), Limonium (Carter *et al.*, 2005) and tomato (Kurth *et al.*, 1986b). Salinity stress delays germination even though the final percentage of germinated seeds may eventually be the same under moderate salinity conditions (Läuchli & Grattan, 2007; Maas & Poss, 1989a). However, if the salinity stress is severe enough, it will reduce the percentage of germinated seeds as well (Kent & Läuchli, 1985; Mauromicale & Licandro, 2002). (The effect of salinity on germination is illustrated in Figure 5.3). The germination rates and percentage of germinated seeds at a particular time varies considerably among species and cultivars (Läuchli & Grattan, 2007).

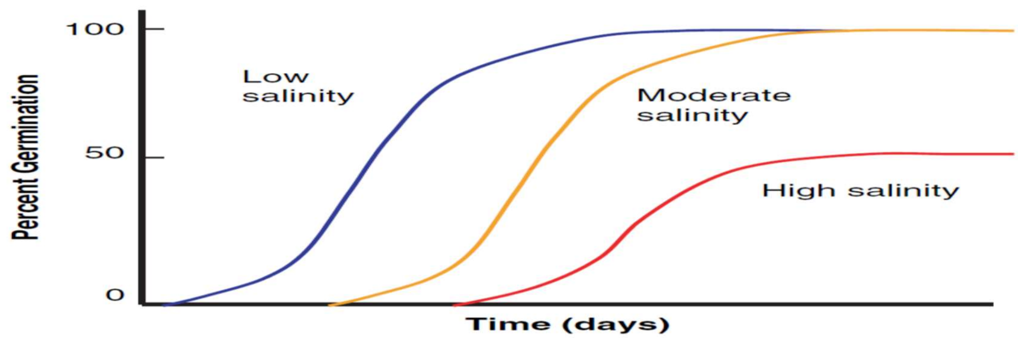


Figure 5.3. Relationship between percent germination and time after exposure to low, moderate and high salinity.

Source: *Läuchli, A. and S.R. Grattan. 2007. Plant growth and development under salinity stress. In. Advances in molecular-breeding towards salinity and drought tolerance. M.A. Jenks, P.A. Hasegawa and S.M. Jain, eds. Springer-Verlag pp. 1-31*

Many crops are more sensitive to salinity during emergence, as compared to germination, which results in a reduction in crop stand (Maas & Grattan, 1999). After germination, the young seedling near the soil surface is subjected to multiple stresses, including large temperature fluctuations, severe changes in soil water content (both water logging and water deficit) and mechanical impedance such as surface crusts. By delaying germination and emergence, salinity provides a longer time for the sensitive seedling to be subjected to these abiotic stresses as well as those imposed by pathogens that can attack the roots. For example, cotton, although it is classified as salt tolerant, is particularly sensitive to salinity after germination, with plant stands being dramatically reduced in fields previously irrigated with saline-sodic drainage water (Mitchell *et al.*, 2000). Conversely, stand-establishment of less tolerant crops, including safflower (Goyal *et al.*, 1999) and tomato (Mitchell *et al.*, 2000), was not nearly as affected as in the case of cotton. Emergence studies using saline-sodic waters, especially those where sodium chloride was the sole salinizing salt, showed that it can cause a deterioration of soil physical conditions, thus reducing oxygen diffusion rates and increasing mechanical impedance (Grattan & Oster, 2003). This condition adds additional abiotic stresses to the emerging seedlings as compared with other salinity studies under saline, non-sodic conditions.

5.2.2. Vegetative growth

While the number of studies examining salt sensitively at different growth stages are limited, most indicate that crops are particularly susceptible to salinity during the seedling and early vegetative growth stage as compared to later stages. This is a developmental growth stage that is characteristic of rapid growth. Shoot growth reduction due to salinity is manifested by stunted shoots with smaller leaves, but the final leaf size depends on both cell division and cell elongation (Läuchli & Epstein, 1990). Although salinity can reduce cell numbers (Munns & Termaat, 1986), leaf extension has been found to be an extremely salt-sensitive process as it is controlled by cell elongation (Papp *et al.*, 1983). It is salinity's effect on these processes that make this growth stage sensitive to salinity.

It is also well known that salinity, even with an adequate supply of calcium, reduces shoot growth more than root growth (Läuchli & Epstein, 1990). Therefore, the effect of salt stress on shoot growth can be partly alleviated by supplemental Ca^{2+} (Läuchli & Epstein, 1990; Cramer, 2002), particularly in crops exposed to high Na^{+}/Ca^{2+} ratios (i.e. saline-sodic conditions) where Ca-deficiency in developing leaves may occur (Maas & Grieve, 1987). The calcium status of the growing region of leaves is particularly sensitive to salt stress. Thus, even though mature tissue samples may indicate adequate calcium nutrition, the inadequacy of calcium in young developing tissue can reduce the growth rate.

5.2.3. Reproductive growth

Research indicates that most crops become progressively more tolerant as the plants grow older (Läuchli & Grattan, 2007). In experiments with wheat (Maas & Poss, 1989a), sorghum (Maas *et al.*, 1986) and cowpea (Maas & Poss, 1989b), where the duration of salinity stress was held constant but the period of salt-stress imposition varied from one developmental stage to the next, investigators found that these crops were most sensitive during vegetative and early reproductive stages, less sensitive during flowering, and least sensitive during the seed filling stage. In all these studies, seed weight was the yield component of interest, but similar conclusions regarding growth stage sensitivity were obtained with both determinate crops (grain crops) and indeterminate crops (cowpea).

Wheat and rice are not only two of the most important grain crops in the world, but they have been the most intensively studied agronomic crops regarding salt sensitivity at different growth stages. These leading grain crops are of particular interest not only because they vary so widely in salt tolerance, but because salinity affects the reproductive processes differently (Läuchli & Grattan, 2007). Studies on wheat and rice have been conducted in a variety of conditions, including the field, greenhouse and laboratory, to better understand detailed changes in developmental processes, as the plants endure various degrees of salt stress at different growth stages.

The reduction in the number of spike-bearing tillers because of salt stress during vegetative and early reproductive development in most cereal crops appears to have a greater negative impact on grain yield than any other yield component. In most cereal crops, the time from planting to maturity typically decreases with increased salinity (Grieve *et al.* 1993), but salinity has just the opposite effect on rice (Läuchli & Grattan, 2007). When salinity was applied to wheat from seedling emergence, it had a profound influence on reproductive development (Grieve *et al.*, 1993). The leaf initiation rate decreased even though the time of flag leaf initiation was unchanged, indicating salinity had no influence on the timing of the transition from vegetative to reproductive development, but the number of tillers and overall grain yield was greatly reduced. Salt stress in rice can reduce seedling emergence and, when imposed at early vegetative stages, reduces tillers and grain-bearing panicles, leading to low yields. However, unlike wheat, certain rice cultivars can develop sterile spikelets, by a mechanism that appears to be genetically controlled, leading to further grain yield losses (Läuchli & Grattan, 2007).

5.3 CROP SELECTION

When irrigating with brackish water, crop selection is an important management decision. Chapters 4 and 5 provide details regarding salt-tolerance mechanisms and differences in crop tolerance among conventional crops. Field crops are generally more tolerant to salinity than annual vegetable crops (see tables 5.1 and 5.2) and many trees and vine crops are prone to damage by ions, such as sodium, chloride and boron. These sensitive perennials should, whenever possible, be excluded from brackish water irrigation. The most desirable characteristics in selecting crops for irrigation with saline water are: 1) high marketability and economic value, 2) high tolerance to salts and specific ions, 3) ability to maintain production and quality under saline conditions, 4) low potential to accumulate trace elements in tissue, and 5) ease of management and compatibility within crop rotation (Grattan & Rhoades, 1990).

Breeding to improve salt tolerance is difficult because tolerance is controlled by multiple genes (Flowers & Yeo, 1995). Nevertheless, some breeding efforts have led to varietal differences among some crops. Plant scientists have managed to isolate markers responsible for salinity tolerance, and some improvements to salinity tolerance (in wheat, for instance) have been achieved (Munns *et al.*, 2012). Classical methods based on tissue culture techniques usually require several years to produce a salt-tolerant variety. New biotechnologies (such as genetic modification) could shorten the development period. Therefore, more salt-tolerant varieties may be introduced and selection of those may be a wise choice in salt-affected areas.

5.4 BRACKISH WATER OPPORTUNITIES FOR NON-CONVENTIONAL CROPS

An estimated 10 million ha of arable land is lost every year globally due to salinization. Salt-affected soils occur in at least 75 countries, occupying more than 20 percent of the world's irrigated area – and more than half the irrigated land in some countries. Dry regions, where arable land is scarce, are particularly prone to salinization, with vast areas of fields being abandoned due to the build-up of salinity in the soil. One possible option for such regions is the production of non-conventional crops with halophytic characteristics, which can be irrigated with brackish water. These crops have great potential in helping to address the widespread problem of soil salinization (Glenn *et al.*, 1998; 1999).

Halophytes are salt-tolerant plant species that are able to grow and complete their life cycle in habitats with soil salinity higher than 200 mM NaCl (Flowers & Colmer, 2008). While they represent only 2 percent of terrestrial plant species, halophytes can be found in about half of the higher plant families.

Halophytes have been tested as substitutes for vegetables, forages and oilseed crops. For example, Salicornia bigelovii is one of the most salt-tolerant of the vascular plants whose young vegetative stems can be eaten raw or cooked. Moreover, this leafless plant can yield 2 tonnes/ha of seed that contain 28 percent oil and 31 percent protein (Glenn *et al.*, 1998; 1999). Other examples include highly salt-tolerant cereals such as quinoa and amaranth (Box 5.1). FAO declared 2013 as the year of quinoa. Quinoa is an attractive non-conventional crop not only because of its tolerance to salinity but because it is one of the only plant foods containing all the essential amino acids (FAO, 2013). Amaranth is not only salt tolerant but this nutritional crop can be consumed as either a vegetable or a grain. Amaranth and quinoa are commonly grown in South America, and they are both salt-tolerant and drought-tolerant (see Box 5.1).

Halophytes can also provide additional benefits. Not only can many of them serve as potential forages (see Box 5.2), they play a key role in the ecosystem, protecting habitats, maintaining ecological stability, preventing soil erosion, preventing seawater intrusion into freshwater habitats, providing a source of biofuel, and providing food and shelter for a range of fauna (Al-Oudat & Qadir, 2011; Sharma *et al.*, 2016). Some halophytes have the potential for commercial-scale production for a variety of uses. Halophytes also represent an important – but so far largely unexploited – source of novel genes to enhance drought and salinity tolerance in crop varieties. They have been used by local communities for millennia and their full potential is still untapped. For example, they could be used to assist in the amelioration of saline soil, to rehabilitate degraded ecosystems, or cultivated on a commercial scale for specific end uses. They could be 'mined' for genes conferring salt and drought tolerance, for use in crop breeding programs. Halophytes have also been explored as bioenergy crops. Both the lignocellulosic biomass and oil from seeds of halophytes can be utilized for biofuel production (Sharma *et al.*, 2016). Researchers indicate that some of the most promising genera include Salicornia (glasswort), Suaeda (sea-blite), Atriplex (saltbush), Distichlis (salt grass) and the succulent ground cover, Batis. HALOPH (Aronson and Whitehead, 1989), a comprehensive database on halophytes, includes 1 554 species. The database has recently been converted to an interactive database titled eHALOPH, available at https://www.sussex.ac.uk/affiliates/halophytes/.

The AWC had also discussed promising halophytic species that may be appropriate in the NENA region. The following section discusses six examples of promising non-conventional halophytes (jatropha, quinoa, Salicornia, Atriplex [fourwing saltbush], amaranth and cassava) and their ideal cropping requisites. One or more of these new crops may be attractive alternatives in the NENA region.

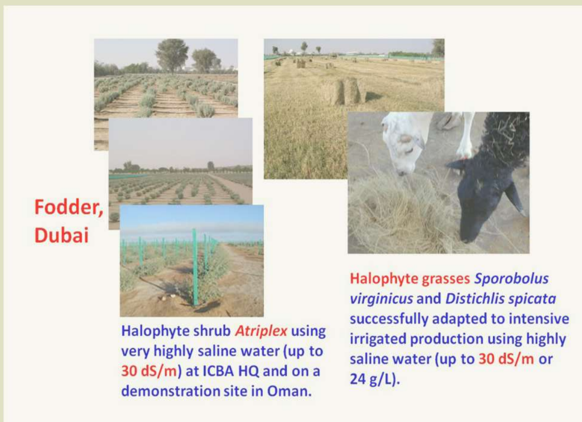
Box 5.1 Quinoa and amaranth

Non-conventional, salt-tolerant crops that can be readily grown with brackish water in the NENA region would be an attractive alternative to more salt-sensitive crops and be a step forward in food security in this water-stressed region. Two crops that have shown promise are quinoa and amaranth (Photo). These crops are not only salt tolerant but contain proteins, minerals and vitamins. These crops may be an attractive alternative cereal to wheat (see photo below). They will be discussed in more detail later in this chapter.

Nutritional characteristics of quinoa and amaranth as suitable alternatives to grain crops in highly saline environments. Ragab, 2012. ©Cordis EU research results
***Source**: Author's own elaboration.*

Box 5.2 Halophytic forages

Many researchers across the globe are looking to halophytic grasses and shrubs as an additional source of fodder (Photo). In California, tall wheatgrass (*Thinopyrum ponticum* cv 'Jose'), creeping wild rye (*Leymus triticoides* cv 'Rio') and paspalum (*Paspalum vaginatum* cv 'Sea lsle') where irrigated with saline drainage water (13.2 dS/m), producing a forage of adequate quality and biomass (Benes *et al.*, 2012). Other studies found that an annual biomass of 4–17 tonnes/ha dry matter could be achieved with the halophytic species *Atriplex lentiformis*, *Distichlis spicata*, *Spartina gracilis*, *Allenrolfea occidentalis, Brassica hyssopifolia* and *Salicornia bigelovii*, irrigated with saline-sodic water, where the average ECe was 29 dS/m and the average SAR was 39 (Diaz *et al.*, 2013). While the quality of the forage was acceptable for ruminant animals from an energy perspective, the ash content in the forage ranged from 6–52 percent which drops these halophytic forages into the low-quality category. Others also found the high salt content in the forage to be a limiting factor when halophytic forages were irrigated with 40 000 mg/l TDS seawater. They also found that the seeds of some halophytes have low salt but high protein content and yielded 0.5 to 3.0 tonnes of protein per hectare (O'Leary *et al.*, 1985). Researchers at the International Center for Biosaline Agriculture (ICBA) in Dubai are irrigating halophytic shrubs (e.g. *Atriplex*) and grasses (e.g. *Sporobolus virginicus* and *Distichlis spicata*) with saline water up to 30 dS/m (see photo below). While the halophytic forages may be of low quality, they could be used as a supplement added in the correct proportions with high quality forages.



Potential halophytic shrubs and grasses as alternative forages in highly saline environments ©ICBA.

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5.4.1. Jatropha

Use of Jatropha: Jatropha seeds are toxic and are not fit for human consumption. Jatropha is primarily used to produce biodiesel from the oil in the seeds ©FAO.

Climate: Jatropha grows in tropical and subtropical regions, within geographical limits extending from 30ºN to 35ºS. It also grows in lower altitudes of 0–500 metres above sea level. Jatropha is not sensitive to day length (flowering is independent of latitude) and may flower at any time of the year (Heller, 1996).

Water Requirements: While Jatropha can survive with as little as 250 to 300 mm of annual rainfall, at least 600 mm are typically needed to flower and set fruit. The optimum rainfall for seed production is between 1 000 and 1 500 mm (FACT, 2007), which corresponds to sub-humid ecologies. While Jatropha has been observed growing in areas with 3 000 mm of rainfall (Achten *et al.*, 2008), higher precipitation is likely to cause fungal attack and restrict root growth in all but the most free-draining soils.

Temperature: Optimum temperatures are between 20 ˚C and 28 ˚C. Very high temperatures can depress yields (Gour, 2006). Jatropha has been seen to be intolerant to frost. The plant is well adapted to conditions of high light intensity (Jongschaap, 2007) and is unsuited to growing in shade.

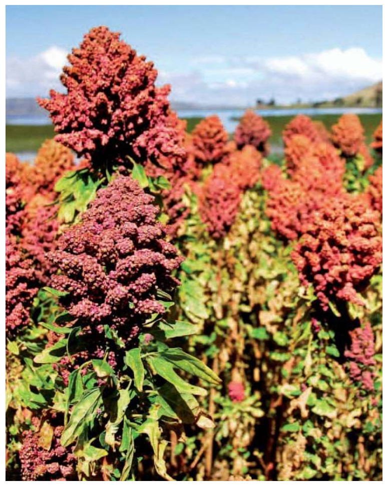
Soil: The best soils for Jatropha are aerated sands and loams with a depth of at least 45 cm (Gour, 2006). Heavy clay soils are less suitable and should be avoided, particularly where drainage is impaired, as Jatropha is intolerant to waterlogged conditions (Dagar *et al.*, 2006). Jatropha is known for its ability to survive in very poor soils and dry conditions considered marginal for agriculture, and can even root into rock crevices. However, survival ability alone does not mean that high productivity can be obtained under marginal agricultural environments.

Planting: Jatropha is planted at densities ranging from 1 100 to 2 500 plants/ha. The yield per tree is likely to increase with wider spacing but with a decline in yield per ha (Achten *et al.*, 2008). Spacing decisions should be based on the environment. Semi- arid, low-input systems should use wider spacing such as 3.0 x 2.0, 3.0 x 2.5 or 3.0 x 3.0 metres.

Seed yields: Heller (1996) reported yields between 0.1 and 8.0 tonnes/ha, however these yield figures are accompanied by little or no information on genetic provenance, age, propagation method, pruning, rainfall, tree spacing, soil type or soil fertility.

Harvesting: Seeds are ready for harvest around 90 days after flowering when the fruits have changed from green to yellow-brown. In wetter climates, fruiting is continuous throughout the year, while the harvest may be confined to two months in semi-arid regions.

5.4.2. Quinoa



Quinoa in Italy ©FAO

Quinoa was a staple food of the Quechua and Aymara peoples in the Andes region of South America; today it is mainly grown in the Plurinational State of Bolivia, Peru and Ecuador. Because of its high nutritional value, quinoa is called *chisiya*, meaning 'mother grain' in the Quechua language. Quinoa is known for its great adaptability to extreme and diverse climatic conditions.

Different varieties or ecotypes of quinoa can be grown in diverse climate zones and at various altitudes, making quinoa an excellent alternative crop in the face of climate change and highlighting its potential contribution to ensuring global food security.

In addition, quinoa is adaptable to diverse soil types. This has led to experimental trials in various potential quinoa producing countries in Africa (Hirich *et al.*, 2012, Fghire *et al.*, 2015), Asia, Europe (Pulvento *et al.*, 2013 a, b), and North America. To date, quinoa has been successfully grown in the United States, Morocco, Kenya and India, with hopes of eventual large-scale commercial production.

Ideal cropping requisites for quinoa:

Climate: Desert, warm and dry, cold and dry, temperate and rainy, temperate with high relative humidity, and puna grassland and high mountain areas. There are varieties or ecotypes adapted to each climate.

Soil: Loam soil with good drainage and high organic matter content, with moderate slopes and average nutrient content. It prefers neutral soils, although it is usually grown on alkaline (up to pH 9) and acid soils (down to pH 4.5).

Water: Quinoa is water-efficient as it has physiological mechanisms that enable it to avoid the impact of moisture deficits.

Temperature: The ideal average temperature is around 15-20 °C, although it can tolerate temperature extremes ranging from 38 °C to -8 °C.

Radiation: Quinoa withstands intense solar radiation enabling it to gain the hours of heat needed to complete its growth and productive period.

Photoperiod: There are varieties or ecotypes that are short-day, long-day or insensitive to photoperiod.

Nutritional value: Quinoa is a healthy food that provides many nutrients. It is comparable in energy to similar foods such as maize, rice and wheat. Quinoa is also a good source of quality protein, dietary fibre, polyunsaturated fats and minerals.

5.4.3. Salicornia

Salicornia europaea, near Southhampton, United Kingdom of Great Britain and Northern Ireland ©Marco Schmidt.

Food uses of Salicornia: Salicornia has a wide variety of food uses. The stems can be eaten raw as a crisp and salty salad plant, pickled, steamed or boiled briefly like thin asparagus. Its seeds can produce a high quality oil (Glenn *et al.*, 1998).

Origins and uses of Salicornia: Cultivation of Salicornia dates back nearly a thousand years to fishing families along the coasts of the Netherlands, Northern France and Great Britain, where it grows in tidal marshes. Historically, Salicornia was known for its digestive and anti-flatulent properties. It has supplied key vitamins and minerals to coastal diets for centuries. More recently, the plant has started to be considered a delicacy and is slowly becoming the new favourite of organic gourmet produce.

Properties of Salicornia: This specialty vegetable is a true halophyte as it thrives on seawater. Like other sea vegetables, Salicornia offers the broadest range of minerals of any food, containing virtually all the minerals found in the ocean. Sea vegetables are a very good source of vitamin B, folate and magnesium, and a good source of iron, calcium and the B-vitamins riboflavin and pantothenic acid.

5.4.4. Atriplex (fourwing saltbush)

Atriplex canescens ©Kurt Schaefer.

Use: Fourwing saltbush is palatable to cattle, sheep and deer in fall and winter. It provides nutritious winter browse in many areas and is a good fall and winter browse plant for bighorn sheep, antelope and elk.

Description: Its multi-branched stems are stout with whitish bark. Mature plants range from 0.3 to 2.4 m in height, depending on the ecotype and the soil and climate. Its leaves are simple, alternate, entire, linear-spatulate to narrowly oblong, canescent (covered with fine whitish hairs) and 1.25 to 5 cm long. Its root system is branched and commonly very deep, reaching depths of up to 6 m when soil depth allows (Kearney *et al.*, 1960).

Adaptation: Fourwing saltbush is adapted to most soils but is best suited to deep, well drained; loamy to sandy to gravely soils. It is sometimes found growing in dense clay soils. It is very tolerant to saline soil conditions and somewhat tolerant to sodic soil conditions (Ogle & St. John, 2008). Under saline conditions, plants take up salt and accumulate it in the plant's scurfy leaf coverings.

Water: Fourwing saltbush most commonly grows in areas that receive 200 to 360 mm of annual precipitation (Ogle *et al.*, 2012). It can be found from sea level in Texas to over 2 400 m in Wyoming (Mozingo, 1987; Powell, 1988).

Establishment: Planting: Fourwing saltbush begins growth in mid to late spring. Seed matures 3 to 4 months after flowering. It typically spreads via seed distribution.

Environmental concerns: Fourwing saltbush is native, long-lived and spreads primarily by seed distribution. It is not considered "weedy", but could slowly spread into adjoining vegetative communities under ideal climatic and environmental conditions. This species is well documented as having beneficial qualities and no negative impacts on wild or domestic animals.

Seeds and plant production: Establishing plants in a greenhouse and transplanting them to the field will result in the most satisfactory stands for seed production. Plant spacing should be 1.8 to 2.4 m within rows and 2.4 to 3.0 m between rows. Planting one male plant for every 5 female plants is recommended. Fourwing saltbush is wind-pollinated and seed production stands should be designed with the majority of the male plants on the windward side of the field. Transplanting into weed barrier fabric can also improve plant establishment, seed production, weed control and moisture conservation. Transplanting is recommended in the spring prior to summer heat. Full seed production is usually reached the third year following transplanting.

5.4.5. Amaranth

FOTOLIA/TAIFTIN ©Ogden Publications, Inc.

Description: There are 60 to 70 varieties of amaranth, 40 of which are considered native to the Americas. Over 400 varieties within these species around are found throughout the world in both temperate and tropical climates, and fall roughly into one of four categories: grain, vegetable, ornamental or weed. Many varieties fit into more than one category.

Major production areas: The main producing areas of Amaranth in South Africa are the Limpopo, North West, Mpumalanga and KwaZulu-Natal provinces.

Temperature: Amaranth is highly tolerant of an arid environment. Amaranth seeds need soil temperatures between 18 °C and 25 °C to germinate and an air temperature above 25 °C for optimum growth. It may grow at different temperature ranges in other countries. The number of growing degree days during the growing season is a major determinant of amaranth plant growth. Lower temperatures and shorter days will induce flowering with a subsequent reduction in leaf yield. Frost damage should not be a problem because the crop grows during summer with the start of the rains. However, frost plays an important role in the harvesting of the crop. Because amaranth is an annual crop, it does not mature completely in areas with a short growing season. Frost would terminate the crop's growth.

Water: Grain amaranth is reported to be drought-tolerant compared to most vegetables. Although amaranth is regarded as being drought-tolerant, the precise mechanism involved is not well understood. In extremely dry conditions it has the ability to wilt temporarily and then revive after rainfall occurs. The crop cannot withstand water- logging. The exposure of the plant to severe drought induces early flowering and halts the production of leaves.

Soil requirements: Amaranth is adapted to a variety of soil types, including marginal soils, but will do best on fertile, well-drained soils and deep soils. Loose and friable soils with high organic matter content are ideal for an early and heavy yield. Selecting soils that are lower in clay and managing the seedbed to minimize the possibility of crusting can help ensure good stands. Amaranth requires good seed–soil contact for rapid germination and emergence, and adequate soil moisture must be maintained at the seeding depth throughout initial establishment. The growth of vegetable amaranth is adversely affected by soil pH of between 4.7 and 5.3. Soil with a pH of 6.4 could produce high yields. If the plants are treated correctly, it should be possible to harvest leaves every two weeks.

Planting: Planting is done when the soil temperature is at least 18 °C and after early weed growth has been controlled by tillage or a contact herbicide. When planted early, amaranth will start flowering after it has accumulated enough growth and heat units. When planted later, flowering is triggered by photo period (day length). There are three ways to plant amaranth:

- Seeds are sown directly into the soil.
- Seeds are sown in shallow rows, 1.5 m apart and covered lightly, using a rake. (The seeds must be watered twice daily until the seedlings emerge.)
- Seeds can be planted in seed trays and transplanted after approximately four weeks (when the plants should be about 15 cm tall) into rows 1.5 m apart and with a spacing of 30 cm within the rows.

Fertilization: One of the essential elements is nitrogen. High levels of nitrogen are essential for the regrowth of leaves after harvesting. To promote better regrowth, a top dressing of LAN (limestone ammonium nitrate) can be given at monthly intervals. Nitrogen will be the most limiting nutrient in most environments. Nitrogen requirements may vary from 50 to 200 kg N/ha and the requirement also differs, depending on the species. Plants can be fertilized by using cow manure at 6 t/ha as well as commercial fertilizers with a high nitrogen content.

Irrigation: Although the plant is drought-resistant, it performs optimally under irrigation. Under irrigation, amaranth leaves can be harvested every two weeks during summer. In sandy soils, an irrigation frequency of four to five days is maintained in the summer season, while in the rainy season the irrigation frequency is based on the soil moisture level. Saline water up to EC = 22 dS m^{-1} can be used (Pulvento *et al.*, 2015a, b)

Harvest maturity: Most amaranth cultivars grow rapidly and may be harvested from 30 to 55 days from sowing, when they reach a height of 0.6 m. Timing of harvest is not as straightforward as with the commodity crops.

Harvesting methods: The plants are harvested by hand only. Young plants can be pulled up or cut six to eight weeks after sowing, when they are about 20 cm tall.

Leaves can be harvested in two ways:

- Picking of individual leaves when these are the size of the palm of a hand.
- Breaking off the leaves around the terminal growth tips of the stems.

Grain harvesting: Harvesting amaranth seeds is done by cutting the seed heads just before these become dry and brittle and drying them in the shade on a cloth or by placing them inside paper or cloth bags with the heads down.

5.4.6. Cassava

Cassava ©FAO

Description: Cassava is a very important staple food crop for many countries. It is also widely grown as a famine reserve crop. It has high yielding capability, is easy to grow and performs well even in marginal areas. Cassava is also a good source of alcohol and industrial starch.

Uses: Cassava can be used as food, for alcoholic beverages, for the production of biofuel, as animal feed, as laundry starch and for medicinal use.

Soil: Cassava can be grown on a wide range of soils but grows best in deep, free draining soils with reasonable fertility levels. Shallow soils which may restrict tuber expansion should be avoided.

Rainfall: Cassava is highly drought resistant and can be grown in many areas where rainfall is low and unreliable.

Altitude: Cassava grows at all altitudes, but grows best at low to medium altitudes. It is low-yielding at altitudes above 1 500 masl.

Water management: Once established, cassava can grow in areas that receive just 400 mm of average annual rainfall, but much higher yields can be obtained with higher levels of water supply. (Maximum root yields in Thailand were correlated with rainfall totalling about 1700 mm.) Optimizing rainfed cassava production requires careful attention to planting dates, planting methods, planting positions and soil management practices that help to conserve water.

Cassava responds well to irrigation. Full surface irrigation can double the root yield obtained without irrigation. Drip irrigation can produce about the same yield as surface irrigation using 50 percent less water.

Propagation: Cassava is propagated using stem cuttings.

Harvest: Cassava takes 8 to 36 months to mature, depending on the variety. Yield also varies depending on variety and soil type. Average yields are 10 to 30 tonnes/ha. Cassava can be harvested individually (one tuber at a time) or by uprooting whole plants. A stick or hoe may be used to remove the tubers. Cassava cannot be stored fresh for long periods and is therefore sliced and dried in the sun. Dry cassava can be pounded into flour which can be stored for long periods of time in dry conditions.

CHAPTER 6

Good agricultural practices (GAPs) for brackish water use

Irrigation should be managed in a manner that optimises the use of resources and ensures that crop yield is maximized, while minimizing crop stress, energy use and loss of nutrients to surface and groundwater sources. Practices to achieve this will vary depending on the quality of the irrigation water and the amount applied, the crop and soil type, and the irrigation method used, as well as site-specific conditions.

Good Agricultural Practices (GAPs) are “practices that address environmental, economic and social sustainability for on-farm practices, resulting in safe and quality food and non- food agricultural practices” (FAO COAG 2003 GAP paper). There are numerous competing definitions of what methods constitute good agricultural practices, so whether a practice can be considered “good” will depend on the standards a farmer is applying. Consequently, the term is generally used to refer to private, voluntary and non-regulatory applications that are being developed and applied in numerous forms by governments, civil society organizations and the private sector to meet farmers’ and consumers’ needs. In the context of the NENA guidelines developed here, the focus is on defining GAPs that optimize irrigation practices using saline and saline-sodic water to produce acceptable crop production in an environmentally sustainable manner. The focus of these GAPs will be on irrigation methods and management, irrigation quality and crop salt tolerance, leaching and drainage, and managing sodicity to sustain soil physical conditions. Therefore, while fertilizer and pest management practices are indeed important GAP considerations, they are beyond the scope of this manual will not be addressed here.

6.1. IRRIGATION SCHEDULING

Whether using non-saline or brackish water for irrigation, irrigation scheduling is critical to ensure that the right amount of water is applied to the crop, as uniformly as possible, and at the correct time. Throughout the season, irrigation supply should replenish water lost from the root zone via evapotranspiration (ET) and drainage, preventing the depletion of soil water below the critical limit. When using brackish water, it is particularly critical that soil moisture remain at a higher matric potential (less dry) than would be tolerated using non-saline water and that the concentration of salts in the soil water is maintained within tolerable levels. This does not necessary imply that crops should be irrigated more frequently (see Figure 6.1, Box 6.1).

There are several methods for scheduling irrigation, and, in many cases, a combination of these methods can be applied.

Some methods monitor the plant and soil, such as those based on monitoring soil salinity and moisture content (e.g. gravimetric soil moisture sampling, dielectric sensors and soil salinity probes, as shown in Box 2.2), those that measure soil moisture tension (such as tensiometers and electrical resistance blocks), and those that characterise plant response to soil water status (monitoring stem-water potential, canopy temperature, sap flow and plant growth rate). Most of these are useful for timing irrigations. Other methods rely on weather data, canopy cover and irrigation management practices to estimate crop ET. It is this water balance approach to irrigation scheduling that is useful in determining the amount of water to apply as it requires the use of weather parameters and formula (such as the Penman-Monteith equation) to quantify crop evapotranspiration (ETc) using reference evapotranspiration (ETo) and site-specific crop coefficients (Kc) (Allen *et al.*, 1998). For detailed information on irrigation scheduling using this approach, see FAO Irrigation and drainage paper 56 (Allen *et al.*, 1998). For detailed information crop yield response to water applications, see FAO Irrigation and Drainage Paper 66 (Steduto *et al.*, 2012).

Box 6.1 Salinity, irrigation frequency and ET

In saline soils, plants will respond to combined salt and water stress. But does that mean that plants in salt-stressed environments should be irrigated more frequently? Clearly, plants will perform better when grown on saline soils if water deficit stress is minimized. However, increasing irrigation frequency does not necessarily improve yields of salt-stressed crops (Bresler & Hoffman 1986; Maas & Grattan, 1999; Shalhevet *et al.*, 1986). Figure 6.1 shows the relative yield of sweet corn in relation to irrigation water salinity (ECw) at different irrigation frequencies. Note that at the highest two salinity levels (ECw 10.4 and 7.9 dS/m), relative yields are not much different as irrigation frequency decreases from every 3.5 days to 21 days. Salt-stressed plants are smaller and grow slower than non-salt-stressed plants, and require less water over a given time when the ET is low. Consequently, salt-stressed plants deplete a smaller percentage of available soil water than non-saline plants, so they are less responsive to frequent irrigations. Thus, increased irrigation frequency benefits salt-stressed plants only when it reduces water stress, maintains the salt concentration in the soil solution below growth-limiting levels and does not contribute to additional stresses such as anoxia or root disease. Therefore, salt-stressed plants should not necessarily be irrigated more frequently; they should be irrigated at lower soil-water depletion (Wadleigh & Ayers, 1945).

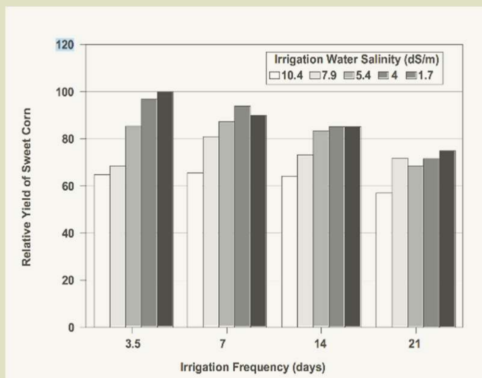


Figure 6.1 Relative yield of sweet corn in relation to irrigation frequency at different salinity levels (after Hanson *et al.*, 2006).

***Source**: Hanson, B., S.R. Grattan and A. Fulton. 2006. Agricultural Salinity and Drainage. Division of Agriculture and Natural Resources. Publication 3375. University of California., Davis. 164 pp*

References

Hanson, B., S.R. Grattan and A. Fulton. 2006. Agricultural Salinity and Drainage. Division of Agriculture and Natural Resources. Publication 3375. University of California., Davis. 164 pp. https://hos.ifas.ufl.edu/media/hosifasufledu/documents/pdf/in-service-training/ist30688/IST30688---24.pdf

Maas, E.V and S.R. Grattan. 1999. Crop yields as affected by salinity. In. Agricultural Drainage, ASA Monograph No. 38. J. van Schilfgaarde and W. Skaggs (eds). American Society of Agronomy. Pp 55-108. https://doi.org/10.2134/agronmonogr38.c3

Shalhevet, J., A. Vinten and A. Meiri. 1986. Irrigation interval as a factor in sweet corn response to salinity. Agronomy Journal 78:539-545. https://doi.org/10.2134/agronj1986.00021962007800030031x

Wadleigh, C.H. and A.D. Ayers. 1945. Growth and biochemical composition of bean plants as conditioned by soil moisture tension and salt concentration. Plant Physiol. 20:106-129. https://doi.org/10.1104/pp.20.1.106

6.2. IMPORTANCE OF LEACHING FOR SALINITY CONTROL

Soil salinity is controlled by avoiding excessive salt accumulation in the crop root zone. The sustained, long- term use of saline water for irrigation, therefore, requires salt to move past the root zone. This downward movement is commonly referred to as leaching and is necessary – regardless of plant type – to optimize plant productivity. The leaching fraction (LF) is defined as the fraction of infiltrated irrigation water that drains below the root zone (see Figure 6.3, Box 6.2). Simply put, it is the volume of drainage water divided by the volume of infiltrated water.

$$Leaching\ fraction\ (LF) = \frac{\text{volume of drainage water}}{\text{volume of infiltrated water}}$$ **Equation 6.1**

The LF needed is dependent on plant tolerance to salinity, the salinity of the irrigation water, crop evapotranspiration and site-specific conditions. The leaching requirement (LR), on the other hand, is the minimum LF needed to maintain the soil salinity at the threshold ECe level (t) for the crop type being irrigated. The greater the salt-tolerance, the lower the required leaching; and for a given salt tolerance, the higher the irrigation water salinity, the greater the required leaching.

When leaching occurs, soil salinity increases with increased depth in the soil profile, as shown in Figure 6.2. But the increase in salinity with depth is dependent upon irrigation water salinity, the LF and the root water extraction pattern. Figure 6.2 shows two distinct soil salinity profiles in an alfalfa field; one using a saline water of 6 dS/m and a high LF of 50 percent and the other using a lower salinity water of 2 dS/m and a lower LF of 7 percent. Note that the average root zone salinities in this alfalfa field under both scenarios are, more or less, equivalent to one another, despite the fact that one irrigation water is three times more saline than the other.

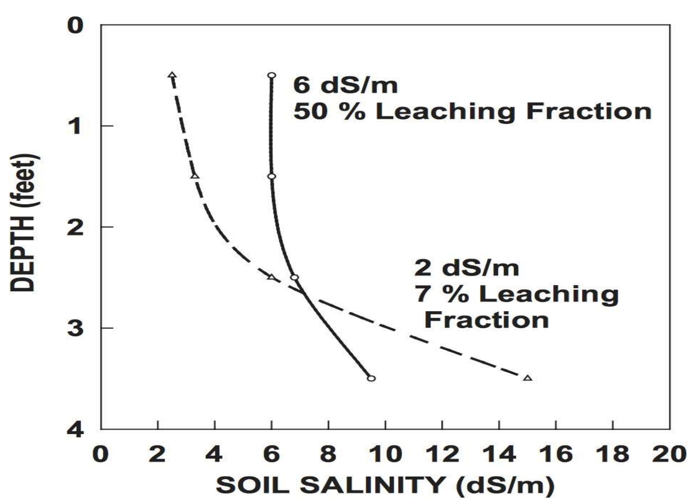


Figure 6.2. Salt distribution in an alfalfa field irrigated with different water salinities and leaching fractions. Note: 1.0 ft = 30.5 cm.

Source*: Hanson, B., Grattan, S.R. & Fulton, A. 2006. Agricultural Salinity and Drainage. Davis, Division of Agriculture and Natural Resources (UCANR) Publication 3375. University of California.*

Box 6.2 Leaching fraction and leaching requirement

Often, leaching fraction (LF) and leaching requirement (LR) are used interchangeably. But the two, in fact, are different. The LF is defined as the volume of water that drains below the root zone divided by the volume of water that infiltrates the soil surface (equivalent to applied water assuming no surface runoff or evaporation) (Figure 6.1). LF can also be estimated based on the salinity of the irrigation water (ECw) and that of the drainage water (ECdw) where LF = ECw/ECdw. The LR, on the other hand, is the lowest leaching fraction needed, given the irrigation water salinity (ECw) and yield threshold (t) for the given crop, to sustain maximum yield.

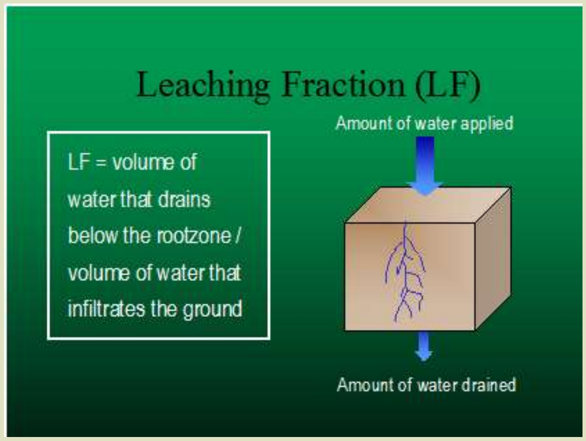


Figure 6.3. Definition of leaching fraction (LF).

Source: *Rhoades, J.D. and S.D. Merrill. 1976. Assessing the suitability of water for irrigation: Theoretical and empirical approaches. In: Prognosis of salinity and alkalinity. FAO Soils Bulletin 31. FAO. Rome pp 69-110.*

LR can be estimated using the following equation (Rhoades & Merrill, 1976):

$$LR = \frac{\text{ECw}}{5(ECet) - ECw}$$ **Equation 6.2**

where ECw (dSm) is the electrical conductivity of the irrigation water and ECet is the yield threshold soil salinity (t) for the crop (available in tables 5.1 and 5.2).

Reference

Rhoades, J.D. and S.D. Merrill. 1976. Assessing the suitability of water for irrigation: Theoretical and empirical approaches. In: Prognosis of salinity and alkalinity. FAO Soils Bulletin 31. FAO. Rome pp 69-110. https://doi.org/10.1104/pp.20.1.106

6.2.1. ECw–ECe–LF relations under conventional irrigation

The obvious practical difficulty with LF, as defined in Equation 6.1, is measuring the volume of drainage water under field conditions. But this difficulty can be overcome by developing relationships (like the ones illustrated in Figure 6.3) between ECw, LF and average root zone salinity (ECe). In order to effectively use the salt tolerance information presented in tables 5.1 and 5.2, a relationship of this type is needed. Relationships between ECw (electrical conductivity in the irrigation water) and ECe (average root zone salinity expressed as the EC of the saturated soil extract) were developed by Ayers and Westcot (1985). They assumed crops are irrigated by conventional methods (i.e. irrigations are infrequent, with 50 percent or more of the available water being depleted between irrigations) and a steady-state LF is achieved (Figure 6.4). Steady-state leaching assumes that the flux of water downward in the soil profile is constant and that the leaching fraction remains fixed for each irrigation. Figure 6.4 was constructed based on the infinite number of scenarios from relationships illustrated in Figure 6.2. Note that as the LF increases, the slope of this relationship decreases. Ayers and Westcot also assumed that the root water extraction pattern would follow a 40–30–20–10 relationship, indicating water uptake for the top, second, third and bottom quarters are assumed to be 40, 30, 20 and 10 percent, respectively.

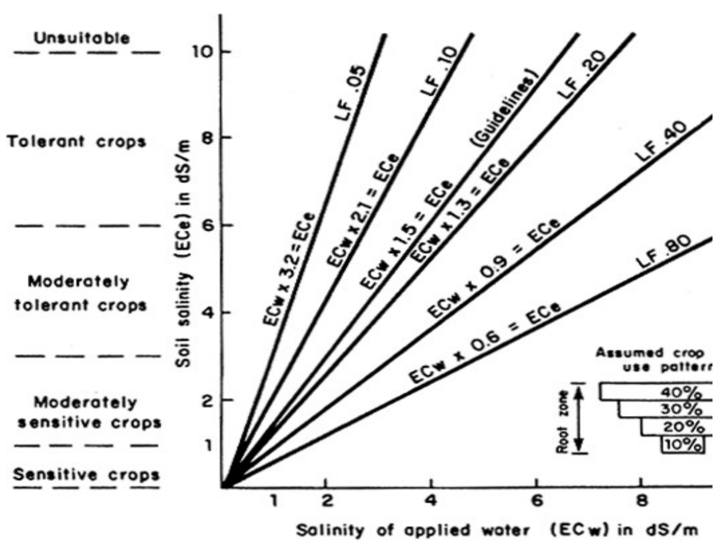


Figure 6.4. Relationship between soil salinity (ECe) and salinity of the applied irrigation water (ECw) under a series of steady-state leaching fractions (0.05 to 0.80).
Source*: Ayers RS, Westcot DW. 1985. Water Quality for Agriculture. FAO Irrigation and Drainage Paper 29, Rev. 1. Food and Agriculture Organization of the United Nations, Rome, Italy.*

Rather than trying to interpret ECe values based on ECw and assumed steady-state LF off the graph, Ayers and Westcot (1985) developed a table with different concentration factors (Fc) for different LFs (Table 6.1). This relationship applies to conventional irrigation practices. This Fc is basically the slope of the relationships in Fig. 6.2 such that ECe = (Fc) ECw.

Table 6.1. Concentration factor (Fc) in relation to the leaching fraction (FC), assuming a 40–30–20–10 percent root water extraction pattern with descending root zone quarters and assuming a linear average. To be used for lower frequency, conventional irrigation such as surface irrigation.

Leaching fraction (LF)	Concentration factor (Fc)
0.05	2.79
0.10	1.88
0.20	1.29
0.30	1.03
0.40	0.87
0.50	0.77

***Source**:* Suarez, D. 2012. Irrigation water quality assessments. In. (W.W. Wallender and K.K. Tanji, eds). Agricultural Salinity Assessment and Management (second edition). ASCE pp 343-370

To better illustrate how this relationship can be applied to crops with different sensitivities to salinity, Ayers and Westcot placed general salt tolerance categories on the y-axis to indicate the soil salinity threshold (t) limits where yields begin to decline. For example, if an irrigation with an ECw of 4.0 dS/m is used with an achievable LF of 40 percent, then the expected average root zone salinity (ECe) would be 3.5 dS/m (see Fig. 6.4 and Table 6.1).

This suggests that only crops classified as moderately tolerant or tolerant to salinity can be grown with this water and LF without a reduction in the yield potential. Ayers and Westcot selected the relationship ECe = 1.5 (ECw) as a reasonable guideline between irrigation water salinity and soil salinity, using an achievable leaching fraction of 15–20 percent based on conventional irrigation methods (i.e. surface irrigation such as flood or furrow irrigation) where irrigations are less frequent than those using drip or micro-sprinklers. This has since been adopted as the standard or guideline by which water quality is assessed. Using the crop salinity threshold (t) from tables 5.1. and 5.2, the ECw can be calculated indicating the maximal salinity of the irrigation water possible, while achieving the full yield potential of a crop, given this leaching-fraction (LF). For example, if the yield threshold ECe is 2.5 dS/m, as it is for tomato, then the maximum ECw that can be used to achieve full-yield potential, assuming a 15–20 percent LF, is 1.7 dS/m. Irrigation waters of a higher salinity can be used to irrigate tomato, but the full potential may not be achieved.

6.2.2. ECw–ECe–LF relations for high-frequency irrigation

Similar ECw–ECe–LF relationships have also been developed with high-frequency irrigation, such as drip irrigation (Figure 6.5). According to the figure, for example, if a leaching fraction of 10 percent could be maintained using drip irrigation with irrigation water with an ECw of 3.0 dS/m, the average root zone salinity (ECe) would be 4 dS/m. Under conventional irrigation, this same water and leaching fraction would produce an ECe of 6.3 dS/m (see Figure 6.4). The difference between high frequency and conventional methods of irrigation is that the average root zone soil salinity is calculated differently. For conventional irrigation, the average root zone salinity is the simple average of the ECe in the first, second, third and bottom quarters of the root zone.

For high frequency irrigation, the average root zone salinity for the four root zone quarters are weighted based on water uptake; where water uptake for the top, second, third and bottom quarters are assumed to be 40, 30, 20 and 10 percent, respectively (Hanson *et al.*, 2006). Therefore, salinity in the upper quarter has four times the weight as that in the bottom quarter. Similar to the previous table, Table 6.2 presents Fc values for different LFs based on root zone salinity weighted according to root water uptake.

Table 6.2. Concentration factor (Fc) in relation to leaching fraction (FC) and percentage of applied water, assuming a 40–30–20–10 percent root water extraction pattern with descending root zone quarters and assuming a root zone salinity weighted according to water uptake (Rhoades *et al.*, 1992; Suarez, 2012). To be used for high frequency irrigation such as drip irrigation.

Leaching fraction (LF)	Concentration factor (Fc)
0.05	1.79
0.10	1.35
0.20	1.03
0.30	0.87
0.40	0.77
0.50	0.70

Sources:

- Rhoades, JD, A. Kandiah and AM Mashali. 1992. The use of saline waters for crop production. FAO Irrigation and Drainage Paper 48. Food and Agricultural Organization of the United Nations. Rome 133 pp
- Suarez, D. 2012. Irrigation water quality assessments. In. (W.W. Wallender and K.K. Tanji, eds). Agricultural Salinity Assessment and Management (second edition). ASCE pp 343-370

The relationships in Figure 6.5 would also be different if the uptake function were changed. For instance, if the root water uptake followed an exponential pattern (i.e. 71-–20–6–2 percent), such as that described by Skaggs *et al.* (2014), the slopes of each of the lines would be even less than those indicated in figure 6.5, implying that waters of even higher salinity can be used. That is, the average root zone salinity would be less because the upper quarters of the profile, where salinity is less, are weighted more. High frequency drip and mini-sprinkler irrigation will allow poorer quality waters to be used than those that can be used with other irrigation methods. Caution is advised because reclamation leaching may be needed at some point to leach salts, or boron, from the root zone during winter months (see section 6.6 on reclamation leaching).

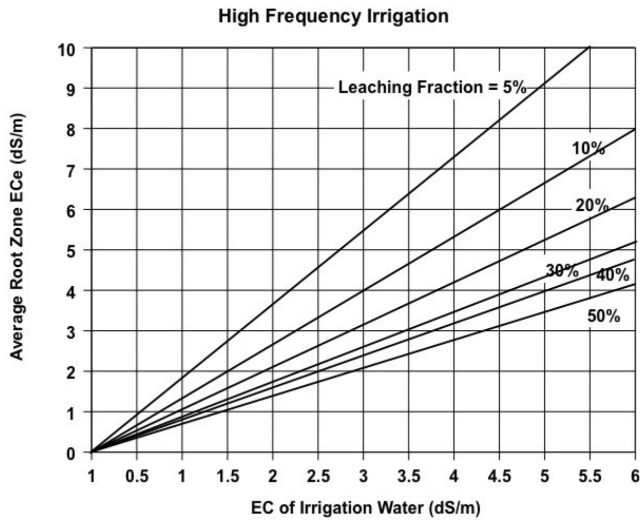


Figure 6.5. Relationship between EC of the irrigation water and the average ECe of the root zone under high frequency irrigation (i.e. drip and mini-sprinklers) (Hanson *et al.*, 2006)

***Source**: Hanson, B.R., S.R. Grattan and A. Fulton. 2006. Agricultural Salinity and Drainage. Division of Agriculture and Natural Resources Publication 3375. University of California. 164pp*

6.3. LIMITATIONS TO THE LEACHING FRACTION CONCEPT

The leaching requirement is an attractive concept, but it has serious limitations. First, the leaching fraction expression has no time element. Therefore, there is no accounting for how long leaching will take, which will differ depending upon the permeability of the soils. Second, the evapotranspiration (ET) of the crop is assumed to be independent of the average root zone salinity. As a result, calculated crop water requirements will be overestimated when the average root zone salinity exceeds the threshold salinity of the crop, which corresponds to a yield potential less than 100 percent (Letey & Dinar, 1986; Shani *et al.*, 2005, Letey & Feng, 2007). That is, a salt-stressed crop will use less water than a non-stressed crop. Consequently, crop ET will be reduced, and leaching, with the same quantity of applied water, will be increased. Other issues also affect the proper calculation of crop water requirements: 1) initial levels of salinity in the root zone,

3) spatial variation in the amount of water applied, 3) the amount of water infiltrates into the soil and 4) the difficulty of achieving adequate infiltration in a field to achieve the desired leaching fraction. In drip irrigated fields, actual LFs are difficult to quantify because LF, soil salinity, soil water content and root density all vary with distance and depth from the drip lines (Hanson *et al.*, 2007). Nevertheless, leaching does occur in drip irrigated fields but the zone of leaching is directly below the emitter. For recommendation on leaching strategies, see Box 6.3.

In light of the discussion above, recent studies have shown that the ECw–ECe relations described by Ayers and Westcot (1985), which are based on steady-state LF conditions, tend to be too conservative and overestimate soil salinity and, therefore, overestimate yield losses in most cases (Corwin *et al.*, 2007; Corwin & Grattan, 2018; Letey *et al.*, 2011). Studies suggest that transient-state models have the potential to more accurately predict soil salinity, as well as soil Cl^-, Na^+ and B. There are many models that predict soil water changes in the root zone and crop response but all vary in function and complexity. Such models include ENVIRO-GRO (Feng *et al.*, 2003), HYDRUS (Šimůnek *et al.*, 2008), TETrans (Corwin *et al.*, 1990), SALTMED (Ragab *et al.*, 2005 a, b), SWAP (van Dam *et al.*, 2008) and UNSATCHEM (Suarez and Šimůnek, 1997), among others.

However, these transient models are complex and most require detailed site-specific information. Additionally, there are uncertainties regarding how the crop responds to salinity and soil water content that vary in the root zone over space and time. For simplicity in developing the guidelines in this report, the high-frequency steady-state method described above was used for developing the irrigation water guidelines described in Chapter 8.

Despite these limitations of the leaching fraction concept, in order to control salinity, leaching must occur – whether it is achieved at the beginning of the season, during the season or at the end of the crop season (Ayers & Westcot, 1985; Shalhevet, 1994). To allow this, soil physical conditions must be maintained such that an adequate amount of water to satisfy the crop, considering crop ET, readily enters the soil. This is an issue when the water used for irrigation is sodic or saline-sodic, where low infiltration rates into the soil reduce water necessary for both crop water requirements and leaching.

Box 6.3 Leaching recommendations: practices recommended to increase leaching efficiency

- Rainfall, if sufficient, is an efficient leaching method because it provides high quality water with high uniformity and relatively low rates of application.
- Leach during the cool seasons instead of during the warm season to increase the efficiency of leaching since ET is lower.
- Consider using more salt-tolerant crops which have a lower LR and thus may have a lower water demand.
- Use tillage to slow losses to runoff and reduce the number of surface cracks, which promote bypass flow and decrease leaching efficiency.
- Use sprinkler irrigation at an application rate below the soil infiltration rate as this favours unsaturated flow, which is more efficient for leaching than saturated flow induced by ponding. More irrigation time but less water is required using sprinkler irrigation than with continuous ponding.
- If sprinklers are unavailable, use intermediate ponding rather than continuous ponding as this is more efficient for leaching and will consume less water, although the time necessary to leach is greater.
- If possible, schedule leaching at periods of low crop water use or postpone leaching until after the crop season.
- If infiltration rates are low, consider pre-plant irrigation or off-season leaching to avoid excessive water applications during the crop season.
- If total rainfall is expected to be insufficient for reclamation leaching, consider post-season irrigation to saturate the soil profile before the start of rainy season.

***Source**: Author's own elaboration (Adapted from various sources)*

6.4. IMPROVING SOIL PHYSICAL PROPERTIES

Soil physical properties can be altered by irrigation with saline-sodic water. This becomes apparent when good quality water is used or rainfall occurs after saline-sodic water application (Oster & Jayawardane, 1998; Oster *et al.*, 1999; Shainberg & Letey, 1984). Potential adverse effects include reduced infiltration and redistribution within the soil, poor soil tilth and inadequate aeration resulting in anoxic conditions for roots (Oster *et al.*, 1999).

These negative impacts, however, can be reduced with appropriate soil and water amendments like gypsum, sulphur, and sulphuric acid (Oster *et al.*, 1992).

The goal in any amendment is to maximize the free Ca^{2+} in the soil solution. Therefore, a direct calcium supplier (such as gypsum) or an acidifying amendment (such as elemental sulphur, sulphuric acid, urea sulphuric acid [N-pHuric] or lime sulphur) to dissolve calcite ($CaCO_3$) in the soil to form free Ca^{2+} are recommended. For more detail on reclaiming sodic soils see Ayers and Westcot, 1985 and Hanson *et al.*, 2006 (see Box 6.3).

In addition, if high levels of B are present in the water, its accumulation in the soil could adversely affect crop production (Grattan & Oster, 2003). Leaching salts and B from the root zone will also leach NO^{-}_{3}. Nitrate losses can be mitigated by additional fertilizer application, but such nitrate losses are not economical and could be environmentally damaging. If, however, leaching can be done at the end of the season when salinity is maximal and soil nitrate concentration is minimal, this would reduce the environmental impact of nitrate contamination of groundwater while at the same time controlling salinity (see Section 6.6).

Box 6.4. Importance of organic matter to control salinity

Maintaining organic matter on the soil surface provides numerous benefits. Organic matter can reduce soil evaporation, minimizing salinity accumulation in the top soil layer, and can minimize the formation of surface crusts. Minimum or zero tillage, as well as mulching, can provide the following beneficial effects:

- reduce soil evaporation – increase water availability;
- increase organic matter;
- reduce soil erosion – increase nutrient availability;
- reduce agrochemical use (through recycling crop residues), labour, machinery, improve biological activity.

Conservation agriculture. No tillage cultivation. ©FAO

Box 6.4. (Cont.)

Deep ploughing (40 to 150 cm) is beneficial for stratified soils having impermeable layers lying between permeable layers. In sodic soils, deep ploughing should be carried out prior to reclaiming the sodicity of the soil. Deep ploughing to 60 cm loosens soil aggregates, improves the physical condition of these layers, increases soil-water storage capacity and helps reduce salt accumulation when using saline water for irrigation. Crop yields can markedly be improved by ploughing to this depth every few years. The selection of the right plough types (shape and spacing between shanks), sequence, and ploughing depth should improve soil structure. Special equipment can even invert problematic soil profiles or break up substrata as deep as 2.5 m. However large tractors are needed to rip the soil to this depth, which may be cost-prohibitive.

Sanding, mixing fine-textured surface soil with sand, is used in some cases to increase the permeability of the soil. While such a practice is infeasible in many instances, when properly done, sanding results in improved soil texture and structure, better root penetration and increased air and water permeability, which facilitates leaching. The method can be combined with initial deep ploughing.

***Source**: Author's own elaboration.*

The incorporation of organic matter into the soil can also affect soil physical conditions. Taylor and Olsson (1987) and Quirk (1978) demonstrated that increased levels of organic matter arising from pasture root systems stabilize soil structure after gypsum is no longer present at the soil surface in sufficient amounts. The adoption of farming practices such as minimum tillage leads to increased retention of crop residues in the form of surface mulches (see Box 6.4). This encourages soil microbial activity (see Box 6.5), including the production of exopolysaccharides (EPSs) that increase and maintain the continuity of large biopores which effectively conduct water and air to subsoils (Jayawardane & Chan, 1994).

Box 6.5 Microorganisms and brackish water

Exopolysaccharides (EPSs), the polymers of monosaccharides, are microbial biopolymers with homo- and hetero- monosaccharide backbones (Ashraf *et al.*, 2013). These EPSs are synthesised and released in the environment by a myriad of microorganisms either for protection from biotic and abiotic stresses (osmotic, ionic, heat, desiccation, drought, water, water turbulence and invasion by other organisms) or in the process of acquiring nutrient from their surroundings as well as in the process of pathogenesis. EPSs are synthesized and released in soil by microorganisms inhabiting the rhizosphere, the roots of the plants and decomposing organic residues. The bacterial EPSs are involved in the formation and stability of soil micro-aggregates, a factor that ensures fertility of the cultivated soils. Rhizosheaths formed around roots by bacterial EPSs contribute to the build-up of soil physical structures, regulate nutrients and water flow from rhizosphere soil to the plants, promote growth and protect roots against pathogens. Thus, bacterial EPSs are directly and indirectly involved in and impact both physico-chemical soil characteristics and plant growth. However, the role of bacterial EPSs in improving soil fertility and their interaction with constituents of the salt-affected soils has rarely been explored.

Reference

M. Ashraf, S. Hasnain, and O. Berge. 2013. Bacterial Exo-Polysaccharides: A Biological Tool for the Reclamation of Salt-Affected Soils. Chapter 42. In Developments in Soil Salinity Assessment and Reclamation by Shabbir A. Shahid • Mahmoud A. Abdelfattah Faisal K. Taha, Editors. Publ. Springer. DOI:10.1007/978-94-007-5684-7_42

6.5. DRAINAGE SYSTEMS

The role of drainage systems in the management of saline soils is particularly important, especially when salinity problems are associated with the presence of a shallow water table or an impermeable soil layer close to the surface causing waterlogging. The presence of a shallow water table may directly influence the soil–water balance and the presence of salts in the root zone through the upward capillary flow of water from the saturated to the unsaturated zone. In such conditions, salt balance cannot be achieved in the root zone.

A subsurface drainage system consists of corrugated plastic tubing with perforations, allowing saturated water to flow into the line (Figure 6.6). This tubing, often referred to as laterals or tile lines, is buried throughout the field at a specified depth and spacing and is connected to a mainline. In the NENA region, drainage systems have been installed in problematic areas planted with cereal and fibre crops. The depth and spacing of the lines vary depending on the soil texture, which is directly related to the soils' hydraulic properties (Table 6.3).

Table 6.3. Drainage practices used in different NENA countries for cereal crops and fibres using brackish water for irrigation

Drainage system
For highly saline soil: Heavy Clay: Surface drainage with spacing of 10 m and 80 cm depth. Clay soil: Surface drainage with spacing of 10 m and 80 cm depth. Loam soil: Surface drainage with spacing of 10 to 15 m and 80 cm depth. Sandy Clay Loam: Surface drainage with spacing of 20 m and 80 cm depth. Mole drainage is recommended at 1.5 m spacing and 45-60 cm depth.
For low salinity soil: Subsurface drainage with spacing of about 50 m and 1.5 m depth.
For sodic soil: Mix gypsum within the 20 cm layer (with ploughing) before crop cultivation to facilitate leaching and drainage.

***Source**:* Data compiled from NENA pilot countries, Author's own elaboration.

Well-designed drainage systems allow the downward movement of water through soils and lower the water table to a desirable level. The goal is to lower the saline water table to a depth that prevents it from contributing to the transport of salts into the root zone by capillary rise. By controlling the groundwater table, the drainage system provides adequate aeration of the root zone and improves the soil conditions for plant growth (Ragab & Amer, 1987). Installing drainage laterals too deep is undesirable in that more drainage water would need to be managed. There are many drainage engineers that have formula for designing drainage systems. For more information on improving subsurface drainage systems, understanding water table depth criteria for drain design, interceptor drains and designing relief drainage systems see Hanson *et al.* (2006).

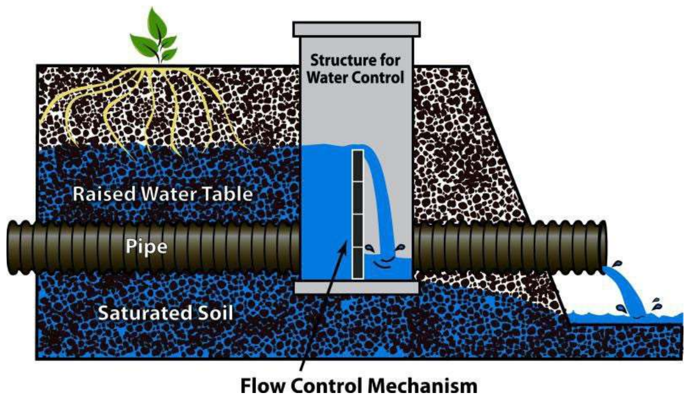


Figure 6.6. Drainage system to lower water tables

(National Resource Concentration Service [NRCS], United States of America).

***Source**: Ogle, D. and St. John, L. (2008). Plants for saline to sodic soil conditions. Plant Materials Technical Note No. 9. USDA-NRCS. Boise, Idaho. 12p.*

Another important role of drainage systems is related to the removal of irrigation water percolated below the root zone. However, the disposal of drainage water can pose serious problems depending on the composition of the drainage effluent, particularly when low quality water is used for irrigation (see Grattan *et al.*, 2012).

6.6. RECLAMATION LEACHING

Researchers have observed that, in many cases, it is more effective to leach salt from the soil at the end of the season than it is to try to impose a LF for each irrigation, especially in fields with low permeability. In many soils, the infiltration rate diminishes throughout the season and the best opportunity to leach the soil is after the growing season, when the evaporative demand is low. Several decades ago, Hoffman (1986) proposed that sprinkler irrigation and intermittent ponding were the most effective means of leaching salts from the soil and developed a leaching reclamation curve (Figure 6.7). This reclamation leaching approach was found to be independent of soil type.

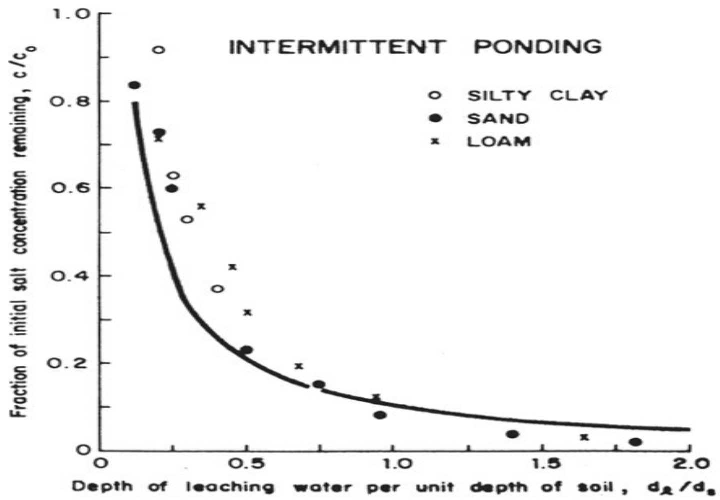


Figure 6.7. Reclamation leaching function under sprinkler irrigation or intermittent ponding (Ayers & Westcot, 1985).

***Source**: Ayers, RS and DW Westcot. 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper 29. Food and Agricultural Organization of the United Nations. Rome.*

The reclamation curve can be used as follows: Suppose the average root zone salinity (ECe) in the top metre of soil is 6.0 dS/m, and the goal is to reduce soil salinity in this 100 cm profile to 3.0 dS/m. Thus, the fraction of salt reduction desired is 0.5 (3.0 dS/m / 6.0 dS/m). According to the graph, the amount of leaching water needed is 0.25 metres of water for every metre of soil. Therefore, 25 cm of water would have to be infiltrated by either sprinkler irrigation or intermittent ponding to reduce the soil salinity in the top metre to 3.0 dS/m. While this is a valuable tool, soil samples should be taken before and after the reclamation process to determine how close the final soil salinity is to the targeted soil salinity.

It is recommended that rainfall be considered in applying this reclamation leaching practice. While annual rainfall in the NENA region is typically low, in some areas rainfall can still contribute to leaching the soil profile.

The reclamation of saline-sodic soils requires an additional step. For reclamation to be effective, the sodicity of the soil must be reduced to improve soil structure. Only an improvement in soil structure will allow the pore size distribution to be adequate to promote drainage and, thus, adequate leaching (see Box 6.6 for more detail).

A reclamation curve is also presented in Ayers and Westcot (1985) for boron. However, this typically requires several times the amount of water to reduce soil boron by the same percentage. This is due to boron's affinity for the soil surface. (A much more detailed discussion on the reclamation of saline-, sodic- and boron-affected soils can be found in Reclamation of saline, sodic, and boron-affected soils by Keren and Miyamoto [2012]).

Box 6.6. Sodicity reclamation

In order to reclaim sodic or saline-sodic soils, the soil structure must be restored so that adequate leaching can take place. This improvement in soil structure can be achieved via chemical amendments and the application of organic matter.

Chemical amendments: In order to reclaim a sodic soil, the exchangeable sodium percentage (ESP) needs to be reduced by replacing adsorbed Na+ with $Ca^{2+.}$ Typically, this is done by adding calcium suppliers (such as gypsum) or amendments (such as acids or acid-forming amendments) to liberate free Ca^{2+} in the soil solution. Some chemical amendments are used to react with calcium carbonate to form free calcium, which then can exchange with the adsorbed Na. This decreases the ESP and should be followed by leaching to remove the sodium-dominated salts (derived from the reaction of the amendments) from the soil. Gypsum is by far the most common amendment for sodic soil reclamation, particularly when using saline–sodic irrigation water. Calcium chloride is highly soluble and would be a satisfactory amendment, especially when added to irrigation water, but the additional Cl can be problematic, particularly to crops sensitive to Cl. Typically, lime is not an effective amendment for reclaiming sodic conditions when used alone. However, when combined with a large amount of organic manure that can produce CO_2 to form carbonic acid, it has a beneficial effect. Sulphur too can be effective. It is inert until it is oxidized by soil micro-organisms to sulphuric acid. Other sulphur-containing amendments (such as sulphuric acid, iron sulphate and aluminium sulphate) are similarly effective because of the sulphuric acid originally present or formed upon microbial oxidation or hydrolysis. (For more information see Hanson *et al.*, 2006.)

The choice of an amendment for a particular situation will depend upon 1) its relative effectiveness in improving soil properties and crop growth, 2) the availability of the amendment, 3) the relative cost and application difficulties, and 4) the time required for the amendment to react in soil and effectively replace the adsorbed sodium.

Attempts have been made to coagulate soil particles to provide better aeration and water permeability deep in the profile by means of chemical treatment. Treating the soil with dilute bituminous emulsions, for example, can result in effective aggregation, improved aggregate stability and reduced surface crust formation. Water infiltration rate is faster in bitumen-treated soil.

Sulphate lignin conditioners can also be used to improve soil structure and soil permeability. Soil conditioners can have practical applications in seedling establishment when soil is irrigated with saline water with a high SAR. Soil aggregate stability prevents dispersion and formation of deposit crusts. Infiltration can be enhanced by the application of small quantities of organic polyelectrolytes to the soil surface, either in the irrigation water or sprayed over the soil surface.

Organic matter, including green manures and mulching: Incorporating organic matter into the soil has two main beneficial effects for soils irrigated with saline water with high SAR and for saline–sodic soils: improvement of soil permeability and release of carbon dioxide and certain organic acids during decomposition. These effects help to lower soil pH and release calcium by dissolving $CaCO_3$ and other minerals, thereby replacing exchangeable Na with Ca, which lowers the ESP. Growing legumes and using green manure will improve soil structure. Green manure has a similar effect to that of organic manure. Salinization during fallowing may be severe where a shallow water table exists. Mulching to reduce evaporation losses will also decrease salinization near the soil surface. When using saline water on soils with high concentration of soluble salts, mulching can help leach salts, reduce ESP, and thus enhance the production of tolerant crops.

References

Hanson, B.R., S.R. Grattan and A. Fulton. 2006. Agricultural salinity and drainage. UC ANR publication No 3375. University of California, Davis. https://hos.ifas.ufl.edu/media/hosifasufledu/documents/pdf/in-service-training/ist30688/IST30688---24.pdf

6.7. IRRIGATION METHODS

The method of irrigation can have a profound influence on how salt is distributed in the soil profile and how the crop responds to the applied irrigation water. The terrain can dictate to some extent what systems can be used. Surface irrigation methods are limited to flat, level landscapes, while undulating landscapes require pressurized systems such as sprinkler and drip irrigation. These pressurized systems require a pump and water must be available at critical times. Surface irrigation methods, such as furrow and flood irrigation, may not require a pump at the farm level, but these methods are not as conducive to frequent irrigations as pressurized systems. Well-designed sprinkler and drip systems typically have higher achievable distribution uniformities (DUs) than surface methods. With higher DUs, not only is irrigation water spread more uniformly over the surface, but water is used more efficiently as less water is lost to deep percolation. There is no one irrigation system that fits all situations and the most suitable irrigation system should be used according to the site-specific conditions. (For more information on irrigation efficiency and optimizing DUs, refer to Hanson *et al.*, 2004).

6.7.1. Salt distribution under different irrigation methods

Salt distribution patterns are greatly influenced by the different irrigation methods, and this affects where the roots proliferate in the soil profile. Figure 6.8 shows typical soil salinity distribution patterns under different irrigation methods.

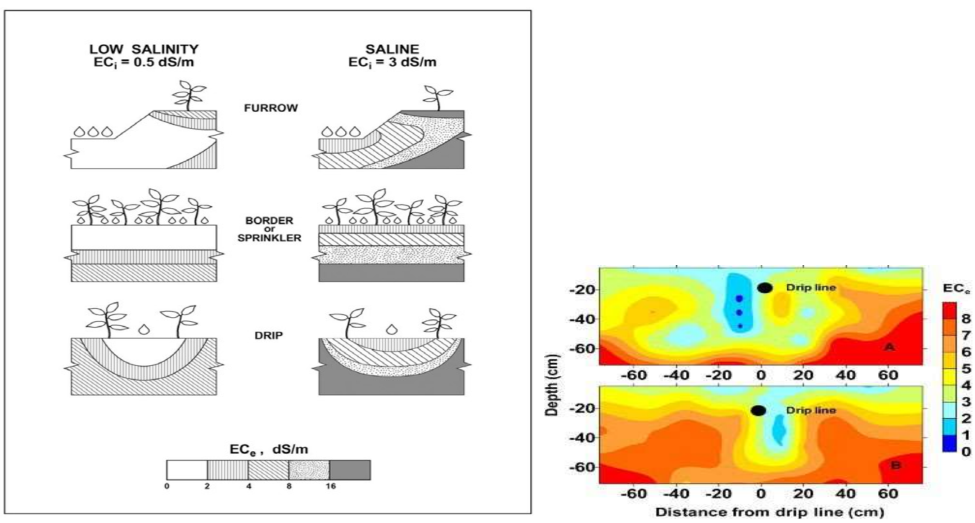


Figure 6.8 Characteristic salt distribution patterns in furrow irrigated, border or sprinkler, and surface drip irrigated fields (left) (Hoffman, 1986) and actual salt distribution in a subsurface drip irrigated field (right) (Hanson *et al.*, 2007).

Sources:

- *Hoffman, G. J. 1986. "Guidelines for reclamation of salt-affected soils." Applied Agricultural Research, Vol. 1(2):65-72.*
- *Hanson, B.R., J.W. Hopmans and J. Šimůnek. 2007. Leaching with subsurface drip irrigation under saline, shallow groundwater conditions. Vadose Zone Journal 7:810-818.*

As shown in Figure 6.8, soil salinity is lowest at the point of entry of the irrigation water. This is true whether the irrigation water enters into a furrow, enters evenly downward under sprinkler irrigation or enters at the point where the drip emitter is in direct contact with the soil. Then, as soil water moves away from the point of entry, roots extract water, concentrating the salts along the way.

It is this water flow direction and root water extraction that creates the characteristic salt patterns. The low salinity zone, regardless of irrigation method, is where most of the roots will proliferate. Note that where soil salinity was characterized in a subsurface drip irrigated field (Fig. 6.8, right), the actual salinity distribution is also influenced by the heterogeneity of the soil.

6.7.2. Furrow irrigation and seedbed management

Investigators have long understood how salts move in soils under different irrigation methods and have developed planting strategies to optimize stand establishment. Yield losses in fields are often attributed to failures in germination and emergence (Hamdy, 1990b; Hamdy, 1993). Thus, seedbed shape and seed location should be managed to minimize salinity effects (Figure 6.9). For soils irrigated with saline water, sloping beds are the best as seedlings can be safely established on the slope below the zone of salt accumulation (Bernstein *et al.*, 1955; Bernstein & Fireman, 1957).

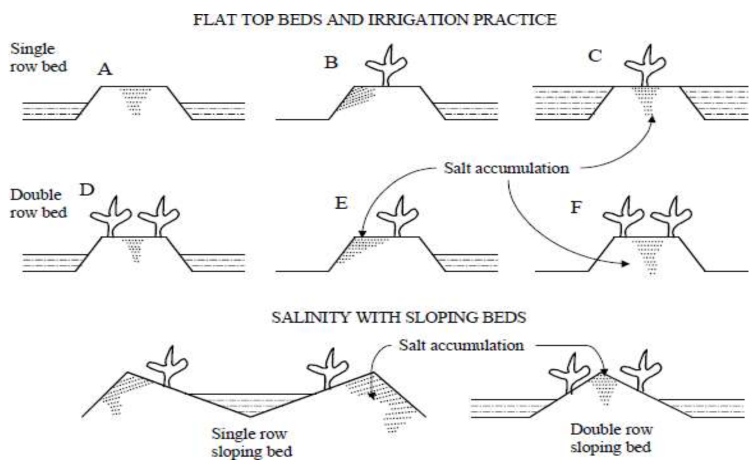


Figure 6.9. Typical salt accumulation pattern in ridges and beds cross section in soils irrigated by furrows *(Bernstein & Fireman, 1957)*

***Source**: Bernstein, L. and M. Fireman. 1957. Laboratory studies on salt distribution in furrow-irrigated soil with special reference to the pre-emergence period. Soil Sci. 83:249-263*

Crop roots will exploit the soil profile in the most favourable conditions of salinity, water content, soil strength, aeration, pH and available nutrients. However, understanding how the plant responds to soil conditions that vary over space and time is very difficult. In regards to irrigation methods, crops typically perform better under brackish water irrigation using drip irrigation and worse under sprinkler irrigation.

6.7.3. Drip irrigation

Under drip irrigation, the salinity of the soil water near the dripper is close to that of the irrigation water or slightly above. Moreover, a well-designed drip system reduces weed growth, improves distribution uniformity, reduces unnecessary water losses and allows for better fertilizer application (see photos below). Because root density is highest where soil conditions are most favourable, crops under drip irrigation can take advantage of this low-salinity zone that does not exist under sprinkler or surface irrigation.

In addition, with frequent irrigation and controlled application rates, inherent soil heterogeneity throughout the field can be partially overcome than would otherwise with surface irrigation methods.

The latter method would lose more water in the sandier soils or portions of the field with the highest infiltration rates. The main limitations of drip irrigation lie in the higher initial cost, the power and water supply needs, and the higher management skills required to effectively run the system. The development of high soil salinity between drippers requires end-of-season leaching to avoid potential damage to subsequent crops. There is also the concern that, under brackish water irrigation, drip emitters will be more vulnerable to chemical clogging. Often, brackish water is alkaline with substantial amounts of calcium. Calcite can precipitate on the outside of the emitters, reducing the emitter flow rate. To correct this, periodic acid injection is recommended to reduce calcite precipitation.

Surface drip irrigation ©FAO

Subsurface drip irrigation with drip tubes buried ©FAO

6.7.4. Sprinkler irrigation

Sprinkler irrigation allows the irrigator to apply the irrigation water uniformly and to control the rate of water application. Sprinkler irrigation is ideal for leaching because salt transport is predominantly downward and pre-plant leaching of the topsoil layer will help with stand establishment.

Under sprinkler irrigation, applied water can be controlled at or below the infiltration rate.

However, this method of irrigation typically wets the canopy, and leaves that are wetted by saline sprinkler water can absorb salts directly, making them more susceptible to sodium and chloride toxicity (see photo, Box 6.7). If sprinkler irrigation can be managed to irrigate the field below the canopy and not wet the leaves, crop damage from foliar absorption of salts can be avoided.

Box 6.7. Sensitivity of crops to saline sprinkler irrigation

Unlike irrigation methods that do not wet leaves, sprinkler irrigation can increase crop sensitivity to saline irrigation due to foliar absorption and potential accumulation of salts to toxic levels. When leaves are wetted by irrigation, salts can accumulate in the leaves by two processes; 1) absorption by roots and translocation to leaves and 2) direct foliar absorption (Maas, 1985; Maas & Grattan, 1999). This makes the crop more sensitive to specific ion effects (see Chapter 4) thereby making them more sensitive to salinity when under sprinkler irrigation. Of course, crops vary in their sensitivity to saline sprinkling water, but this sensitivity is not related to their sensitivity to salinity under conventional or surface irrigation. The vulnerability to foliar salt injury is related to the rate of foliar absorption, which is related to the leaves' wettability and leaf surface features (such as cuticle composition, presence of trichomes, etc.). Therefore, wettable leaves, such as tomatoes (see photo) and potatoes, which also have trichomes on the leaf surface, absorb salt much faster through the leaves than do non-wettable, waxy leaves, such as cauliflower or sorghum and are therefore more sensitive to saline sprinkler irrigation (see Table 6.4).

Table 6.4. Relative susceptibility of crops to foliar injury from saline sprinkler water (from Maas & Grattan, 1999).

Minimum concentration of Na or Cl in the saline sprinkler water that causes injury (meq/l)			
< 5	5-10	10-20	>20
Almond	Grape	Alfalfa	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Tomato	Corn	Sugar beet
Plum		Cucumber	Sunflower
		Safflower	
		Sesame	
		Sorghum	

Source: *Maas, E.V and S.R. Grattan. 1999. Crop yields as affected by salinity. In. Agricultural Drainage, ASA Monograph No. 38. J. van Schilfgaarde and W. Skaggs (eds). American Society of Agronomy. Pp 55-108.*

Note: Susceptibility is directly related to foliar absorption rate of Na and Cl. Because irrigation frequency and environmental conditions influence the rate of absorption and injury, these guidelines are very general and apply to daytime sprinkling.

Climatic conditions and irrigation frequency also affect the rate of foliar absorption of salts. Because the rate of foliar absorption is related to temperature, humidity, wind and duration of water retention times on the leaf, strategies to reduce foliar absorption from saline sprinkling water include 1) reducing the frequency of sprinkler irrigations, and 2) irrigating crops at night (Maas, 1985).

Increasing impact of salt injury from sprinkler irrigation. Leaf on left from non-saline sprinkler irrigated plants and the three on the right were sprinkler irrigated with 30 meq/l salt solution. Photo by S. Grattan, US Salinity Laboratory. ©US Salinity Laboratory.

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Maas, E.V. 1985. Crop tolerance to saline sprinkling water. Plant Soil 89:273-284. https://link.springer.com/content/pdf/10.1007/978-94-009-5111-2_18.pdf

Maas, E. V. and S. R. Grattan. 1999. Crop yields as affected by salinity. In R. W. Skaggs and J. van Schilfgaarde (eds) Agricultural Drainage. Agronomy Monograph 38. ASA, CSSA, SSA, Madison, WI. https://doi.org/10.2134/agronmonogr38.c3 pp. 55-108

6.8. IRRIGATION STRATEGIES USING BRACKISH WATER

Use of brackish water for irrigation requires improved management practices other than the standard water management ones such as 1) selecting the appropriate crops and crop rotations, 2) identifying the most appropriate method of irrigation, 3) determining the amount, timing and method of irrigation to achieve the necessary leaching, and 4) selecting the type and amount of amendments if soils are also sodic. To sustain good management practices, continuous monitoring of the irrigation water, soils and plants must be conducted to make sure salinity and sodicity are controlled within manageable limits. Most of the scientific foundation for management decisions has been laid out earlier in this chapter, however the focus has been on just one source of irrigation water – brackish water. To optimize crop production, management decisions should consider whether low salinity water is also available for irrigation. If two sources of water, saline and non-saline, are available, several other irrigation strategies can be considered.

6.8.1. Mixing or blending irrigation waters

When two sources of water are available for irrigation, blending the two in proportions that provide a water of suitable quality for the crop is an obvious option. The goal is to blend two sources of irrigation water together to achieve a larger volume of water of suitable quality for irrigation. The suitability of the water depends on the salt tolerance of the crop being irrigated.

The following formula can be used to blend two sources of irrigation water of different qualities. The blending ratio (BR) is the volume of good quality irrigation water applied to the field divided by the volume of saline water applied to the field. It is calculated as follows (where ECw, ECs and ECb are the electrical conductivities of the good quality water, the saline water and the blended water, respectively):

$$BR = (ECs - ECb) / (ECb - ECw) \qquad \textbf{Equation 6.2}$$

Crops that are more tolerant can use lower blending ratios. The ECb can be assigned depending upon the crop salt tolerance or acceptable level of yield decline based on targeted leaching. The BR is then calculated knowing the EC of the two different water sources.

Mixing irrigation waters is a way to increase the amount of water available for irrigation. However, there are limits on how salty the saline water can be. Blending only expands the usable water supply when the saline water component, if applied independently without blending, can still produce a crop. In other words, the crop can still extract water from the saline water and grow, albeit at a very low rate. The water is too salty for blending if it is applied by itself and kills the crop, regardless of management and leaching (Grattan & Rhoades, 1990; Rhoades *et al.*, 1992). For example, 1 litre of fresh water mixed with 1 litre of seawater equals 2 litres of water at half sea-water strength. If onions or rice were the crop selected, this blended water is too salty and cannot be used to irrigate these crops. In this example, it would be better to use the one litre fresh water without blending. Blending these waters for onion or rice production, then, would simply result in the loss of 1 litre of fresh water from the system, because the blended water would be too salty to use to irrigate the crop.

6.8.2. Cyclic or alternate use of saline and non-saline water

The cyclic strategy alternates between the use of saline irrigation water and fresh water, usually at different times in the growing season and/or for different crops within a crop rotation. Typically, fresh water is used early on to reduce soil salinity in the upper profile, facilitating germination and permitting crops with lower tolerances to salinity to be included in the rotation (Rhoades *et al.*, 1992). Saline water is used for more salt-tolerant crops or for more salt-sensitive crops later in the season.

The objective of the cyclic strategy is to minimize soil salinity (i.e. salt stress) during the salt-sensitive growth stages, or when salt-sensitive crops are grown in a rotation of crops. This does not simply imply that saline water is only applied to salt- tolerant crops after they reach a salt-tolerant growth stage or that fresh water is only used to irrigate salt-sensitive crops. Soil salinization lags behind saline water application, so that it takes time for a soil profile to become salinized. This allows a more salt-sensitive crop to be irrigated with saline water later in the season in conditions where the soil was initially non-saline at the beginning of the season (Shennan, *et al.*, 1995; Bradford & Letey, 1992). Similarly, without pre-plant leaching or sufficient rainfall, it is often difficult to return to a salt-sensitive crop using non-saline water in a soil that was previously salinized.

6.8.3. Comparing irrigation strategies

Each method of irrigation with saline water has its advantages and disadvantages. Mixing is the easiest practice, while alternating fresh and saline waters requires some knowledge on the varying crop tolerance levels during different growth stages (see Chapter 5). In addition, mixing requires that both fresh and saline water are always available. Alternating saline and fresh water, on the other hand, offers a better salt leaching mechanism. That is, when saline water irrigation is followed by fresh water, the latter will leach the salts accumulated in the soil from the saline irrigation. This keeps the soil profile in a transient state. Mixing does not offer this possibility as it continuously adds salts; thus, salinity is only controlled by post-season leaching. While the cyclic method has advantages over the blending method, it requires a higher level of management skill to make this practice sustainable.

Irrigation with saline-sodic water requires a higher level of management over the long term, than does irrigation with non-saline water, not only to avoid long-term salinization but to maintain soil physical conditions. Soil physical properties can be affected by irrigation with saline-sodic water, particularly when saline-sodic irrigation is followed by irrigation with good quality water or by rainfall (Grattan *et al.*, 2012). The adverse effects of this include reduced infiltration, poor soil tilth and poor aeration, resulting in anoxic conditions in the root zone (Oster & Shainberg, 2001). These negative impacts can be minimized by applying amendments like gypsum, sulphur and sulphuric acid either to the soil or in the irrigation water (Oster *et al.*, 1992). In addition, if high levels of B are present in the water, its accumulation in the soil could adversely affect crop production (Grattan & Oster, 2003). Boron is particularly problematic in that it takes roughly three times the amount of irrigation water to reclaim soil affected by boron than it does to reclaim saline soil.

As indicated previously, leaching salts and B from the root zone will also leach nitrate. Nitrate losses can be mitigated by additional fertilizer application, but such losses are environmentally damaging and economically unwise. On the other hand, if saline drainage water contains NO^-_3 and is used for irrigation, some crops can be adversely affected, while other crops can benefit (Kaffka *et al.*, 1999). That is, in some crops, excess nitrate in the soil water late in the season can induce excessive vegetative growth and produce poor quality crops. Furthermore, trace elements such as Se or Mo, if present in the saline-sodic water, could accumulate in the crop and pose a health risk to animal and human consumers. Both negative and positive aspects of using saline-sodic waters need to be carefully evaluated before adopting a management strategy.

6.8.4. Sequential use of brackish water

Sequential (or multiple) use of brackish water is applicable in fields with saline water tables with drain lines installed to collect the drainage water. In this practice, the farm is divided into a conventional irrigation area and a brackish water reuse area. The conventional portion of the field contains high value, salt sensitive crops that are irrigated with low saline water. The brackish reuse area consists of a sequence of fields that are irrigated with saline water of increasingly higher concentrations (see Grattan et *al.*, 2012). That is, the drainage water is collected under the field planted with conventional crops. This drainage water, which is more saline than the original irrigation water, is then used to irrigate the next field in the sequence, where the volume of drainage water decreases and the salinity of the water increases (Figure 6.13). The process then continues to the next field. The main purpose of this system is to obtain an additional economic benefit from the available water resources, minimize the area affected by shallow water tables and reduce the volume of drainage water that requires disposal.

Although sequential reuse is a conceptually attractive means of recycling drainage water on a farm or at a district level, there is a significant lag time for salts at the beginning field to reach the final stage of the sequence. Using a transfer function model, assuming typical drain-line spacing and water management practices, investigators found that such a reuse system would never effectively reach steady-state. Rather, it could take decades or even much longer for water and dissolved salts to move though the sequential system (Jury *et al.*, 2003). In addition, the salt removal via harvesting of salt-tolerant and halophytic plants represents a very small fraction of salt removed from the sequential system. Therefore, caution is advised for those designing sequential reuse systems and estimating the rate of salt movement through the system, particularly if steady-state assumptions are used (Grattan *et al.*, 2014). Additionally, drainage water reuse systems are subjected to fluctuating water tables, due to off-farm conditions. These fluctuations, particularly where the water table depth is below the tile lines, will also affect the time needed to establish quasi steady-state conditions.

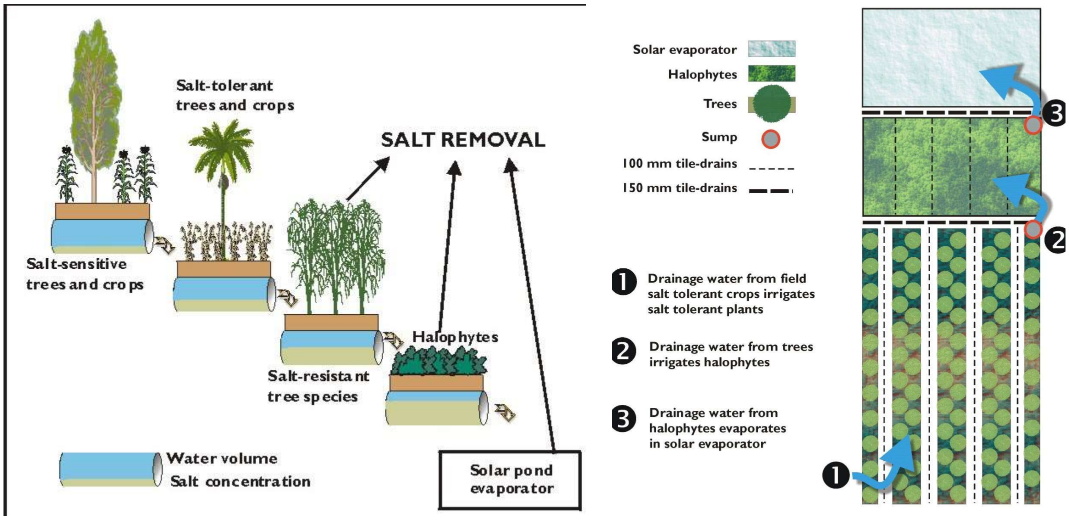


Figure 6.10. Sequential or multiple use of brackish water

Source*: Ragab Ragab (2012). Challenges and issues on measuring, modelling and managing the water resources under changing climate and land use. In: Integrated water resources management in the Mediterranean region, dialogue towards new strategy (Book), by Choukrallah et AL (Ed.). Springers, ISBN 978-94-007-4755-5 ISBN 978-94-007-4756-2(eBook), DOI 10.1007/976-94-007-4756-2, Library of Congress Control Number: 2012948957*

Brackish water could be used multiple times in various parts of a farm as illustrated in Figure 6.10. Here, drainage water is collected under the field of the least salt-tolerant crop first and used to irrigate a crop of higher tolerance. This process is repeated, collecting the drainage water and using it to irrigate sequentially more salt-tolerant crops in order to maximize the benefit of the brackish water.

CHAPTER 7

Evaluating the potential for brackish water irrigation in the NENA region

The question of whether irrigated agriculture in arid and semi-arid climates can be sustained indefinitely has been posed by prominent scientists with considerable expertise in saline agriculture, including Daniel Hillel (2000) and Mark van Schilfgaarde (1994). Both Hillel and van Schilfgaarde have recognized the socio-economic benefits that irrigated agriculture has provided societies over the years, recognizing at the same time that some civilizations have risen and fallen under irrigated agriculture while others have maintained sustainable irrigation for thousands of years. To illustrate this dichotomy, these scientists provide historical comparisons between two contrasting regions within the NENA region (Box 7.1). In ancient Mesopotamia, between the Tigris and Euphrates rivers, the combination of siltation, waterlogging, lack of drainage and resulting salinization impacted crop production causing shifts in cropping patterns. Ultimately, lands were so adversely affected they were banned from production. In the Nile Valley of Egypt, the natural flooding from the Nile not only supplied a continual source of nutrients but provided a natural flushing of salts to the Mediterranean Sea. Ultimately, the difference in the long-term sustainability of irrigated agriculture in the two areas was attributed to salinity build-up vs. salinity control via leaching of salts. Mesopotamia did not have effective leaching and salinity was not controlled. The Nile Valley, on the other hand, had periodic leaching due to water table fluctuations, allowing agriculture to flourish for centuries. However, after the construction of the Aswan High Dam, the natural salinity control mechanism was short-circuited and growers must implement good management practices in irrigated fields to avoid salinization.

Box 7.1 Ancient Egypt and Mesopotamia compared

Irrigation agriculture has been practiced in what is now known as Iraq and Egypt for thousands of years. However, the historical sustainability of irrigated agriculture in the two regions was quite different (Hillel, 1994). Below is a short summary from Hillel.

In Mesopotamia, known as the Fertile Crescent due to its deep alluvial soils, agricultural productivity flourished in ancient times. But diversion of water for irrigation from the Tigris and Euphrates rivers led to a series of problems. The first was siltation, which filled waterways and irrigation channels, flooding adjacent fields. The second problem was salinization of farmlands due to waterlogging of flood-irrigated fields. Perched, saline water tables prevented drainage, and salinity continued to build up in soils.

Box 7.1 (Cont.)

Eventually, moderately salt-tolerant wheat was replaced with more salt-tolerant barley and later, soils became so salt-affected that fields were removed from cultivation. Over the centuries, the Sumer, Akkad, Babylonia and Assyria civilizations rose and declined due to this unsustainable irrigation system.

Unlike Mesopotamia, irrigated agriculture in the Nile Delta region thrived for several thousand years. Why the difference? The answer involves differences between the two regions in soil–water dynamics, involving the inputs and outputs of salts and nutrients. In the Nile Delta, the Nile brought nutrients to the fields: silt from the eroded fertile volcanic highlands of Ethiopia via the Blue Nile and swamp nutrients from the Sudd in southern Sudan via the White Nile. These nutrients reached the soil through annual flooding. As the Nile crested in the late autumn, the seepage from the river raised the water table in the delta soils, then lowered it as river flow receded. This annual pulsation of river flow changes caused the water table to fluctuate in the free draining flood plain of the Nile Delta, allowing salts to be naturally flushed from the delta soils to the Mediterranean Sea. (This natural cycle has since been eliminated with the construction of the Aswan High Dam.)

Figure 7.1. Ancient Egyptians used shadufs (a counter weight system) to lift water from the Nile River to a canal network to irrigate crops as illustrated in this frieze from c. 2000 B.C.E.
***Source**: Water Encyclopedia.com. 2018. Advameg, Inc. http://www.waterencyclopedia.com/Hy- La/Irrigation-Systems-Ancient.html)*

References

Hillel, D. 1994. Rivers of Eden: The struggle of water and the quest for peace in the Middle East. Oxford University Press, New York. https://doi.org/10.1111/j.1949-3606.1996.tb00660.x

Water Encyclopedia.com. 2018. Advameg, Inc. http://www.waterencyclopedia.com/Hy-La/Irrigation-Systems-Ancient.html

7.1 BRACKISH WATER USE ACROSS THE GLOBE

Across the globe, brackish water sources have gone unused because of concerns that this poor-quality water is unsuitable for irrigation and may damage crops. However, this 'unsuitable' water has been used successfully to irrigate crops. Many examples of this are described in detail by Ayers and Westcot (1985) and by Rhoades *et al.* (1992). Some of them are summarized briefly here. It is important to emphasize, however, that successful practices avoided the sustained accumulation of salts through adequate leaching, drainage and amendment applications. It is also important to note that, while successful, yields in some cases were far from optimal.

In the United States, successful use of brackish water (averaging over 4.2 dS/m) to irrigate alfalfa, cotton, sugar beets and small grains has been demonstrated for decades in the Arkansas River Valley (Colorado), the Salt River Valley (Arizona) and the Rio Grande and Pecos River Valleys (New Mexico and Texas) (Rhoades *et al.*, 1992). The success is partly due to management measures that minimize crusting and poor stand establishment. In addition, saline drainage water (EC 8-12 dS/m) on the west side of the San Joaquin Valley, in California, has been successfully used to irrigate crops and forages, including tall wheatgrass (*Thinopyrum ponticum* cv 'Jose') and creeping wild rye (*Leymus triticoides* cv 'Rio') for over a decade (Grattan *et al.*, 2012). This drainage water is somewhat unique in that it is dominated by sodium sulphate, with considerable amounts of boron and trace elements such as selenium and molybdenum. However, the success of drainage water reuse is enhanced when a supplemental supply of good quality water is available at certain times of the year for leaching (in order to maintain soil salinity within tolerable limits during critical times) and when disposal of concentrated drainage water is managed via a system of sequential reuse (Grattan *et al.*, 2012).

While 30 percent of the land in Australia is salt-affected, 60 percent of the country's irrigation water is used for crops grown in the Murray Darling Basin (Rengasamy, 2006; Stillard, 2011). The Murray Darling Basin is affected by salinity but efforts have been made to intercept saline drainage water and groundwater and divert it away from the Murray river system in order to maintain river salinity within manageable levels (Murray-Darling Basin Authority, 2018). Climate change will only exacerbate the problem in the basin where more frequent droughts will place more stress on the existing water supplies. The report by Stillard (2011) acknowledges that irrigation waters with an ECw > 1.5 dS/m will play an important role in supplementing the declining losses in surface water. In addition to salinity, over 80 percent of the irrigated lands in Australia are sodic which affects soil structure, root growth and soil aeration (Rengasamy and Olsson, 1993). Therefore, irrigation management in closely linked with management of sodicity such as gypsum applications to reduce the ESP of the soils. While research and development remains as a key factor for successfully managing salinity and sodicity, combinations of good drainage, crop type selection for better tolerance (Munns, 2002), and good management practices (see Chapter 6) will remain the key for successful use.

In India saline water is found in both groundwater and in many stretches of rivers. The Ganges River is primarily non-saline (about 200 mg/l TDS) as it flows east from the Himalayas. But where it flows in the West Bengal delta, salinity can exceed 2 000 mg/l (Gupta, 1990). It is estimated that 32 to 84 percent of the groundwater surveyed from different states is either saline or sodic (Minhas, 1996).

The composition of the groundwater varies, including bicarbonate-dominated; mixed bicarbonate and chloride-dominated; mixed chloride and sulphate-dominated; and chloride-dominated (Minhas & Gupta, 1992).Unlike many arid regions, crops grown with brackish water in many parts of India benefit from monsoon rains, most of which fall from June to September. These monsoon rains leach accumulated salts from the soil profile. In the Hisar area of Haryana, brackish water is used to irrigate cotton, millet, wheat and mustard, with average yields of 81 percent (using saline water of approximately 4-6 dS/m) and 59 percent (approximately 6-8 dS/m) (Bouman *et al.*, 1988, as cited by Rhoades *et al.*, 1992). Even higher EC water is used to produce wheat (Dhir, 1976). Soil types in this area are predominantly sandy loam, and annual monsoon rainfall is 300 to 1 100 mm, both being conditions that facilitate saline irrigation.

7.2. BRACKISH WATER USE IN THE NENA REGION

The NENA region is faced with a wide range of salinity problems and there are a number of examples in the region of the successful use of brackish water for agricultural production. The region's agricultural practices have evolved through the experience of farmers growing crops under their particular situations of water availability, prevailing agricultural conditions and economic factors. Each country has its own experience in producing crops under its local conditions and each country has its own crop varieties, developed through research and farmers' experiences. Many published papers and reports present case studies of the use of brackish water in agriculture in the NENA region, particularly under water scarcity. Such publications can serve as reference material (see Annex 2), providing important information on success stories and lessons learned.

Table 7.1 details the key crops produced successfully using brackish water and the conditions under which they were grown. The information is based on responses to templates and questionnaires sent to the participating NENA countries (Annex 3) and includes key cereal, fibre, vegetable, fruit and forage crops. As the table indicates, the salinity of the irrigation water used to grow the crops varied widely, from 1.1 to 14 dS/m, albeit with different yield potentials. Sesbania, a halophytic forage crop, was even grown in Syrian Arab Republic with irrigation water that was over 75 percent the salinity of seawater.

Table 7.1 Selected grain, fibre, vegetable, fruit and forage crops successfully produced using brackish water in the NENA region.

Crop	Countries	Irrigation method	ECw	LF[2]
Grain and fibre crops				
Barley	Iraq, Morocco, Syrian Arab Republic	Surface and sprinkler irrigation	2.0–16	10–30
Cotton	Egypt, Yemen	Surface and sprinkler irrigation	3.4–6	10
Rice	Egypt, Iraq	Flood (10 cm above soil surface)	1.1–7.5	10–20
Wheat	Algeria, Egypt, Iran (Islamic Republic of), Iraq, Morocco, Syrian Arab Republic, Tunisia	Surface and sprinkler irrigation	2–7	10–40
Vegetable crops				
Artichoke	Morocco	Surface drip	0.9–6	10
Cucumber	Saudi Arabia	Surface sprinkler	1.4	10
Potato	Tunisia	Drip	0.9–7.5	10–20
Squash	Jordan	Surface drip	3.8–4.5	10–15
Tomato	Egypt, Iraq, Saudi Arabia, Syrian Arab Republic, Tunisia	Surface drip	0.9–6	10
Fruit trees				
Citrus	Algeria	Surface drip	4–7	10–20
Date palm	Algeria, Iraq, Morocco, Saudi Arabia, Yemen	Surface drip	1.2–11	10–20
Olive	Morocco	Surface drip	2–14	10–20
Peach	Tunisia	Drip	5–6	10–20

[2] Leaching fraction (LF) range depending upon the irrigation water and soil salinity.

Forages				
Alfalfa	Morocco	Surface and sprinkler irrigation	2.2–8	25–30
Atriplex	Syrian Arab Republic	Drip/Sprinkler	6–12	25–30
Sorghum (fodder)	Yemen	Surface and sprinkler irrigation	< 3.0	-
Sugar beet	Egypt, Syrian Arab Republic	Surface and sprinkler irrigation	3.5	20

Source: *Author's own elaboration.*

There is also evidence that many brackish water sources are underutilized and poorly managed in the region and that there are many common problems across the region such as waterlogging, poor drainage and seawater intrusion salinizing coastal aquifers. A summary of the status of each country is provided below, including information provided in FAO papers by Ayers & Westcot (1985) and Rhoades *et al.* (1992) as well as information from individual reports submitted in 2012 by the different Arab countries in the region.

7.2.1. Algeria

Algeria is a large country with a land area of 2.38 million km^2, only 18 percent of which is used for agriculture. About 90 percent of the country is in the Sahara Desert, where rainfall is rare but where there are large underground reserves of brackish water. The remaining 10 percent of the land, along the northern coast, has a Mediterranean climate and has renewable surface and groundwater resources (Lahouati & Halim, 2012). It is this small coastal strip, with rainfall varying from 400 to 600 mm, which is most favourable for irrigated agriculture. Much of the land is salt-affected, largely because of inadequate drainage – some of which is linked to excessive flood-irrigation practices and some of which is caused by impermeable soil layers. In the Sahara region, saline groundwater is used for irrigation and in the north, seawater intrusion salinizes coastal aquifers which affects the irrigation potential. While much of the country uses brackish water for irrigation, such practices lack regulation or irrigation management strategies.

7.2.2. Egypt

In Egypt's Nile Delta, producers began implementing agricultural drainage water reuse practices in the 1930s, alongside the development of drainage projects. The reuse of agricultural drainage water increased with the expansion of irrigated agriculture, particularly since 1950. However, much of the drainage water is lost to the Mediterranean Sea via return flows to the Nile River, where about 75 percent has a salinity less than 3000 mg/l TDS (Abu-Zeid, 1988). Over the last three decades, the drainage system has been well developed in the Nile Delta. The system covers all arable lands, with subsurface, perforated lateral-pipes discharging the drainage water into larger subsurface collector pipes. The collector pipes convey drainage water to open-drain branch networks by gravity and subsequently to the disposal sites, usually by pumping. At present, all arable land in Egypt is served by surface and subsurface drainage systems that are essential to control waterlogging and soil salinity. Because of fresh water shortage, drainage water reuse for irrigation has been and will continue to be an important resource for irrigated agriculture in Egypt.

In Egypt, Law 12/1984 regulates the use of agricultural drainage water and groundwater (Fahmy et *al.*, 2000). Government policy is to recycle drainage water by blending it with fresh water from the Nile River, the main source of irrigation water for the country, to achieve blended water with a salinity of about 1.0 dS/m (Abo Soliman, 2012; Rhoades et *al.*, 1992), although typically the salinity ranges a bit higher (from 800 to 1000 mg/l TDS). The Ministry of Water Resources and Irrigation (MWRI) manages the operation of the pumping stations and thus the reuse volume is well monitored and recorded. The drainage water salinity ranges between 1.3 and 4.0 dS/m, except in the most northern part of the Delta near the Mediterranean Sea, where drainage water salinity exceeds 5 dS/m in some locations. Growers in the Beheira, Kafr-El-Sheikh, Damietta and Dakhlia governorates have even used drainage water directly to irrigate barley, berseem clover, cotton, rice, sugar beet and wheat, although though yields are not optimal due to soil salinization and waterlogging (Rhoades et *al.*, 1992). However, with good management and crop selection practices, growers have successfully used drainage water with ECw of 2 to 2.5 dS/m without adverse effects (Rhoades et *al.*, 1992). And in the Nile Valley and Delta, saline groundwater (2.0 to 4.0 dS/m) has been used successfully to irrigate crops for decades.

Extensive groundwater reserves exist in Egypt, but these have been used only to a limited degree. There are several factors that contribute to this, including 1) the uncertainty of salinity changes as groundwater is extracted for irrigation, 2) the difficulty of disposing of the effluent, and 3) the areas of groundwater abundance are in low-demand areas (Abo Soliman, 2012).

7.2.3. Iran (Islamic Republic of)

As presented in the Iran (Islamic Republic of) Assessment Country Report (Cheraghi Halim, 2012), the use of brackish water for crop production has a long history in Iran (Islamic Republic of), Management practices employed by the farmers in using these waters are similar to those practiced with the use of non-saline waters. In general, crop production is based on using high inputs of seeds, fertilizer and water. Agronomic practices such as land preparation, irrigation methods, management and crop rotation are suboptimal. In years when rainfall is normal or above normal, good yields are obtained with the use of brackish waters. Rainfall, in addition to high leaching fraction, which is applied with irrigation, leaches the salt below the root zone. However, under drought conditions, crop yields drop sharply and are lower than average yields in non-saline conditions.

A national salinity strategic plan should be developed and implemented with strategies that optimize to use of brackish water on salt-affected lands (Cheraghi & Halim, 2012).

7.2.4. Iraq

Over the past few decades, Iraq has transformed from a water-abundant country to a water-stressed country (Abdul Halim & Halim, 2012). This transformation is attributed to 1) variability of the hydrological regime in the Tigris and Euphrates river systems, 2) the increasing frequency and severity of droughts due to climate change, 3) the degradation of Iraq's surface water system due to increased development projects upstream, 4) the lack of a regional water management strategy and standards for transboundary water quality control, 5) government policy, and 6) inefficient water management practices. Most of Iraq's surface water supply originates in other countries.

In terms of areas irrigated using surface water, the total Tigris river basin area is approximately 2.2 million hectares, about half of which is using brackish water, and on the Euphrates, it is approximately one million hectares, almost all of which is using brackish water, and on Shatt Al-Arab it is approximately 0.1 million hectares, also all is considered using brackish water. As for the groundwater quality, it differs in place and depth, but is mostly brackish and found at some distance from the rivers, with the exception of the mountain and hilly section in Northern Iraq where water is of good quality.

Evidently, the water supplies have decreased and salinity has increased over threefold in the past 50 years. Therefore, the country will be more dependent on brackish water in the years to come.

7.2.5. Jordan

In Jordan over 60 percent of the produce is grown in the Jordan Valley, where 63 percent of the land is salt affected (Ammari *et al.*, 2013). Salinity increases from the northern part of the valley, where soils are generally well drained, to the south, where soils have a restrictive marl layer affecting drainage in many soils (McCormick *et al.*, 2001). Fresh, surface water sources are limited in Jordan, the largest being the Yarmouk River, which converges with the Jordan River in the north where it feeds into the King Abdullah Canal (KAC), the irrigation water conveyor that delivers water to the valley (McCormick *et al.*, 2001). Other source of water are the Mukheibeh wells, springs and a number of wadis throughout the valley. In addition, municipal waste water from the city of Amman is blended with existing rainwater stored in the King Talal Reservoir (KTR), reducing its overall quality, where it enters the KAC in the Middle Directorate. Since 1998, Jordan's National Water Strategy has been to include waste water reuse as a supplemental source of irrigation water. The salinity of KTR has increased over the years from 1.9 dS/m during the period 1994–1999 (McCormick, *et al.*, 2001) to about 2.2 dS/m in recent years (Alshboul and Lorke, 2015). Despite being poorer quality water, with good irrigation management, the water is technically suitable for irrigation, although less productive for crops sensitive or moderately sensitive to salinity if used undiluted (McCormick *et al.*, 2001).

The Jordan Valley Authority partnered with the German Technical Cooperation (GTC) to evaluate crop production in the middle and southern portions of the Jordan Valley with brackish water ranging between 2 and 7 dS/m over a four year period (GTC, 2003). The goal was to develop guidelines for growers in this region, considering local conditions and practices. Because soil types, crop varieties, growing season and management practices (irrigation, fertilization, plant density, etc.) varied widely from farm to farm, it was difficult to develop reliable guidelines that would be applicable to all areas. Nevertheless, it was found that all the crops in the study group (squash, eggplant, wheat, barley, tomato, potato, sweet corn and two leaf crops) could be successfully grown even though yield potentials were not optimal and only the more tolerant crops could be successfully grown at the high salinities (Figure 7.2).

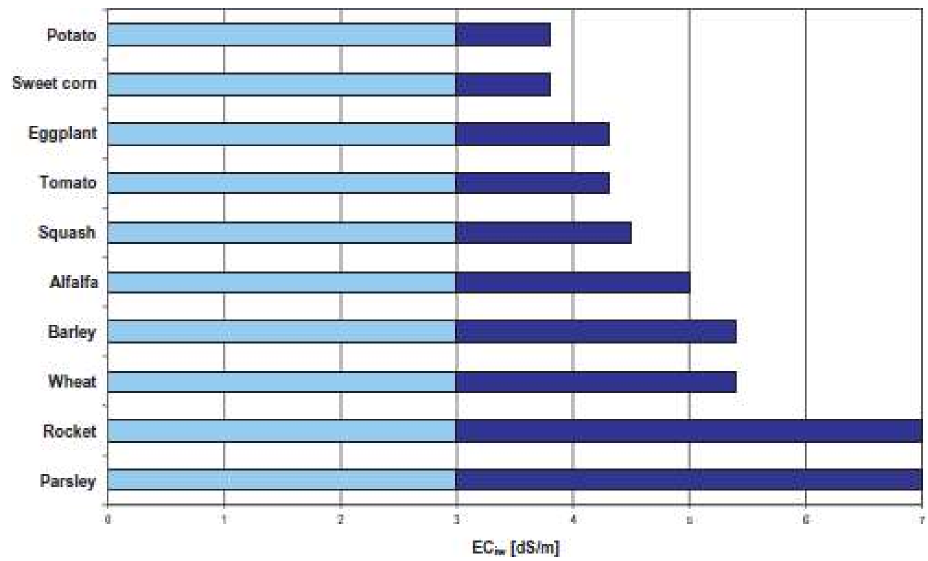


Figure 7.2. Maximum irrigation water salinities that were used to successfully irrigate selected crops in the middle and lower Jordan Valley (GTC, 2003).

***Source**: German Technical Corporation. (GTZ). 2003. Guidelines for brackish water irrigation in the Jordan valley, brackish Water Project, Jordan Valley Authority (JVA) , (GTZ), November 2003*

7.2.6. Morocco

While 21 percent of the land in Morocco is arable, only 1.5 million hectares are irrigated (Choukr-Allah & Halim, 2012). Of the irrigated land, 70 percent is irrigated by surface methods and the remaining is irrigated by pressurized systems. More than 60 percent of the irrigation water comes from groundwater and Morocco's primary freshwater supply comes from rivers flowing out of the Atlas Mountains. Salinity threatens the sustainability of irrigated agriculture in the country because of the use of saline irrigation water, seepage from unlined canals, waterlogging, lack of adequate drainage systems and poor water management (Choukr-Allah & Halim, 2012). In many aquifers salinity exceeds 2000 mg/l TDS. These problems not only affect crop production but the country's social and economic status as well. Saline water is used to irrigate some tree crops, including date palm, fig and olive; grain crops such as barley; field crops such as sugar beet and cotton and even some vegetable crops, such as gumbo and artichoke (Choukr-Allah & Halim, 2012). In the Oualidia area, near the coast, some growers successfully grow tomatoes using saline water (ECw 3-6 dS/m) even though the fruit size is substantially smaller.

7.2.7. Oman

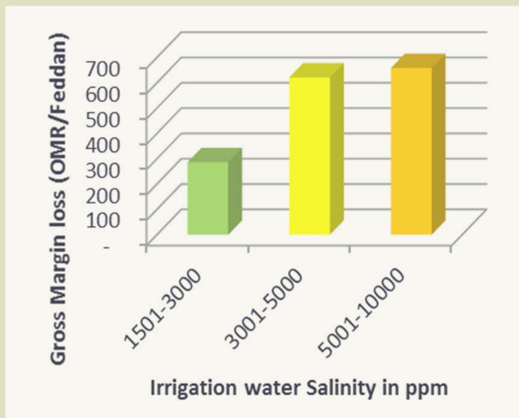
In 2012, the Ministry of Agriculture and Fisheries of Oman entered into a partnership with the International Center for Biosaline Agriculture (ICBA, 2011) to prepare a strategic plan to combat salinity and protect water resources from pollution and salinity, in collaboration with other relevant partners in Oman. The development of the strategy involved a comprehensive assessment of the current status of agricultural systems in different governorates, covering the extent of the salinity problem, distribution of water resources, productivity of different agricultural systems, the impact of salinity on farmers' income, as well as policy and legislation consideration. A survey of 268 farms conducted by ICBA in 2011 (see Box 7.2) found that crop yields and farm profitability decreased substantially with increased soil salinity (ICBA, 2011). Moreover, many salt-sensitive vegetable crops could no longer be grown.

The strategy that was developed – the Oman Salinity Strategy, or OSS – addresses socio-economic aspects and capacity-building needs at all levels. The strategy also identifies alternative scenarios for sustainable water resources and production systems to bring about more efficient and sustainable use of natural resources.

Box 7.2 Salinity reduces farm profitability

The losses per feddan as a function of farm size and salinity class are shown in the figure. These losses are estimated as the difference between the first class salinity (benchmark) and the respective class. Annual losses range from OMR 286/feddan when fresh water becomes low saline, to OMR 658/feddan when freshwater areas become highly saline.

Farm losses as a function of salinity class



***Source**: ICBA OSS Surveys, 2012. Data from 268 farms. Oman Salinity Strategy. Sultanate of Oman.*

The losses resulting from increasing salinity not only reflect the lower crop yields but also the increased costs of pumping due to the need to apply greater volumes of irrigation water to ensure adequate leaching of soil salts. The survey data show that the electricity demand for groundwater pumping increases with the salinity level from OMR 8.3 to 10.8/feddan. In addition, electricity demand in summer is 2.4 OMR/feddan higher than in winter because of increased water demand in the summer.

These costs also take into account the farmer's coping costs for domestic water supply. Ninety-four percent of farmers use well water when salinity is less than 1 500 ppm. But when salinity increases, farmers have to find alternative and more costly sources. Most farmers shift to tap water whenever the service is available or to tank water when the groundwater salinity is higher than 3 000 ppm.

The OSS survey data also exhibits a spectrum of crops that are abandoned with increased salinity. Losses due to abandoned crops vary considerably. The most affected crops are vegetables, with almost 50 percent of the cropped area abandoned due to salinity.

***Source**: Oman Salinity Strategy. 2012 Ministry Of Agriculture and Fisheries (Maf), Sultanate of Oman. - ICBA / UAE. https://maqsurah.com/uploads/items/74078/files/FULL/2021-06-16_11_28_121974225.pdf*

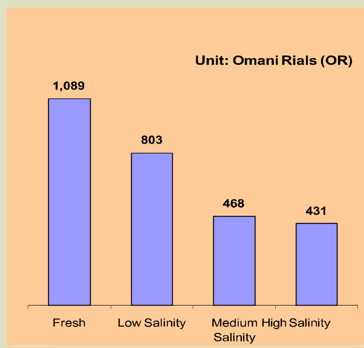
The strategy showed that the salinity of water used for irrigation in 40 – 50 percent of the farms is more than 5 dS/m (Oman Salinity Strategy, 2012), therefore, with the exception of a few salt-tolerant crops such as date palm and Rhodes grass, many crops cannot be successfully grown and the productivity of most other crops is far below their yield potential. Crop varieties that tolerate soil salinity and provide acceptable yields in salt-affected soils, when employing crop management practices to reduce soil salinity, have been proposed to maintain crop productivity.

Box 7.3 Farm incomes fall as salinity increases (Case study from Oman)

According to a survey conducted in 2011 by the International Center for Biosaline Agriculture (ICBA) as part of the Oman Salinity Strategy (OSS) farm income drops with increasing salinity.

The impact of salinity on farm profitability was studied using data collected from farmers. For this purpose, a survey was designed to identify the crop mix, crop yields and costs of production per crop in four classes of salinity:

Farm profitability declines with salinity



Source: *ICBA OSS Surveys. Data from 268 farms. Oman Salinity Strategy. 2012 Ministry Of Agriculture and Fisheries (Maf), Sultanate of Oman. - ICBA / UAE.*
https://maqsurah.com/uploads/items/74078/files/FULL/2021-06-16_11_28_121974225.pdf

The analysis also took into account farm size, the expectation being that for farms of similar size, the higher the salinity of the groundwater, the lower the profit.

The weighted average annual gross margin for the farms benefiting from the best quality water (salinity less than 1 500 ppm) is OMR 1 089*/feddan, regardless of the size of the farm. When the salinity is low (between 1 501 and 3 000 ppm) the annual gross margin is OMR 803/feddan, which is 74 percent of the gross margin for fresh water. For medium salinity (between 3 001 and 5 000 ppm) the annual gross margin is OMR 468/feddan and represents 43 percent of the Class 1 gross margin. Finally, the annual gross margin for high salinity is OMR 431/feddan, representing only 40 percent of the profit achievable with fresh water.

* OMR 1= USD 2.6 USD

Reference: Al-Dakheel. A, ICBA OSS Surveys. Data from 268 farms. Oman Salinity Strategy. 2012 Ministry Of Agriculture and Fisheries (Maf), Sultanate of Oman. - ICBA / UAE.
https://maqsurah.com/uploads/items/74078/files/FULL/2021-06-16_11_28_121974225.pdf

7.2.8. Saudi Arabia

Like other countries in the NENA region, Saudi Arabia suffers from a shortage of fresh water and a continual degradation in water quality. About 80 to 85 percent of Saudi Arabia's water supply comes from groundwater and is classified as a non-renewable water resource where groundwater extraction exceeds groundwater recharge (Al-Omran *et al.*, 2012). As a result, aquifers are being depleted and the groundwater is becoming more saline. For example, the ECw of the groundwater in the Saq aquifer increased from 1.9 dS/m in 1983 to 2.8 dS/m in 1987. A survey of key groundwater aquifers reveals that salinity ranges from 1.6 to 8.2 dS/m with an average of 3.8 dS/m (Falatah *et al.*, 1999 as reported by Al-Omran *et al.*, 2012).

The most popular crops grown with brackish water in Saudi Arabia are wheat, sorghum, alfalfa and barley. Brackish water is also used to irrigate tomato, onions and watermelon (Al-Omran *et al.*, 2012). Cyclic reuse strategies using brackish and desalinized water have been experimented with for the production of tomato and lettuce, showing that this method can be successful for commercial production. Research indicates that the country has the opportunity to expand the use oftreated waste water and brackish groundwater for irrigation.

7.2.9. Tunisia

Like all countries in the NENA region, surface water in Tunisia is scarce. More than 80 percent of the surface water originates in the north of the country. Most of this water (over 80 percent) has a salinity of less than 1500 mg/l TDS (ECw about 2.4 dS/m) (Achour & Halim, 2012). However, over 95 percent of the surface water that originates in the south of the country has a salinity of over 1500 mg/l TDS. The average annual salinity of the Medjerda River is 3.0 dS/m and is successfully used to irrigate date palm, sorghum, barley, alfalfa, rye grass and artichokes (Rhoades et *al.*, 1992). As to groundwater, much of the country's groundwater is also saline, with only 21 percent having a salinity of less than 1500 mg/l TDS, and sea water intrusion is problematic in aquifers near the Mediterranean coastline (Achour & Halim, 2012). The clay soils are calcareous with low infiltration rates but crack when dry allowing water to enter. Waterlogging and the lack of adequate drainage limits the use of brackish water in many areas.

Throughout the country, vegetables, cereals, fodder, industrial crops and perennial wood plants are produced using brackish water. Even crops fairly sensitive to salinity such as peppers, lettuce and carrots are irrigated with saline water but there are negative aspects related to production, the environment (groundwater pollution) and society in general. Even municipal waste water, which is saline, is widely used throughout Tunisia to irrigate crops. However, much of the water is used with minimal treatment posing potential health risks.

7.2.10. Yemen

Irrigated agriculture accounts for about 90 percent of the water use in Yemen. Salinity varies across the country and surface waters are generally much higher quality than groundwater sources (Al-Sabri & Halim, 2012). For example, the salinity in many dams varies between 0.8 and 1.2 dS/m, except those downstream of large cities where the salinity can range between 2.0 and 2.9 ds/m. Groundwater quality, on the other hand, is much more complex in nature. In many of the highland and lowland basins the salinity can range from 2.0 to 5.0 dS/m, particularly near wadis. But in coastal areas, groundwater salinity can be as high as 8.0 to 14.0 dS/m due to seawater intrusion resulting from excessive pumping. Vegetables and fruits are the primary irrigated crops in the country. However, irrigation with brackish water is mainly used for salt-tolerant crops in the coastal plains. The main crops irrigated with brackish water are forages, grains (millet and sorghum), cotton, tobacco, sesame, dates and tomatoes. Poor quality effluents from waste water treatment plants are also used for irrigation.

As indicated above, the NENA countries share common problems such as 1) shortage of fresh water, but the existence of unused saline groundwater, 2) waterlogging and poor drainage, 3) inefficient irrigation methods and management, and 4) salinization of aquifers, particularly those near the sea. The evidence and experiences described demonstrate that brackish irrigation water can, in fact, be used for the production of selected crops under proper field management, although yields are often far less than optimal. At the same time there is considerable room for improvement in all countries. The use and reuse of non-conventional water resources for crop production is indeed a complex one as it is linked to different aspects of environmental quality, human health, water resource management and the society in general (van Schilfgaarde, 1994). Recognizing these complex linkages, great efforts are now being directed to the development and use of non-conventional water resources for irrigation, notably treated waste water, drainage water and brackish groundwater. Only with a complete understanding of these linkages and subsequent implementation of effective measures can irrigated agriculture using brackish water be sustainable. Increased use of brackish water will certainly result in generating greater amounts of water for irrigation but this will require infrastructural changes (such as improved irrigation networks and drainage systems) and more sophisticated irrigation management (requiring site-specific guidelines and extension education) in order for brackish water irrigation to be successful and sustainable.

7.3. INITIAL ASSESSMENT OF PERCEIVED BRACKISH WATER LIMITS IN THE NENA REGION

The AWC developed an extensive questionnaire and template to assess the status of brackish water resources, brackish water quality and irrigation practices in participating countries involved in the NENA study region, namely Algeria, Egypt, Iraq, Iran (Islamic Republic of), Jordan, Kingdom of Saudi Arabia, Morocco, Tunisia, and Yemen) (Figure 7.3).

Figure 7.3. Selected NENA countries involved in the study

***Source**: FAO. 2022. The State of Land and Water Resources for Food and Agriculture in the Near East and North Africa region Synthesis report. Cairo. https://doi.org/10.4060/cc0265en. Modified by authors.*

The survey focused on the water quality parameters deemed most limiting to crop production. These parameters include 1) water salinity (ECw), 2) the sodicity hazard of the water (i.e. SAR), 3) the concentration of chloride (Cl) in the brackish water, and 4) the concentration of boron (B) in the irrigation water. Information was also gathered regarding soil texture, irrigation systems, drainage, crop types and management practices, as these factors also influence the feasibility of using brackish water for irrigation (Annex 3). Anecdotal evidence from these surveys indicates four common problems in the use of brackish water for irrigation in the region:

- absence of suitable drainage systems;
- salinization of soils and underlying groundwater aquifers;
- substantial reduction in crop yields;
- lack of management guidelines for using brackish water.

The questionnaire asked each participating NENA country to provide a range of their perceived upper-limit for each of these four parameters. The data and information presented below are based on actual field data obtained from these NENA countries (Table 7.2).

Table 7.2. Data summary of the main water quality parameters (ECw, SAR, Cl and B) representing the perceived upper limits from the participating NENA countries.

Analysis type	Irrigation water salinity, ECw (dS/m)		Irrigation water SAR		Irrigation water Cl (meq/l)		Irrigation water B (mg/l)	
	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest
Minimum	0.50	2.40	1.19	5.00	1.00	15.00	0.60	2.00
25th percentile*	1.43	5.98	2.59	9.50	1.63	30.25	0.60	2.15
Median	2.00	7.81	3.00	12.00	3.65	55.80	0.70	2.80
75th percentile **	3.71	11.00	5.60	21.00	13.00	76.73	0.70	3.00
Maximum	9.36	36.00	13.00	58.10	21.00	130.00	0.70	3.00
Average	2.65	11.70	4.34	17.02	7.42	57.87	0.67	2.65

**25 percent of the data are less than the values in the row*

*** 75 percent of the data are less than the values of the row*

***Source**: Author's own elaboration.*

It is not surprising that there is considerable variation in the range of the perceived upper limits of the various water quality parameters. Many variables, such as crop type, soil type, water availability, irrigation management, drainage and climate, must be considered. These will vary considerably, not only among countries but among different areas within a country. Salt-sensitive crops grown on poorly drained soils, for example, will have a much lower upper-limit than a salt-tolerant crop grown on soil with adequate drainage. Also, it is difficult to know if these limits are based on optimal production or acceptable production, which led to considerable variation in threshold estimates from different countries.

In an effort to fine-tune the range of these maximum limits, information was considered based on 1) reports and guidelines from key FAO publications (FAO Irrigation and Drainage Reports 29, 33 and 48), and 2) input from several regional workshops involving local and national experts from each country; international consultants from United Kingdom of Great Britain and Northern Ireland (the), United States of America (the), India and Italy; experts form several regional organizations such as FAO, AWC, ACSAD and ICBA; and Egyptian experts from the National Water Research Center and the faculties of agriculture of several universities. In consultation with national and international experts, the AWC established the upper limits of the various parameters. The upper limit of irrigation water salinity (ECw) for the NENA region was set at 13 dS/m. This value is in agreement with the guidelines of the FAO

Irrigation and Drainage Paper 29 (Ayers & Westcot, 1985) which indicate that the most salt-tolerant of the common crops (i.e. tall wheatgrass) can be grown under good management practices (LF 15-20 percent) in order to achieve a 50 percent yield potential using this quality water. The upper limit for SAR was set at 15, which was a surrogate for Na tolerance. This SAR limit was not directed to infiltration hazard as there was no corresponding ECw value. (It is important to have a sliding SAR scale with ECw since these two parameters predict the impact on aggregate stability, particularly in the upper part of the soil profile [see Fig. 3.1, Chapter 3]). The upper limit of Cl in the irrigation water was set at 27 meq/l (27 mmolc/l) to protect the most tolerant of the tree and vine crops. This Cl concentration, with good irrigation management (that is, with a LF of 15 to 20 percent), will protect the most salt-tolerant of the grape rootstocks (salt creek, 1613-3) (Ayers & Westcot, 1985). (Most crop plants, except trees and vines, are fairly tolerant to chloride. Depending upon the rootstock, some trees and vines are more tolerant to Cl than others [see Chapter 4]). In the case of boron, there is a small difference in concentration levels necessary for optimal crop growth and those which are toxic (see Chapter 4). While some crops (such as most deciduous fruit and nut trees and citrus trees) can be adversely affected at boron concentrations under 1.0 mg/l, others (such as cotton and asparagus) can tolerate over 6.0 mg/l. Despite this variation among crop species, the AWC set upper limit at 3.0 mg/l, recognizing that although this level is toxic to many sensitive species, it falls in the range that protects most moderately boron-tolerant crops and all the more-tolerant crops (Ayers & Westcot, 1985).

The AWC developed general water quality limits for protecting irrigated crops with different sensitivities. These are presented in Table 7.3. Note that crops are loosely categorized into very general rankings and therefore the information is not very useful on a crop by crop basis. More specific information is provided in Chapter 8.

Table 7.3. Brackish water quality guidelines for irrigation of crops in the NENA region

Parameter	Min.	Max.	Crop restriction
EC_{iw} (dS/m)	< 1		Salt-sensitive crops
	1	1.5	Moderately salt-sensitive crops
	1.5	4	Moderately salt-tolerant crops
	4	6	Tolerant crops
	6	13	Can be used on tolerant and some moderately tolerant crops with reduction in crop yield
		>13	Unusable except for halophytic species

SAR_{iw}	<5		Sensitive crops
	5	9	Moderately sensitive crops
	9	15	Moderately tolerant crops
		>15	Tolerant crops
Boron (mg/l)	< 0.7		Sensitive crops
	0.7	3	Moderately sensitive to moderately tolerant crops
		> 3	Tolerant crops
Chloride (meq/l)	<2		Very sensitive tree and vine crops
	2	4	Sensitive tree and vine crops, with some damage
	4	10	Moderately tolerant tree and vine crops
	10	27	Tolerant tree and vine crops

Source*: Author's own elaboration.*

CHAPTER 8

The guidelines

The previous chapters provide a solid foundation, based on scientific principles, with regard to soil and crop impacts from brackish water irrigation, crop tolerance limits to soil salinity (ECe) and specific ions, and irrigation management strategies that optimize the use of saline–sodic waters. The information provided clearly demonstrates that brackish water has been used successfully in arid and semi-arid climates around the world, including the NENA region, and that there is potential for further successful use of brackish water. It is this scientific foundation that is necessary for the development of brackish water guidelines for the NENA region. However, water quality guidelines, by definition, are general rules, principles or advice, and cannot be used as the sole predictor of crop performance in the field. Rather, a host of factors related to site-specific conditions (such as climate, soil type, soil drainage characteristics, achievable leaching fraction, water management restrictions related to irrigation methods and intervals, soil fertility and pressures from weeds, pests and pathogens) affect plant performance. Furthermore, these factors can impose other abiotic and biotic stresses that interact with one another and affect the crop in field conditions (Mittler, 2006). Thus, the unique set of conditions of each farm must be taken into account for successful use of brackish water. As such, applying these guidelines, combined with good agricultural practices, requires a balance between scientific principles and the art of the practice. The guidelines will likely require site-specific adjustment to account for these site-specific conditions. The information and principles presented in this manual will help farm managers make such informed adjustments.

The NENA region faces two important limitations in the successful use of brackish water for agricultural production. One is that many places in the region lack the infrastructure (namely, state-of-the-art irrigation and drainage networks) needed to apply the good management practices necessary for brackish water use. Without investment in the necessary infrastructure, good irrigation management practices cannot be implemented. Drainage, in particular, is a key issue in the region as many areas suffer from waterlogging, and, in fact, the guidelines presented here can only be applied in those areas where adequate leaching and drainage are feasible for only in areas with adequate drainage can a salt balance be achieved. Another important limitation is that many countries lack the knowledge and understanding of good agricultural practices for brackish water use (described in Chapter 6.)

In assessing the suitability of brackish water in the NENA region for irrigation by the AWC found that the key irrigation water quality concerns in the region are 1) the salinity hazard (ECw), 2) the infiltration hazard (SAR and ECw), and 3) the hazard posed by specific ions (Cl, B and Na). These hazards were examined individually to develop suitable guidelines for using brackish water to irrigate crops in the NENA region.

8.1. SALINITY HAZARD

The water quality guidelines for salinity presented in the FAO Irrigation and Drainage Paper 29 (see Ayers & Westcot, 1985 and Table 4) are conservative[4] and are intended to cover a wide range of conditions encountered in irrigated agriculture across the globe. The guidelines predict various yield potentials that can be achieved based on the ECw alone but do not account for rainfall or other sources of water available for irrigation. The guidelines assume that conventional surface irrigation is used, with water being applied infrequently (at 50 percent allowable depletion or more) and that the root water extraction pattern generally follows a 40–30–20–10 distribution, representing percentages of root water extraction from descending quarters of the root zone. Soil textures are assumed to range from sandy loam to clay loam with no restricting layers and drainage is assumed to be adequate, with a 15 to 20 percent leaching fraction achieved for each irrigation.

8.1.1. Scientific approach for developing salinity (ECiw) guidelines

The guidelines developed here are founded on scientific principles using steady-state conditions. While it is recognized that transient models do exist that could improve the guidelines (see Box 8.1), site-specific conditions vary dramatically between and within countries in the NENA region. Inputs are often needed with regard to soil and water chemistry, soil type and water transport characteristics, weather (e.g. daily rainfall and parameters to estimate ETc), and crop varieties. Even if this information is known, many assumptions are implied and there are uncertainties about how plants respond to salinity as this varies over space and time and how competing abiotic and biotic stresses affect crop response. This discussion is best summarized in this quote from Rhoades *et al.* (1992):

Conceptually, a transient state (dynamic) model would be preferred for assessing water suitability for irrigation because it could incorporate the specific influences of the many variables that can influence crop response to salinity, including climate, soil properties, water chemistry, irrigation and other management practices (Rhoades, 1972). However, many of the inputs required for use of such models are generally not available for most practical applications and there is much uncertainty about how to relate crop response to time- and space-varying salinity and water potential, such as might be predicted with such models. For these reasons, the practicality and value of such complex models may be less appropriate under some circumstances than a conceptually inferior model for the practical purpose of assessing suitability of saline water for irrigation. Furthermore, the steady-state model composition likely represents the worst-case situation (maximum build-up of salinity and sodicity) that would likely result from irrigation with the water." (Rhoades et al., 1992, p. 52).

[4] While such guidelines are very useful as a first approximation, they tend to be overly conservative on several grounds. First, the guidelines may not be crop-specific but rather represent protection of the most salt-sensitive of crop species, as is the case in FAO Irrigation and Draining Paper 29. Non crop-specific guidelines are also presented here in Table 7.3. Second, the guidelines are based on irrigation using water from a single source and do not account for other irrigation water sources or rainfall to partially meet crop water requirements or to leach salt from the soil. Third, the critical ECw values are determined based on steady-state assumptions that consider the downward movement of water in the soil profile, predicted root water extraction behaviour and assumed leaching at each irrigation where crops typically perform better under more realistic transient-state conditions (Letey *et al.*, 2011). Fourth, guidelines assume that other stresses (e.g. nutrient, pest, water stress, etc.) are not present. Finally, water suitability is not necessarily restricted to waters that will achieve maximum yield potential but rather, when managed effectively, waters that can produce crops that are profitable.

Box 8.1 Steady-state vs transient-state models for developing guidelines

In the past few decades, scientists have developed more complex transient-state models that predict soil water dynamics better than simple, steady-state models. Transient models, for example, can account for transient soil-water conditions and take into account precipitation-dissolution reactions, preferential flow and rainfall. Transient models are not as conservative as steady-state models, which overestimate the leaching requirements and exaggerate the negative consequences of irrigating with saline waters (Letey *et al.*, 2011). Transient models include UNSATCHEM (Šimůnek & Suarez, 1994; Suarez & Šimůnek, 1997), TETrans (Corwin *et al.*, 1990), ENVIRO-GRO (Feng *et al.*, 2003), HYDRUS (Šimůnek *et al.*, 2008), and SALTMED (Ragab *et al.*, 2005). However, there is no single best transient state model. Each model has advantages and disadvantages (Corwin *et al.*, 2007; Corwin & Grattan, 2018; Letey *et al.*, 2011). For example, TETrans is the most user-friendly model but lacks solution chemistry predictions for arriving at a more accurate LR. For a transient model to replace steady-state model, it must have the user-friendliness of TETrans but the complexity of UNSATCHEM. Unfortunately, no such model currently exists and steady-state models often provide an acceptable approximation of more complex transient-state conditions (Corwin & Grattan, 2018).

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For a transient model to replace the steady-state model, it needs to have a combination of 1) complexity and sophistication to predict plant response over a changing set of conditions, 2) user-friendliness, and 3) the flexibility to adjust to different sets of conditions. Such a transient model does not yet exist (Corwin and Grattan, 2018) and for these reasons, a steady-state model is used here to develop these guidelines.

The salinity guidelines presented here (Tables 8.1, 8.2, 8.3 and 8.4) differ from those developed by Ayers & Westcot (1985) in that they provide more detailed guidelines with reference to crop types and irrigation management practices. Here, a wider range of crops are presented and the yield potential ranges from full yield potential (100 percent) to 60 percent yield potential. No EC_{iw} values are provided that would likely produce less than 60 percent yield potential, using good management practices, as less than 60 percent is not likely to be economically desirable. For each crop, EC_{iw} guidelines are provided based on either 1) conventional or low frequency irrigation, where crops extract up to 50 percent of the available water between irrigations, and 2) high frequency irrigation, where the allowable depletion is considerably less than 50 percent. Under high frequency irrigation, such as drip irrigation, crops can tolerate higher salinity with a given leaching fraction as the crop typically responds to the root-water uptake weighted ECe in the root zone as opposed to the linear average (see Chapter 6). In each situation, it is assumed that soils are adequately drained and a 20 percent LF is achieved.

8.1.2. EC_{iw} guidelines for fibre, grain and specialty crops

In regards to fibre, grain and specialty crops (Table 8.1), there is wide a range of EC_{iw} values that will achieve maximum or 60 percent yield potentials, based on the crops overall sensitivity to salinity. For example, moderately salt-sensitive crops (refer to Table 5.1) such as corn, flax, peanut and paddy rice can only use waters less than 5 dS/m to achieve greater than 60 percent yield potential. On the other hand, salt-tolerant grains such as barley, rye and durum wheat can tolerate 12-13 dS/m and still achieve 60 percent yield potential. Even an irrigation water with an EC_{iw} of 6 dS/m can be used to achieve full yield potential of barley, rye and semi-dwarf wheat provided a LF of 20 percent is achieved and no other stresses are impeding growth. The high frequency category in Table 8.1 is not likely applicable to most of these crops as most would likely be surface irrigated.

Table 8.1. Maximum salinity (EC_{iw}, dS/m) of the irrigation water that will achieve 100, 80 and 60 percent yield potentials for common fibre, grain and specialty crops under low-frequency irrigation (conventional or surface) and high-frequency irrigation (drip). Assumes a steady-state leaching fraction of 20 percent is achieved.

Crop	EC_{iw} (dS/m)					
Yield potential (%)	100		80		60	
Irrigation system	Low frequency	High frequency	Low frequency	High frequency	Low frequency	High frequency
Fibre, grain and specialty crops						
Barley	6.2	7.8	9.3	11.7	12.4	15.5
Canola or rapeseed	7.5	9.4	8.6	10.8	9.8	12.2
Corn	1.3	1.7	2.6	3.3	3.9	4.9
Cotton	6.0	7.5	8.9	11.2	6.7	15.0
Crambe	1.6	1.9	4.0	5.0	6.4	8.0
Flax	1.3	1.7	2.6	3.3	3.9	4.9
Guar	6.8	8.5	7.8	9.7	8.7	10.9
Kenaf	6.3	7.9	7.6	9.5	8.9	11.2
Lesquerella	4.7	5.9	5.6	7.0	6.4	8.0
Peanut	2.5	3.1	3.0	3.8	3.6	4.5
Rice, paddy	2.3	-	3.6	-	4.9	-
Rye	8.8	11.1	10.3	12.9	11.7	14.7
Sorghum	5.3	6.0	6.6	7.9	7.2	9.0
Soybean	3.9	4.9	4.7	5.8	5.4	6.8
Sugar beet	5.4	6.8	8.1	10.1	10.7	13.4
Sugarcane	1.3	1.7	4.0	5.0	6.6	8.3
Sunflower	3.7	4.7	6.8	8.5	9.9	12.4
Triticale	4.7	5.9	10.9	13.7	17.1	21.5
Wheat	4.7	5.8	6.8	8.5	9.0	11.3
Wheat (semi-dwarf)	6.7	8.3	11.8	14.8	17.0	21.3
Wheat (durum)	4.6	5.7	8.7	10.9	12.7	13.4

Source*: Author's own elaboration.*

8.1.3. EC_{iw} guidelines for grass and forage crops

Grass and forage crops also exhibit a wide range in suitable irrigation water salinities (Table 8.2). Many of the grass forages, such as tall wheatgrass, Bermuda grass and wheat, are considerably more tolerant to salinity than the legume forages (such as alfalfa, clovers and trefoils). Therefore, these tolerant grasses can be irrigated with brackish water with an EC_{iw} of 10-15 dS/m using conventional irrigation and still achieve a 60 percent yield potential or higher if a 20 percent LF is achieved. Again, it is better to compare guidelines in the low-frequency category as most of these will use surface irrigation methods. Rainfall or pre-irrigations with higher-quality water would enhance their performance. Even irrigation with nearly 6 dS/m water can produce acceptable yields (such a 60 percent) with alfalfa. Recent field studies in California have shown that some salt-tolerant alfalfa varieties can perform even better than these guidelines indicate (D. Putnam, unpublished data).

Table 8.2. Maximum salinity (EC_{iw}, dS/m) of the irrigation water that will achieve 100, 80 and 60 percent yield potentials for common grasses and forage crops under low-frequency irrigation (conventional or surface) and high-frequency (drip). Assumes a steady-state leaching fraction of 20 percent is achieved.

Crop	EC_{iw} (dS/m)					
Yield potential (%)	100		80		60	
Irrigation system	Low frequency	High frequency	Low frequency	High frequency	Low frequency	High frequency
Grasses and forage crops						
Alfalfa	1.6	1.9	3.6	4.6	5.8	7.3
Barley (forage)	4.6	5.8	6.8	8.5	9.0	11.3
Bermuda grass	5.3	6.7	7.8	9.7	10.2	12.9
Broad bean	1.2	1.6	2.9	3.6	4.5	5.6
Clover (alsike)	1.2	1.5	2.5	3.1	3.7	4.7
Clover (berseem)	1.2	1.5	3.9	4.9	6.6	8.3
Clover (ladino, red, strawberry)	1.2	1.5	2.5	3.1	3.7	4.7
Corn (forage)	1.4	1.7	3.5	2.2	5.6	7.0
Cowpea (forage)	1.9	2.4	3.3	4.2	4.7	5.9
Fescue (tall)	3.0	3.8	6.0	7.5	8.8	11.0

Foxtail (meadow)	1.2	1.5	2.8	3.5	4.4	5.5
Harding grass	3.6	4.5	5.6	7.0	7.7	9.6
Love grass	1.6	1.9	3.4	4.3	5.3	6.6
Orchard grass	1.2	1.5	3.6	4.6	6.2	7.8
Rye (forage)	5.9	7.4	9.1	11.4	12.2	15.3
Ryegrass (perennial)	4.3	5.4	6.4	8.0	8.4	10.6
Sesbania	1.8	2.2	4.0	5.0	6.2	7.8
Sphaerophysa	1.7	2.1	4.0	5.0	6.1	7.7
Sudan grass	2.2	2.7	5.8	7.3	9.4	11.7
Trefoil (big)	1.8	2.2	2.6	3.3	3.4	4.3
Trefoil (narrow leaf)	3.9	4.9	5.4	6.8	7.0	8.7
Vetch (common)	2.3	2.9	3.7	4.7	5.1	6.4
Wheat (forage)	3.5	4.4	9.5	11.8	15.4	19.3
Wheat (durum)	1.6	2.0	7.8	9.8	14.0	17.6
Wheat (standard crested)	2.7	3.4	6.6	8.3	10.5	13.1
Wheatgrass (fairway)	5.8	7.3	8.1	10.1	10.4	12.9
Wheatgrass (tall)	5.8	7.3	9.5	11.9	13.2	16.5
Wild rye (beardless)	2.1	2.6	4.7	5.8	7.3	9.1

Source: *Author's own elaboration.*

8.1.4. EC_{iw} guidelines for vegetable and annual fruit crops

Unlike the fibre, grains and forage crops in tables 8.1 and 8.2, many crops in the vegetable and annual fruit crop category are more sensitive to salinity (Table 8.3). Particularly sensitive are common beans and strawberry. Production of these crops would need to take place in areas with the highest quality water available and would be inappropriate for most other areas. Many vegetable crops will not be grown to their full potential. On the other end of the spectrum are the tolerant vegetables such as asparagus, Swiss chard and turnip, which, in many places, can be grown with brackish water as high as 10 dS/m and still achieve an acceptable yield provided soils are well drained and leaching of 20 percent or higher can be achieved. In this category of crops, either conventional or high-frequency drip irrigation may be appropriate. Under high-frequency drip, the crop can tolerate about 25 percent higher salinity than under conventional irrigation because of the differences in how the crop responds to the salinity in the root zone.

Table 8.3. Maximum salinity (EC_{iw}, dS/m) of the irrigation water that will achieve 100, 80 and 60 percent yield potentials for common vegetable and annual fruit crops under low-frequency irrigation (conventional or surface) and high-frequency irrigation (drip). Assumes a steady-state leaching fraction of 20 percent is achieved.

Crop	EC_{iw} (dS/m)					
Yield potential (%)	100		80		60	
Irrigation system	Low frequency	High frequency	Low frequency	High frequency	Low frequency	High frequency
Vegetable and annual fruit crops						
Artichoke	4.7	5.9	6.0	7.6	7.4	9.3
Asparagus	3.2	4.0	10.9	13.7	18.7	23.4
Bean (common)	0.8	1.0	1.6	2.0	2.4	3.0
Bean (mung)	1.4	1.7	2.2	2.7	2.9	3.6
Beet (red)	3.1	3.9	4.8	6.0	6.5	8.2
Broccoli	1.0	1.3	2.0	2.5	2.9	3.7
Cabbage	1.4	1.7	3.0	3.8	4.6	5.7
Carrot	0.8	1.0	1.9	2.3	3.0	3.8
Cauliflower	1.2	1.5	2.2	2.8	3.3	4.2
Celery	1.4	1.7	3.9	4.9	6.4	8.1
Corn (sweet)	1.3	1.7	2.6	3.3	3.9	4.9
Cowpea	3.8	4.8	5.1	6.4	6.4	8.0
Cucumber	1.9	2.4	3.1	3.9	4.3	5.4
Eggplant	0.9	1.1	3.1	3.9	5.3	6.7
Fennel	1.1	1.4	2.1	2.6	3.0	3.8
Garlic	3.0	3.8	4.1	5.1	5.2	6.5
Lettuce	1.0	1.3	2.2	2.7	3.4	4.3
Muskmelon	0.8	1.0	2.6	3.3	4.5	5.6
Onion (bulb)	0.9	1.2	1.9	2.4	2.9	3.6
Onion (seed)	0.8	1.0	2.7	3.4	4.7	5.8
Pea	2.6	3.3	4.1	5.1	5.6	7.0

Pepper	1.2	1.5	2.2	2.8	3.4	4.3
Potato	1.3	1.7	2.6	3.3	3.9	4.9
Purslane	4.9	6.1	6.5	8.1	8.1	10.2
Radish	0.9	1.2	2.1	2.6	3.3	4.2
Spinach	1.6	1.9	3.6	4.5	5.7	7.1
Squash (scallop)	2.5	3.1	3.5	4.4	4.4	5.5
Squash (zucchini)	3.8	4.8	5.3	6.6	6.7	8.4
Strawberry	0.8	1.0	1.2	1.6	1.7	2.1
Sweet potato	1.2	1.5	2.6	3.2	4.0	5.0
Swiss chard	5.4	6.8	8.1	10.2	10.9	13.6
Tomato	1.9	2.4	3.5	4.4	5.0	6.3
Tomato (cherry)	1.3	1.7	3.0	3.8	4.7	5.9
Turnip	0.7	0.9	2.4	3.0	4.1	5.1
Turnip (greens)	2.6	3.2	6.2	7.8	9.8	12.2

Source*: Author's own elaboration.*

8.1.5. EC_{iw} guidelines of tree and vine crops

Tree and vine crops are typically more sensitive to salinity than are annual crops. The most sensitive crops in this category are berry, nut and fruit crops. If an additional source of good quality water is not available or rainfall is insufficient to leach much of the accumulated salts in the root zone, an EC_{iw} of the irrigation water of about 3 dS/m cannot be exceeded and expect to achieve at least a 60 percent yield potential. This of course assumes that the irrigation with saline water can achieve a 20 percent LF. There are many tree and vine crops classified as salt-sensitive (refer to Table 5.2), but salinity coefficients that describe the threshold and slope yield reductions do not exist. Until such coefficients are developed under controlled experimental conditions, the guidelines for sensitive trees provided in Table 8.4 can be used as a surrogate for other salt-sensitive tree crops where salinity coefficients do not yet exist, at least as a first approximation. It is important to consider that the guidelines above are salinity guidelines only and that additional yield losses would be expected if ion toxicities are significant (see guidelines for Cl, Na and B). Ion toxicities often become a major factor in later years as the trees mature (see Aragüés *et al.*, 2005). While most of the tree and vine crops are rated as sensitive or moderately sensitive to salinity, date palm is one crop that is listed as tolerant. The guidelines in Table 8.4 indicate that an ECw of 7.4 to 9.3 can produce 80 percent yield potential, which is considerably more than any other tree or vine crop listed. However, from a six-year study with Medjool dates, investigators found that an EC_{iw} of 4 dS/m reduced fruit production by as much as 35 to 50 percent, suggesting that dates may not be as tolerant to salinity as these older guidelines indicate (Tripler *et al.*, 2011). Therefore, the guidelines for date palm listed here should be used with caution.

Table 8.4. Maximum salinity (EC_{iw}, dS/m) of the irrigation water that will achieve 100, 80 and 60 percent yield potentials for common tree, vine and woody crops under low-frequency irrigation (conventional or surface) and high-frequency irrigation (drip). Assumes a steady-state leaching fraction of 20 percent is achieved.

Crop	EC_{iw} (dS/m)					
Yield potential (%)	100		80		60	
Irrigation system	Low Frequency	High Frequency	Low Frequency	High Frequency	Low Frequency	High Frequency
Tree, vine and woody crops						
Almond	1.2	1.5	2.0	2.5	2.8	3.5
Apricot	1.2	1.6	1.9	2.3	2.6	3.2
Blackberry	1.2	1.5	1.9	2.3	2.6	3.2
Boysenberry	1.2	1.5	1.9	2.3	2.6	3.2
Date palm	3.1	3.9	7.4	9.3	11.7	14.7
Grape	1.2	1.5	2.8	3.5	4.4	5.5
Grapefruit	0.9	1.2	2.1	2.6	3.3	4.1
Guava	3.6	4.6	5.2	6.5	6.8	8.5
Guayule (rubber yield)	6.0	7.6	7.5	9.4	8.9	11.2
Lemon	1.2	1.5	2.4	3.0	3.6	4.5
Olive[5]	2.3	2.9	3.1	3.9	4.0	5.0
Orange	1.0	1.3	2.2	2.7	3.4	4.3
Pistachio[6]	2.3	2.9	3.6	3.9	4.8	5.0
Plum; prune	2.0	2.5	2.5	3.1	3.0	3.8

Source*: Author's own elaboration.*

[5] Based on tree growth from three-year field study using Arbequina olives where Na toxicity also contributed to growth loss (Aragüés *et al.*, 2005).

[6] Based on tree growth from one-year sand-tank study (Ferguson *et al.*, 2002).

8.2. ION TOXICITY HAZARD

Sodium, chloride and boron are all constituents in the irrigation water that can pose potential toxicity to crops. These effects are in addition to those posed by salinity (that is, osmotic effects). There is wide range in crop sensitivity to ion toxicity. The irrigation guidelines for these potentially toxic ions are presented below.

8.2.1. Sodium

As indicated in Chapter 4, sodium can be problematic to the crop in several ways. It can be directly toxic to the plant, it can interfere with the nutritional status of the plant (as in Na-induced Ca deficiency) or it can indirectly affect the crop due to its adverse effect on soil structure. Many trees can develop Na^+ toxicity, even with concentrations as low as 5 meq/l. Based on this sensitivity, Table 8.5 was constructed that provides the critical Na concentration of the irrigation water above which injury and yield loss can occur in sensitive trees. Using the same method of converting critical ECe values to EC_{iw}, critical Na concentrations as low as 1.9 to 2.4 meq/l in the irrigation water can allow average soil water concentrations to reach the critical 5 meq/l level. However, it would likely take several years for such low levels to induce Na toxicity in these sensitive trees (refer to Fig. 4.4).

Unlike trees, many annual crops are not specifically sensitive to the Na^+ concentration but rather to the Na/Ca ratio in the soil solution. With adequate Ca^{2+}, the cell membranes surrounding root cortical cells remain selective and minimize the amount of Na^+ taken up by the plant. However, there are varietal differences in the plants' ability to regulate Na^+ uptake. In addition, many grasses and crops (such as tomatoes, cucumbers and artichokes) have difficulty regulating the distribution of Ca internally to low-transpiring organs, such as the fruit (in tomatoes and cucumbers), the internal leaves (in lettuce) and the internal bracts (in artichokes) (Grattan & Grieve, 1992). However, even with the most sensitive annual crops, if the SAR of the irrigation water is less than 15, Na *per se* is not typically problematic from a direct Na-toxicity perspective. This is different when assessing Na's indirect effect on soil structural stability (see section 8.4 Infiltration Hazard).

Table 8.5. Critical Na^+ concentrations of the irrigation water for very sensitive trees or vines under high-frequency or low-frequency irrigation, assuming a LF of 20 percent is achieved, and SAR of the irrigation water above which injury or nutritional distress can occur in annual crops.

Crop[7]	Critical Na^+ concentrations or SAR of the irrigation water	
Irrigation system	Low Frequency	High Frequency
	Na+ concentration (meq/l)	
Avocado	1.9	2.4
Citrus	1.9	2.4
Stone fruits	1.9	2.4
Berries	1.9	2.4
SAR		
Annual crops	<15	

Source*: Author's own elaboration.*

8.2.2. Chloride

Like Na^+, chloride toxicity is primarily restricted to tree and vine crops. And as indicted in Chapter 4, Cl^- toxicity is largely controlled by the scion and its ability to regulate Cl^- transport from the rootstock to the shoot. Sensitive rootstocks are those that are unable to control long-distance transport of Cl^- to the leaves and thus the leaves on the scion can accumulate Cl^- to potentially toxic levels. The critical levels of Cl^- toxicity to sensitive tree and vine crops that are presented in Table 4.1 are based on the concentration of the soil water. To develop guidelines for the critical concentration of Cl^- in the irrigation water above which injury and yield losses occur, these critical values from Table 4.1 were converted to Clw (meq/l) based on a sustained leaching fraction of either 10 or 20 percent and on whether the crop was irrigated by conventional means or by high-frequency irrigation (Table 8.6). This conversion is similar to the approach for converting critical ECe to EC_{iw}. There is a wide range in tolerance of Cl in the irrigation water. For example, almonds grown on Nemaguard rootstock can be sensitive to Cl concentrations in the irrigation water above 2.3 meq/l, whereas grapes on salt creek (also referred to as Ramsey) rootstock can tolerate up to about 38.8 meq/l before injury occurs. At this level of Cl, osmotic stress is already affecting the vines, with yield losses in excess of 20 percent (see Table 8.4).

[7] Many tree crops are sensitive to Na^+ toxicity after several years when sapwood converts to heartwood, releasing Na^+ from the root to the shoot. Most annual crops are insensitive to Na^+ *per se*, provided there is sufficient Ca^{2+} in the soil solution to maintain membrane integrity and ion selectivity. Hence, the ratio of Na/Ca is more critical (Grattan & Grieve, 1992).

Table 8.6. Critical Cl concentration (meq/l) in the irrigation water above which injury occurs, assuming different irrigation management practices and achieving a LF of either 10 or 20 percent.

Crop	Rootstock	Critical Cl concentration (meq/l) in the irrigation water			
		Leaching fraction (%)			
		10		20	
Irrigation system		Low Frequency	High Frequency	Low Frequency	High Frequency
Avocado	West Indian	4.0	5.6	5.8	7.3
	Guatemalan	3.2	4.4	4.7	5.8
	Mexican	2.7	3.7	3.9	4.9
Citrus	Sunki mandarin, grapefruit, Cleopatra mandarin, Rangpur lime	13.3	18.5	19.4	24.3
	Sampson tangelo, rough lemon, sour orange, Ponkan mandarin	8.0	11.1	11.6	14.6
	Citrumelo 4475, trifoliate orange, Cuban shaddock, calamondin, sweet orange, Savage citrange, Rusk citrange, Troyer citrange	5.3	7.4	7.8	9.7
Grape	Salt Creek (Ramsey), 1613-3	21.3	29.6	31.0	38.8
	Dog ridge	15.9	22.2	23.3	29.1

Stone Fruits	Marianna (plum), Hansen (peach-almond), Empyrean, Viking	13.3	18.5	19.4	24.3
	Lovell, Shalil (peach)	5.3	7.4	7.8	9.7
	Yunnan (peach)	4.0	5.6	5.8	7.3
	Nemaguard (peach)	2.3	3.1	3.3	4.1
	Cultivars				
Berries	Boysenberry, Olallie blackberry	5.3	7.4	7.8	9.7
	Indian Summer raspberry	2.7	3.7	3.9	4.9
Grape	Thompson seedless, Perlette	10.6	14.8	15.5	19.4
	Cardinal, black rose	5.3	7.4	7.8	9.7
Strawberry	Lassen	4.0	5.6	5.8	7.3
	Shasta	2.7	3.7	3.9	4.9

***Source**: Author's own elaboration.*

Chloride toxicity in annual crops is less problematic. Rather than causing direct toxicity, Cl^- is often the major anion contributing to osmotic stress (see Chapter 4). To assign a maximum allowable concentration of Cl^- to the irrigation water, the expression below can be used:

$$[\boldsymbol{CI}- = \mathbf{10}\ (\boldsymbol{ECw})$$ **Equation 8.1**

The sum of the cations or anions in water, expressed as meq/l, is roughly equal to 10 times the ECw (dS/m). Here, the Cl concentration in meq/l (or mmolc/l) can be estimated based on the critical ECw (dS/m) values, since most salinity experiments to determine the threshold and slope values (refer to Tables 5.1) were based on studies using combined NaCl and $CaCl_2$ salts (Maas, 1990).

Most fibre, grain and specialty crops are fairly tolerant to Cl^- (see Table 8.7). For example, canola, rye and semi-dwarf wheat can be grown with 67 to 88 meq/l Cl^- in the irrigation water and sustain maximum yields, provided a LF of 20 percent is sustained. Because of the category of these crops, only conventional, low-frequency irrigation is considered. Corn, flax and sugarcane, on the other hand, can only tolerate 13 meq/l and still achieve maximal yields. The highly salt-tolerant grains (such as barley, triticale, durum and semi-dwarf wheat) can tolerate 120–170 meq/l Cl and still achieve 60 percent yield potential.

Table 8.7. Maximum Cl concentration (meq/l) in the irrigation water at which 100, 80, or 60 percent yield potential of popular fibre, grain and specialty crops can be achieved, assuming good management practices with low- or high-frequency irrigation. This assumes a 20 percent LF is sustained.

Crop	Cl_w (meq/l)					
Yield potential (%)	100		80		60	
Irrigation system	Low Frequency	High Frequency	Low Frequency	High Frequency	Low Frequency	High Frequency
Fibre, grain, and specialty crops						
Barley	62	78	93	117	124	155
Canola or Rapeseed	75	94	86	108	98	122
Corn	13	17	26	33	39	49
Cotton	60	75	89	112	67	150
Crambe	16	19	40	50	64	80
Flax	13	17	26	33	39	49
Guar	68	85	78	97	87	109
Kenaf	63	79	76	95	89	112
Lesquerella	47	59	56	70	64	80
Peanut	25	31	30	38	36	45
Rice, paddy	23	–	36	–	49	–
Rye	88	111	103	129	117	147
Sorghum	53	60	66	79	72	90
Soybean	39	49	47	58	54	68
Sugar beet	54	68	81	101	107	134
Sugarcane	13	17	40	50	66	83
Sunflower	37	47	68	85	99	124
Triticale	47	59	109	137	171	215

Wheat	47	58	68	85	90	113
Wheat (semi-dwarf)	67	83	118	148	170	213
Wheat (durum)	46	57	87	109	127	134

***Source**: Author's own elaboration.*

Most grass and forage crops can also tolerate high concentrations of Cl (Table 8.8). For example, Bermuda grass, rye and wheatgrass can all tolerate over 50 meq/l Cl in the irrigation and achieve full yield potential provided a 20 percent leaching fraction is sustained. Again, only conventional irrigation methods are considered since it is likely that most grass and forage species will be irrigated by conventional, surface methods. The legume forage species are, for the most part, more sensitive because they are more sensitive to osmotic stress (salinity), where Cl acts as the major anion. For example, alfalfa, broad bean and clover can only tolerate 12–16 meq/l Cl in the irrigation water and still sustain full yield potential. One interesting exception is narrow leaf trefoil, which can tolerate up to 39 meq/l Cl and still sustain full yield. However, doubling this concentration will result in more than a 40 percent loss in yield potential. At the extreme level, Bermuda grass, rye, wheat and wheatgrass can all tolerate more than 100 meq/l and still sustain 60 percent yield potential.

Table 8.8. Maximum Cl concentration (meq/l) in the irrigation water at which 100, 80, or 60 percent yield potential of popular grass and forage crops can be achieved, assuming good management practices, with low- or high-frequency irrigation. This assumes a 20 percent LF is sustained.

Crop	Cl_w (meq/l)					
Yield potential (%)	100		80		60	
Irrigation system	Low Frequency	High Frequency	Low Frequency	High Frequency	Low Frequency	High Frequency
Grasses and forage crops						
Alfalfa	16	19	36	46	58	73
Barley (forage)	46	58	68	85	90	113
Bermuda grass	53	67	78	97	102	129
Broad bean	12	16	29	36	45	56
Clover (alsike)	12	15	25	31	37	47
Clover (berseem)	12	15	39	49	66	83
Clover (ladino, red, strawberry)	12	15	25	31	37	47

Corn (forage)	14	17	35	22	56	70
Cowpea (forage)	19	24	33	42	47	59
Fescue (tall)	30	38	60	75	88	110
Foxtail (meadow)	12	15	28	35	44	55
Harding grass	36	45	56	70	77	96
Love grass	16	19	34	43	53	66
Orchard grass	12	15	36	46	62	78
Rye (forage)	59	74	91	114	122	153
Ryegrass (perennial)	43	54	64	80	84	106
Sesbania	18	22	40	50	62	78
Sphaerophysa	17	21	40	50	61	77
Sudan grass	22	27	58	73	94	117
Trefoil (big)	18	22	26	33	34	43
Trefoil (narrow leaf)	39	49	54	68	70	87
Vetch (common)	23	29	37	47	51	64
Wheat (forage)	35	44	95	118	154	193
Wheat (durum)	16	20	78	98	140	176
Wheat (standard crested)	27	34	66	83	105	131
Wheatgrass (fairway)	58	73	81	101	104	129
Wheatgrass (tall)	58	73	95	119	132	165
Wild rye (beardless)	21	26	47	58	73	91

***Source**: Author's own elaboration.*

With a few exceptions, the maximum concentration of Cl^- in the irrigation to achieve targeted yield potentials for most vegetable and annual fruit crops is considerably less than those of grains, grasses and forages. For example, popular vegetables such as carrots, common bean, eggplant, onions, muskmelons, radishes and turnips cannot tolerate 10 meq/l Cl^- and still achieve full yield potential. This assumes that crops are irrigated by conventional methods and achieve a 20 percent LF. However, most of these crops can achieve full yield potential with 10 meq/l Cl^- water if high-frequency irrigation methods are used and systems are managed to achieve a 20 percent LF. On the other hand, more tolerant crops such as artichoke, asparagus, red beet, celery, cowpea, purslane, zucchini squash, Swiss chard and turnip greens can tolerate over 60 meq/l and still achieve at least 60 percent yield potential using conventional irrigation. One vegetable crop that stands above the rest is asparagus. With its extreme salt tolerance, it can withstand over 180 meq/l Cl and still achieve at least 60 percent yield potential if a 20 percent LF can be sustained over the long term.

Table 8.9. Maximum Cl concentration (meq/l) in the irrigation water at which 100, 80, or 60 percent yield potential of popular vegetable and annual fruit crops can be achieved, assuming good management practices with low- or high-frequency irrigation. This assumes a 20 percent LF is sustained.

Crop	Cl_w (meq/l)					
Yield potential (%)	100		80		60	
Irrigation system	Low Frequency	High Frequency	Low Frequency	High Frequency	Low Frequency	High Frequency
Vegetable and annual fruit crops						
Artichoke	47	59	60	76	74	93
Asparagus	32	40	109	137	187	234
Bean (common)	8	10	16	20	24	30
Bean (mung)	14	17	22	27	29	36
Beet (red)	31	39	48	60	65	82
Broccoli	10	13	20	25	29	37
Cabbage	14	17	30	38	46	57
Carrot	8	10	19	23	30	38
Cauliflower	12	15	22	28	33	42
Celery	14	17	39	49	64	81
Corn (sweet)	13	17	26	33	39	49
Cowpea	38	48	51	64	64	80
Cucumber	19	24	31	39	43	54
Eggplant	9	11	31	39	53	67
Fennel	11	14	21	26	30	38
Garlic	30	38	41	51	52	65
Lettuce	10	13	22	27	34	43
Muskmelon	8	10	26	33	45	56

Onion (bulb)	9	12	19	24	29	36
Onion (seed)	8	10	27	34	47	58
Pea	26	33	41	51	56	70
Pepper	12	15	22	28	34	43
Potato	13	17	26	33	39	49
Purslane	49	61	65	81	81	102
Radish	9	12	21	26	33	42
Spinach	16	19	36	45	57	71
Squash (scallop)	25	31	35	44	44	55
Squash (zucchini)	38	48	53	66	67	84
Sweet potato	12	15	26	32	40	50
Swiss chard	54	68	81	102	109	136
Tomato	19	24	35	44	50	63
Tomato (cherry)	13	17	30	38	47	59
Turnip	7	9	24	30	41	51
Turnip (greens)	26	32	62	78	98	122

***Source**: Author's own elaboration.*

8.2.3. Boron

As mentioned in Chapter 4, boron is a trace element that is required by plants but can become toxic with only small increases in concentration above what is required for optimal growth. Like Na and Cl, many trees and vines are particularly sensitive to boron, but there are a number of annual crops that are sensitive as well. Most of the tolerance limits for boron are based on the development of incipient injury when boron concentration in the soil water reaches critical concentrations. But boron has a higher affinity for adsorption to the soil than common ions. Boron's affinity for the soil is dependent upon many characteristics including clay content, texture, organic matter, pH, soil water content and temperature, among others (Goldberg *et al.*, 2000). Because of boron's higher affinity to the soil, it takes several times more water to reduce soil boron by a certain percentage than it does to reduce soil salinity by that same percentage (Hanson *et al.*, 2006).

Because of these boron adsorption processes, the relationship between boron concentration in the irrigation water and boron concentration in the soil solution is much more complicated than considering salinity alone. Canadian researchers developed a method to estimate boron in the soil water based on boron in the irrigation water for a given leaching fraction (Jame *et al.*, 1982; Layshone & Jame, 1993). A mass balance equation was used to calculate the boron concentration in the soil solution at equilibrium (after the soil adsorption sites were saturated with boron) at different soil depths (i.e. root zone quarters).

They assumed that boron uptake was directly related to the root distribution and that the root water uptake was 40, 30, 20, and 10 percent in relation to top, second, third and bottom root zone quarters. Their predictive model showed that the boron concentration of the soil water in well-drained soil is close to that of the irrigation water near the soil surface but increases with depth in the root zone. As the LF decreased, the rate of increase in boron concentration with root zone depth, increased. They found that for irrigation waters containing 0.50–10.0 mg B/L, the weighted average boron concentration in the soil solution would be 1.4–1.9 times that of the irrigation water, if the LF was 0.25. On the other hand, if the LF was only 0.10, the relationship between boron in the irrigation water and boron in the soil solution was increased to 1.9–2.7. The relationship between boron concentration in the irrigation water (Bw) and boron concentration in the soil water (Bss) is given in Figure 8.1. This relationship was used to develop the guidelines for maximum concentration of boron in the irrigation water, considering different irrigation methods and leaching fractions (see Table 8.10).

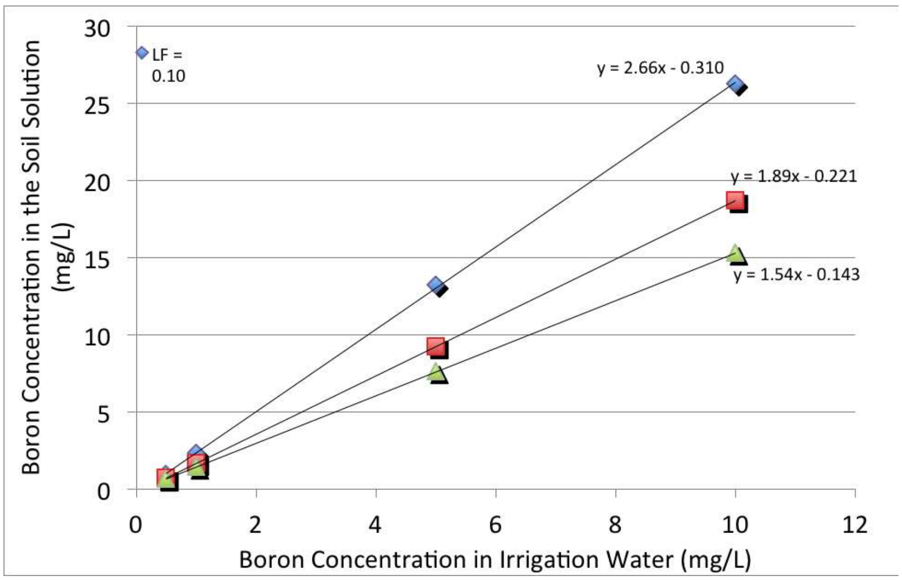

Figure 8.1. Relationship between boron in the irrigation water (B_w) and the weighted average root zone boron in the soil solution (B_{ss}) at three leaching fractions (LF). The blue diamond, red square and green triangle represent LF of 0.1, 0.25 and 0.4, respectively. This relationship assumes a root water uptake pattern of 40, 30, 20, and 10 percent in each root zone quarter (top to bottom).

***Source**: Jame, Y.W., W. Nicholaichuk, A.J. Leyshon and C.A. Campbell. 1982. Boron concentration in the soil solution under irrigation: A theoretical analysis. Can. J. Soil Sci. 62:461-471.*

It is important to note that the concentration guidelines in Table 8.10 assume long-term irrigation achieving a LF or 10 and 25 percent with conventional irrigation methods. During the first several years, much of the boron from the irrigation water will be adsorbed onto the soil particles thereby reducing the boron concentration in the soil water (Gupta *et al.*, 1985). This will allow higher tolerance during these first few years. However, once all the boron adsorption sites are saturated, boron concentration in the soil water will behave similar to common salts (D. Suarez, personal communication). Because fine textured soils, such as clays and clay-loams, have a higher adsorption capacity, it will take longer to saturate all adsorption sites than it would a coarser textured soil like a sandy loam. For example, it was estimated that irrigation water containing 1.0 mg/l of boron would take between 10 (sandy loam) to 55 years (clay loam) to reach equilibrium, if the LF was 0.25 and if soils started out boron-free (Jame *et al.*, 1982; Layshone & Jame, 1993). Therefore, injury is more likely to appear on sensitive plants in sandy soils than those in clay soils given the same Bw and LF. However, after the adsorption sites are saturated, regardless of soil type, the boron concentration in the soil water will increase.

The guidelines indicate that, for most crops, the maximum tolerable concentration of boron in the irrigation water is 0.4–1.5 mg/l if a 10 percent LF is achieved. At this low LF, citrus, avocado, stone fruits and nuts, and grapes can only tolerate up to 0.4 mg/l over the long term, and the tolerance limits are even less for lemon and blackberry. Increasing the leaching fraction from 10 to 25 percent raises the tolerable limits by about 50 percent.

There are some crops that can tolerate 2 mg/l of boron or higher in the irrigation water even at the lower leaching fraction. Crops that can tolerate this level of boron in the irrigation water include alfalfa, asparagus, red beet, celery, cotton, onion, parsley, scallop squash, sorghum, tomato and purple vetch.

Table 8.10. Critical boron (B) concentration (mg/l) in the irrigation water above which injury occurs, assuming different irrigation management practices and achieving a LF of either 10 or 25 percent over the long term. Average Bss threshold values from Table 4.2 were used and the relationship in Fig 8.1.

Crop	B_w (mg/l)	
	Leaching Fraction (%)	
	10	25
Alfalfa	2.0	2.8
Apricot	0.4	0.4
Artichoke, globe	1.2	1.7
Artichoke, Jerusalem	0.4	0.6
Asparagus	4.8	6.7
Avocado	0.4	0.4

Barley	1.4	1.9
Bean (kidney, lima, mung)	0.4	0.6
Bean, snap	0.5	0.6
Beet, red	2.0	2.8
Blackberry	<0.3	<0.4
Bluegrass, Kentucky	1.2	1.7
Broccoli	0.5	0.6
Cabbage	1.2	1.7
Carrot	0.7	0.9
Cauliflower	1.6	2.2
Celery	3.8	5.3
Cherry	0.4	0.4
Clover, sweet	1.2	1.7
Corn	1.2	1.7
Cotton	3.1	4.3
Cowpea	1.1	1.4
Cucumber	0.7	0.9
Fig, Kadota	0.4	0.4
Garlic	1.7	2.4
Grape	0.4	0.4
Grapefruit	0.4	0.4
Lemon	<0.3	<0.4
Lettuce	0.6	0.8
Lupine	0.4	0.6
Muskmelon	1.2	1.7
Mustard	1.2	1.7
Oats	1.2	1.7
Onion (bulb)	3.5	4.8
Orange	0.4	0.4

Parsley	2.0	2.8
Pea	0.7	0.9
Peach	0.4	0.4
Peanut	0.4	0.6
Pecan	0.4	0.4
Pepper, red	0.7	0.9
Persimmon	0.4	0.4
Plum	0.4	0.4
Potato	0.7	0.9
Radish	0.5	0.6
Sesame	0.4	0.6
Sorghum	2.9	4.0
Squash (scallop)	2.0	2.7
Squash (winter)	0.5	0.6
Squash (zucchini)	1.1	1.5
Strawberry	0.4	0.6
Sugar beet	1.9	2.7
Sunflower	0.4	0.6
Sweet potato	0.4	0.6
Tobacco	1.2	1.7
Tomato	2.3	3.1
Turnip	1.2	1.7
Vetch, purple	2.0	2.8
Walnut	0.4	0.4
Wheat	0.4	0.6

Source*: Author's own elaboration.*

In addition to the threshold boron concentration guidelines reported in Table 8.10, a number of studies were conducted to develop yield responses to increasing boron in the soil water in a similar manner as the Maas-Hoffman salinity coefficient model. The B tolerance threshold and slope coefficients are found in Table 4.2. The first step in determining the Bw guidelines was to determine the maximum boron concentration in the soil water (Bss) to achieve 100, 80 and 60 percent yield potential. Next, this Bss was converted to Bw using Figure 8.1. The guidelines for the maximum Bw concentrations allowable to achieve these respective yield potentials are presented in Table 8.11. For most crops, while sensitive to boron at low concentrations, yields do not dramatically decrease with increasing Bw as they do with increasing salinity. For example, broccoli and radish have maximum tolerable Bw concentrations of 0.5–0.6 mg/l to achieve full yield potential but can tolerate up to 12.4 and 15.8 mg/l, respectively, and achieve 60 percent yield potential if a 25 percent LF can be sustained over the long term. However, some crops remained sensitive to increasing Bw concentrations. For example, the maximum tolerable Bw concentration for snap bean and cowpeas to achieve full yield potential, using a LF of 25 percent, was 0.6 and 1.4 mg/l, respectively. However, as the Bw concentration increased to only 2.4 and 3.2 mg/l, the respective yield potential for snap bean and cowpea decreased to 60 percent. Increasing the LF from 10 to 25 percent increased the maximum tolerable Bw concentration by about 40 percent. Of the 17 crops listed, 14 could tolerate 2.5 mg/l or higher and achieve an 80 percent yield potential even if only a 10 percent LF was achieved. Over half of the crops could tolerate 4 mg/l or higher concentrations of boron in the irrigation water and achieve 80 percent yield potential.

Table 8.11. Maximum boron (B) concentration (mg/l) in the irrigation water at which 100, 80, or 60 percent yield potential of popular vegetable and annual fruit crops can be achieved, assuming good irrigation management practices and achieving a 10 or 25 percent LF.

Crop	B_w (mg/l)					
Leaching fraction	10	25	10	25	10	25
Vegetable and annual fruit crops						
Barley	1.4	1.9	3.1	4.3	4.8	6.7
Bean, snap	0.5	0.6	1.1	1.5	1.7	2..4
Broccoli	0.5	0.6	4.7	6.5	8.8	12.4
Cauliflower	1.6	2.2	5.6	7.8	9.5	13.4
Celery	3.8	5.3	6.2	8.6	8.5	11.9
Cowpea	1.1	1.4	1.7	2.3	2.3	3.2
Garlic	1.7	2.4	4.5	6.3	7.3	10.2
Lettuce	0.6	0.8	5.0	7.0	9.5	13.3
Onion (bulb)	3.5	4.8	7.4	10.4	11.4	16.0
Radish	0.5	0.6	5.9	8.2	11.2	15.8
Sorghum	2.9	4.0	4.5	6.3	6.1	8.5

Squash (scallop)	2.0	2.7	2.7	3.8	3.5	4.9
Squash (winter)	0.5	0.6	2.2	3.1	4.0	5.6
Squash (zucchini)	1.1	1.5	2.6	3.6	4.0	5.6
Sugar beet	2.0	2.7	3.8	5.3	5.6	7.9
Tomato	2.3	3.1	4.5	6.2	6.7	9.4
Wheat	0.4	0.6	2.7	3.8	5.0	7.0

Source: *Author's own elaboration.*

8.3. ADJUSTING GUIDELINES TO SITE-SPECIFIC CONDITIONS

The water quality guidelines for salinity and toxic ions presented here should be considered a first approximation. They will likely need some adjustment when applied in the field, depending upon the field conditions, available water sources (both quantity and quality), irrigation methods and climatic conditions. Field conditions must be assessed for soil type, existing salinity and sodicity, and how readily the soils drain. As such, the field must be evaluated for soil texture and potentially restricting layers within the soil profile. As indicated earlier, brackish water cannot be used effectively over the long term in soils that do not readily drain. Furthermore, if perched water tables exist, a drainage system would need to be installed to lower the water table to a manageable level below the soil surface. If soils can effectively drain and there is no perched water table, then salinity and sodicity must be assessed. Saline soils may require reclamation leaching before growing crops (refer to Figure 6.5). Saline-sodic soils would require reclamation by adding Ca^{2+} suppliers, such as gypsum, or Ca^{2+} liberators (acidifying amendments) prior to leaching (see Hanson *et al.*, 2006). This will help reduce the ESP near the soil surface and improve soil structure, thus increasing infiltration and leaching. Reclamation leaching should be conducted to reduce root zone salinity to acceptable levels.

As previously stated, good irrigation management practices require a proper balance between the fundamental scientific principles that were used to develop the guidelines and the ‘art of the practice’. The ‘art of the practice’ comes only from a growers’ experience adjusting water management practices to adapt the guidelines to site-specific conditions. It is this experience, combined with the understanding of scientific principles, that allow the grower or farm manager to adjust the guidelines one way of the other to make them more suitable to the conditions on the farm. The successful grower is able to apply this flexibility on their farm. Table 8.12 provides a list of crop, soil, management and climatic factors and provides the direction of adjustment needed to accommodate that factor. This list of factors is qualitative rather than quantitative. Because multiple factors are likely to be at play, the art comes from balancing a net adjustment to account for the most limiting factors, some of which may be working in opposite directions. Balancing these adjustments could be approached more quantitatively using transient models and this would likely provide more effective adjustment (see Chapter 9).

Table 8.12. Crop, soil, climate and management factors and how they affect the direction of adjustment of the guidelines.

Factor affecting water-quality guideline	Relative adjustment to water-quality guidelines		
Crop factor			
Salt tolerance of variety	More salt-tolerant variety	Less salt-tolerant variety	
	Increase	Decrease	
Root water extraction pattern[8]	40-30-20-10 pattern	Exponential pattern	
	Same	Increase	
Soil factors			
Soil Texture	Soils coarser than sandy-loam, Higher infiltration rates	Soils finer than clay-loam, Lower infiltration rates	
	Increase	Decrease	
Climate factors			
Temperature	Higher temperature	Lower temperature	
	Decrease	Increase	
Humidity	Higher humidity	Lower humidity	
	Increase	Decrease	
Effective rainfall	Significant contribution to leaching	Insignificant contribution to leaching	
	Increase	Decrease	
Management factors			
Leaching fraction (LF)	Higher LF	Lower LF	
	Increase	Decrease	
Irrigation method	Sprinkler (leaves wetted)	Surface	Drip (high frequency)[1]
	Decrease	Same	Increase

Source: Author's own elaboration.

[8] Root water extraction pattern is assumed to follow '40–30–20–10' indicating that 40 percent of the root water uptake occurs in the top quarter of the root zone and 30, 20, and 10 percent occurs in descending root zone quarters. Under high-frequency drip irrigation, roots preferentially extract water closer to the soil surface and typically follow an exponential extraction pattern. Therefore, a root-water uptake weighted function, rather than a linear average function, is used to estimate the effective root zone ECe for high frequency, drip irrigated systems.

Some countries in the NENA region have developed cultivars with higher salinity tolerance than those used to develop the guidelines. Higher salinities can be used to grow these more tolerant varieties. It is important to stay informed of promising new cultivars that are available on the market.

Soil conditions can have a profound influence on whether leaching requirements can actually be achieved. The guidelines here assume soils that adequately drain and apply to soil textures from sandy loam to clay loam. If soil textures are more coarse, such as well-drained sands, theoretically they can tolerate higher irrigation water salinity (and higher Na^+ and Cl^- concentrations) if they are irrigated frequently enough to maintain soils near field capacity. In most conditions in the NENA region, this may be difficult or impractical as the crops could experience combined salt and water stress in such conditions. If soils are very heavy clays and drain poorly, then targeted leaching fractions cannot be achieved and the guidelines would have to be adjusted downward. That is, the evaporative demand would exceed the downward hydraulic conductivity so targeted leaching would not be achieved.

In India, guidelines were developed that allow adjustment based on soil texture (Minhas & Gupta, 1992). These guidelines were based on a large countrywide data set (1972– 1990) from the "All India Coordinated Research Project on Management of Salt-affected Soils and Use of Saline Water in Agriculture" (AICRP-SAS), which comprises eight centres representing different agro-ecosystems (P.S. Minhas, personal communication). The data was drawn from long-term studies using different salinities, SARs and RSCs. Based on this data, guidelines were developed using a SALT model (SALTMED) that included the tolerance of crops under different conditions in India. For example, they show that the guidelines are reduced by about a half to a third when considering clay soils vs those that are moderately coarse (Minhas & Gupta, 1992). According to the survey of soil texture collected from each of the pilot NENA countries, soil texture ranges from sandy loams to clays. It was suggested that the guidelines on clay soils (> 30 percent clay) be reduced to a quarter of those on soils with 10–20 percent clay such as sandy loams, loams and silty loams (Annex 3). The degree of reduction in the listed guidelines need to evaluated on a farm by farm basis in the NENA region.

The climate will also affect the degree of guideline adjustment. In the NENA region, the climate is arid and semi-arid, but rainfall can vary from location to location. While the average rainfall in the region is 150 mm and in some areas near the coast of the Mediterranean Sea rainfall can reach over 600 mm, much of the NENA region has annual rainfall of less than 100 mm. In areas where rainfall is effective at leaching salts from the root zone, the guidelines can be adjusted upwards. The degree of adjustment will be related to the fraction the effective rainfall contributes to the crop water requirements. But the degree of contribution is dependent upon the crop, growing season, climate and soil conditions, and, thus, cannot be based on average rainfall alone. Temperature and humidity are also known to influence crop salt tolerance. As such, the guidelines could be adjusted upward or downward depending upon the conditions being abnormally cool (upward) or warm (downward). Crop salt tolerance is also higher in more humid climates where the evaporative demand is less. Keep in mind that the salt tolerance guidelines provided in this chapter are based largely on research studies conducted in hot, arid conditions.

Irrigation management can have a profound influence on the guidelines. The guidelines presented here already account for two management aspects: leaching and irrigation frequency. Higher salinity, Cl, Na and B waters can be used if higher LFs are achieved. And, if irrigations can be applied more frequently, root water extraction will be proportionally higher in the upper, less saline portion of the root zone. This practice will also allow for higher salinity water to be used. As indicated in Chapter 6, good irrigation management also requires knowledge of crop water requirements in order to determine the crop water needs. But it is important to remember that salt-stressed crops use less water than non-stressed crops, largely because they are stunted and have less ground cover than non-stressed crops of the same age. For more information on crop water requirements, refer to FAO Irrigation and Drainage Paper 56 (Allen *et al.*, 1998) and FAO Irrigation and Drainage Paper 66 (Steduto *et al.*, 2012).

8.4. INFILTRATION HAZARD

For decades, the sodium adsorption ratio (SAR) has been the standard used for assessing the infiltration hazard of irrigation water (Ayers & Westcot, 1985; US Salinity Laboratory Staff, 1954). The actual infiltration hazard is assessed by balancing the opposite effects of salinity and SAR on aggregate stability. Typically, the adjusted SAR (SARadj) is used rather than the SAR (see Chapter 3) as it more accurately accounts for calcite precipitation and dissolution processes in the soil solution near the soil surface that control the free Ca^{2+} concentration. At the same time, soil scientists have also known that the flocculation power of Mg^{2+} is considerably less than that of Ca^{2+}. Therefore, the SAR expression places too much weight on the effects of Mg^{2+} on protecting aggregate stability. Also, the SAR expression ignores K^+, which is typically not problematic for most irrigation waters since K^+ concentrations are usually very low compared to the other cations. The recently developed $CROSS_{opt}$ index (Oster *et al.*, 2016; Smith *et al.*, 2015) that was presented in Box 3.2 is a better predictor of the soil aggregate stability by decreasing the flocculating power of Mg^{2+} and it includes K^+, which can be important for many brackish waste waters from the food industry that could be used for irrigation. The concentration of K^+ in many of these effluents are often high.

$$CROSSopt = \frac{Na\ + 0.335K}{\sqrt{(Ca\ + 0.0758Mg)}} \qquad \textbf{Equation 8.2}$$

The $CROSS_{opt}$ expression above can then be substituted for the SAR expression to predict whether the irrigation water will likely have a severe reduction in infiltration (red zone), a slight to moderate reduction in infiltration (yellow zone) or no reduction in infiltration (blue zone), as shown in Figure 8.2 (J. Oster & G. Sposito, personal communication). For example, if an irrigation water has the composition Ca^{2+} = 11.60, Mg^{2+} = 9.30, Na^{+} = 19.4, K^{+} = 0.40, Cl^{-} = 27.40, HCO_3^{-} = 4.10, and SO_4^{2-} = 9.20 meq/l and the ECw is 4.0 dS/m, in order to determine the water infiltration hazard, the first step is to adjust the Ca^{2+} concentration (Cax) in a manner equal to the adjusted SAR (refer to Table 3.2). In this case the Cax is determined using the ECw of 4.0 dS/m and the HCO_3/Ca of 4.10/11.6 = 0.35. Then, using Table 3.2, Cax = 4.91 meq/l and $CROSS_{opt}$ can be determined as

$$CROSSopt = \frac{19.4 + 0.335(0.4)}{\sqrt{(4.91 + 0.0758(9.30))}} = 8.2 \qquad \textbf{Equation 8.3}$$

Then, using $CROSS_{opt}$ = 8.2 and ECw = 4.0 dS/m, the point of intersection falls in the "no reduction in infiltration zone" in Figure 8.2. Therefore, irrigation water with this quality and composition will not likely impose an infiltration hazard.

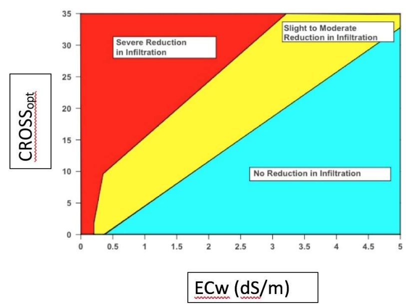

Figure 8.2. Relationship between the salinity of the irrigation water (EC_{iw}) and the cation ratio of soil structural stability ($CROSS_{opt}$) as it relates to zones of a likely reduction in infiltration rate (red), slight to moderate reduction in infiltration rate (yellow) and no reduction in infiltration rate. Adapted from Hanson *et al.*, 2006; Oster *et al.*, 2016.

***Sources**:*

- *Hanson, B., Grattan, S.R. & Fulton, A. 2006. Agricultural Salinity and Drainage. Davis, Division of Agriculture and Natural Resources (UCANR) Publication 3375. University of California.*
- *Oster, J. D., G. Sposito and C.J. Smith. 2016. Accounting for potassium and magnesium in irrigation water quality assessment. Calif. Agric. 70(2):71-76.*

CHAPTER 9

Conclusions, recommendations and future outlook

9.1. CONCLUDING REMARKS

The following remarks summarise the discussions, workshop deliberations and information gathered throughout the one-year joint AWC/FAO collaborative preparation of "Guidelines for Brackish Water Use for Agricultural Production in the NENA Region", and subsequent information provided by experts who reviewed and revised the original May 2015 report.

- It is evident that the NENA region has limited freshwater resources and an increasing gap between water demand and supply. The average annual rainfall in the region is less than 150 mm. Therefore, to ensure food and feed security, it is necessary to consider increasing water supplies by exploiting non-conventional water resources. Such water supplies include brackish surface and groundwater supplies, agricultural drainage water and treated waste waters.

- In order to facilitate the use of these brackish water sources, a set of scientifically sound guidelines using good management practices must be developed to guide sustainable irrigation practices in the NENA region.

- To that end, the AWC, FAO and nine selected countries from the NENA region (Algeria, Egypt, Iraq, Iran [Islamic Republic of], Jordan, Saudi Arabia, Morocco, Tunisia and Yemen) were involved in developing and refining the proposed guidelines through the following activities:
    - ✓ National (representing each of the nine participating NENA countries) and international experts were identified to participate in the project.
    - ✓ Brackish water information and experiences were gathered from regional and international organizations.
    - ✓ Data were collected from participating countries regarding the use of brackish water through questionnaires, field data templates, personal communications and email correspondence.
    - ✓ Two regional workshops were conducted where general guidelines were presented. The first was held in May 2014, in Doha, Qatar, on the occasion of the Second Arab Water Conference, and the second took place in Cairo, Egypt, in December 2014, on the occasion of the Third Arab Water Forum.
    - ✓ A draft report summarizing the activities and generalized guidelines was prepared in May, 2015.

- ✓ The report was sent out for review by international experts from FAO, AWC, ACSAD and ICBA as well as experts from India, Italy, Spain, United Kingdom of Great Britain and Northern Ireland (the) and United States of America (the). The report was revised based on comments and recommendations received from the reviewers.

- The information collected from country surveys by the AWC showed that, when assessing the suitability of brackish water in the NENA region for irrigation, the key irrigation water quality concerns are 1) the salinity hazard (EC_{iw}), 2) the infiltration hazard (SAR and EC_{iw}), and 3) the hazard posed by specific ions (Cl, B and Na).

- Chapter 2 provides the definition of brackish water and specific terms and definitions used to describe saline–sodic water and soils.

- Salinity and sodicity both affect soil physical conditions and the infiltration rate (Chapter 3). As salinity increases and sodicity (i.e. SAR) decreases, soil physical conditions are improved and the infiltration hazard is reduced.

- A new term referred to as $CROSS_{opt}$ (optimal cation ratio for soil structural stability) is introduced as a replacement for SAR. This term includes K^+, to be added to Na^+, as a contributing cation to dispersion which, at the same time, diminishes the flocculating power of Mg^{2+}. This revised expression has been shown to be more appropriate for assessing the infiltration hazard and can be applied to a wide range of brackish waters, including waste waters with unusual chemistry.

- Plants are affected by salinity in several ways (Chapter 4). Osmotic effects, due to the excessive concentration of salts present in the soil solution, are those that reduce the growth of plants, regardless of the salt composition. Specific ion effects are those that further reduce growth potential by either adversely affecting mineral nutrition or by imposing toxicity or injury to the crop.

- Na^+ and Cl^- toxicity mainly affect tree and vine crops (Chapter 4). Most annual crops are generally tolerant to these constituents. However, crops sprinkler-irrigated with saline water can develop injury if leaves are wetted by irrigation. Sprinkler irrigation sensitivity is related to the rate of foliar salt absorption and rather than tolerance to soil salinity.

- Boron is a micro-nutrient required by all plants, however the concentration difference between what is optimal and what is toxic is fairly narrow (Chapter 4). Many tree and vine crops are sensitive to boron as are a number of annual crops

- Crops vary in their tolerance to salinity (Chapter 5). Typically, most tree and vine crops are more sensitive to salinity than are grass, grain and forage species. Many vegetables are moderately sensitive to salinity.

- Good management practices are needed when using brackish water. The key to saline irrigation is maintaining a salt balance by leaching salts below the root zone (Chapter 6).

- Without adequate drainage, good management practices cannot be implemented. Therefore, the brackish water guidelines developed here only apply to areas where a proper salt balance can be achieved. The guidelines are not appropriate in waterlogged areas with little to no drainage.

- There are several irrigation strategies that are effective under saline irrigation. These include blending water supplies, alternating irrigations between saline and fresh water and sequential irrigation. Leaching can be done at each irrigation but typically is most effective at the end of the season when evaporative demand is low.

- Blending fresh water with saline water is the simplest and easiest practice, while alternating fresh and saline waters requires some knowledge of the varying crop tolerance during the different growth stages and the dynamic changes in soil salinity over the season. Moreover, mixing requires that both fresh and saline water be always available at the same time. Alternating saline and fresh water offers a better salt-leaching mechanism since fresh water, applied following saline irrigation, will leach the salt that has accumulated in the soil with the saline irrigation.

- The guidelines presented here reflect the importance of using non-conventional water resources within proper management to secure food production, enhance farmer income and safeguard the environment.

- The generalized, non-crop specific guidelines were developed by the AWC, local, national and international experts through questionnaires, discussions and several workshops. These guidelines are as follows (see Table 7.3):
    - EC_{iw} guidelines ranged from < 1 to 13 dS/m, depending upon the salt tolerance of the crop and acceptable level of yield decline.
    - SAR guidelines, as a surrogate for Na^+ tolerance, ranged from < 5 for sensitive crops to > 15 for tolerant crops.
    - Bw guidelines ranged from < 0.5 for sensitive crops to > 3 mg/l for tolerant crops.
    - CI guidelines ranged from < 2 for sensitive tree and vine crops to 27 meq/l for tolerant tree and vine crops.

- More detailed, crop-specific brackish water guidelines were developed based on sound, scientific principles (see Chapters 3–6) that assume long-term, steady-state conditions (Chapter 8). While these crop-specific guidelines generally agree with the generalized guidelines above, they provide more detail regarding specific allowances on a crop-by-crop basis. The guidelines vary depending upon the type of irrigation management (conventional vs high frequency), the targeted yield potential (100 to 60 percent), and assumed leaching fraction.

- The EC_{iw} guidelines were based on current crop salt-tolerance information and were developed based on conventional irrigation-management practices, assuming a 20 percent LF (Chapter 8). To achieve 100 percent yield, depending on crop salt-tolerance, ECw ranged from 0.7 to 8.8 dS/m. However, if a 60 percent yield potential is acceptable, ECw ranges from 1.7 to 18.7 dS/m.

- Sodium toxicity is often seen in sensitive tree crops such as avocado, citrus, stone fruits and berries. Irrigation water concentrations as low as 1.9 to 2.4 meq/l can develop foliar injury in these sensitive trees but usually after years of irrigation. The rootstock plays an important role on Na+ tolerance. Tolerant cultivars restrict the amount of Na+ transported to shoots. After several years, the Na+ accumulated in the sapwood is released when sapwood converts to heartwood and will translocate to the leaves where it can accumulate to toxic levels.

- For most annual crops, Na+ toxicity is not typically problematic provided the soil solution has adequate calcium to regulate ion selectively across the membrane of root cortical cells. Therefore, the SAR is a more appropriate index. Most annual crops lack Na+ toxicity when the SAR is < 15.

- Chloride toxicity is mainly restricted to tree and vine crops (Chapter 8). Sensitivity to Cl toxicity is related to the rootstock. Tolerant cultivars restrict the amount of Cl entering the scion. Depending upon the rootstock, LF (10–20 percent), and the irrigation method (low frequency or high frequency), avocado can tolerate between 2.7 to 7.3 meq/l Cl in the irrigation water. For stone fruits, the range is 2.3 to 9.7 meq/l. For citrus, the range extends from 5.3 to 24 meq/l. And for grapes on salt tolerant rootstocks, the range extends even further from 16 to 39 meq/l. However, other grape cultivars tolerate only 2.7 to 19 meq/l Cl. For annual crops, Cl tolerance is related to salt tolerance. Therefore, some grain and forage crops can tolerate over 100 meq/l and still achieve over 60 percent yield potential.

- Crop tolerance to boron varies widely. At 10 percent LF, the maximum tolerable boron concentration in the irrigation water, achieving full yield potential, varies from < 0.3 mg/l (lemon) to 4.8 mg/l (asparagus). These guidelines increase to < 0.4 and 6.7 mg/l if a 25 percent LF can be achieved. Only a limited number of studies have been conducted to determine how crop-yield responds to increased boron in the soil water beyond the threshold level. Of the 17 crops listed (Table 8.11), 14 can tolerate 2.5 mg/l or higher and achieve an 80 percent yield potential even if only a 10 percent LF is achieved. Over half of the crops can tolerate 4 mg/l or higher of boron in the irrigation water and achieve 80 percent yield potential. This indicates that yields for many crops do not decrease with increased Bw to the extent they do with increased salinity.

- Site-specific adjustments to the proposed guidelines are likely necessary as conditions vary from location to location (Chapter 8). For example, there are differences in climate, soil type, ability of soils to readily drain, ability to achieve targeted leaching fractions, restrictions on water management, soil fertility, pressures from weeds, pests and pathogens, etc.), all of which affect plant performance. Each country, and locations within each country, has its own experience in producing crops that is specific to its local conditions. And each country has its own crop varieties, developed through research and farmer experiences. Therefore, Table 8.12 lists various factors and the direction the guidelines need to shift to account for these differences. Different factors require that the guidelines be adjusted upward or downward, but the net degree of adjustment will have to be done on a farm-by-farm basis.

- The guidelines to assess the infiltration hazard are based on the combination of salinity (ECw) and the optimal cation ratio of soil structural stability ($CROSS_{opt}$). $CROSS_{opt}$ is an improved index to replace SAR as it accounts for K^+ and discounts the flocculating power of Mg^{2+} (Figure 8.2). As a result, $CROSS_{opt}$ > SAR, which makes the infiltration hazard assessment more conservative. This new index has a wider application for brackish and waste waters with varied compositions.

9.2. RECOMMENDATIONS

The following are the main recommendations and future vision concluded from the deliberations of the three brackish water regional workshops and from consultants' comments throughout the life-span of the project:

- When brackish water is used for irrigation, a higher level of management is required. It is important to monitor the irrigation water, soil and plant tissue to determine whether salinity is problematic. Specific ions (Cl, Na and B) and sodicity also need to be monitored. If problematic, corrective measures are needed to reduce salinity and/or sodicity.

- Brackish water use requires a suitable and effective irrigation and drainage system. Flood irrigation (or surface irrigation) could promote excessive drainage and aggravate waterlogging. Well-designed and managed drip systems allow higher salinity water to be used as frequent irrigations allow higher root water extraction in the upper, less saline portion of the root zone. In addition, there are ongoing new developments for drippers suitable for brackish water use that will potentially reduce the problems with emitter clogging.

- Overhead sprinkler irrigation systems that wet the foliage should be avoided as the salt could accumulate in leaves via foliar absorption, causing leaf burn. New technologies, such as low elevation sprayers, allow irrigation water to be sprayed below the canopy level, avoiding wetting the leaves.

- Brackish water use requires a suitable irrigation application strategy. Keeping the root zone at a higher moisture content prevents the plant from experiencing water stress in addition to salt stress. This does not necessarily suggest that irrigations should be more frequent but rather, that irrigations should be scheduled when the roots deplete only a fraction of the available water. Avoid prolonged soil wetting as this can induce disease.

- The use of brackish water requires an integrated approach to soil, water and crop management. In terms of soil management, minimum or zero tillage, as well as mulching, can help increase the organic matter in the soil, which improves its physical condition and the nutrient status and reduces soil evaporation. In terms of crop management, only crops with adequate salt tolerance should be selected.

- Typically, brackish water guidelines are based on crops achieving a leaching fraction during each irrigation. In field conditions, it is often better to implement reclamation leaching when salinity levels exceed tolerable levels. Usually this is better done at the end of the season.

- Implementation of the guidelines in some experimental areas in the region, adjusting them for site-specific conditions, is encouraged.

- A change in crop type should be considered as soil salinity increases over time, with little chance for leaching by rainfall or fresh water application.

- Non-conventional crops should be considered when using high saline groundwater. Quinoa and amaranth, rather than the classical cereals (wheat, barley, maize), may serve as an attractive alternative in highly saline areas. These are drought- and salt-tolerant cereals originally grown in South America that are currently grown in Europe and North Africa.

- There is a continued need to develop salt-tolerant varieties using biotechnology.

- Salt-stressed crops use less water than non-stressed crops. Therefore, it is important to know the evapotranspiration of the crop in the field. Also, monitoring the soil for water content and salinity will help with management decisions.

9.3. FUTURE OUTLOOK

- The scale of brackish water use must be evaluated on a country-by-country and region-by-region basis. Because brackish water resources are limited, the scale or extent (hectares) of brackish water use should be evaluated on an ongoing basis.

- To facilitate the use of these brackish water guidelines, a growers' manual should be written in non-technical, easily understood language suitable for farmers. The growers' guide should include appropriate crop types/varieties in relation to brackish water source(s), appropriate irrigation management practices, dates and scheduling of irrigation and all other important information that could be useful to farmers. The manual can be used by extension service officers who, in turn, can train growers in its use.

- Capacity building and institutional development programs should be organized at regional and national levels and at stakeholder/end-user levels.

- A training manual should be developed on the use of non-conventional water resources.

- User-friendly transient models, if available and successfully calibrated and validated, may help predict the long-term impact of using saline water on soil and yield. Such a model may help improve the site-specific guidelines. Models, if reliable, are a cheap alternative to field experiments and could improve management decisions.

- Friendly and easy-to-use digital guidelines in the form of a decision-support system (DSS) should be developed.

- As groundwater in most of the NENA countries is considered a non-renewable water resource, attention should be given to the use of treated domestic waste water as it is a renewable and guaranteed steady supply of water. Waste water is typically classified as saline water and, depending upon the level of treatment, pathogens may exist and could be a health hazard. Supplemental guidelines that address these microbial concerns should be developed.

- Mapping saline brackish water in the NENA region using EM38 sensors, innovative GIS and remote sensing techniques could be beneficial to the region, especially for water authorities, planners and policymakers at national and regional levels.

- Establishing a digital database hosted by the Arab Water Council (AWC) would be of great interest and benefit to the NENA region, promoting information dissemination and knowledge-sharing.

- As an application of these guidelines, brackish water use within the water–food– energy nexus would be of a great importance to the NENA region. This could be a joint AWC/FAO research activity.

- Alternative uses of saline water, in addition to irrigation, should be carefully considered. These could include use of saline water in agro-forestry, aquaculture (see Box 9.1) fish/shrimps–rice production or multiple cropping systems. In any of these applications, the least saline-tolerant element in the system is the determinant factor.

- Finally, as with all water management endeavours, understanding the overall impacts and interactions with the environment is critical. Therefore, an ecosystems approach must be adopted that considers brackish irrigation water off site.

Box 9.1 Aquaculture

Brackish-water aquaculture has become an important source of seaweed, shellfish and finfish, especially for human food and industrial use. This is likely to expand well into the next century if sea-level rise maintains its present pace and this has both direct and indirect impacts on biodiversity in terms of the consumption of natural resources and the production of wastes. Most of the brackish-water aquaculture (particularly shrimp farms) has developed in mangrove ecosystems as the water has congenial parameters and tidal action. Brackish-water aquaculture is an economic activity that transforms natural resources through inputs of capital and labour into products valued by society. In so doing, wastes are inevitably produced. The impact of aquaculture on the environment and on biodiversity thus arises from these three processes: the consumption of resources, the aquaculture process itself and waste production (Beveridge *et al.,* 1994).

Statistics produced by FAO show that world aquaculture production is currently around 25 million tonnes (FAO, 1996), equivalent to 20 percent of world fisheries production (capture + culture) by weight and around twice this by value. Production from the marine environment accounts for around 51 percent of aquaculture production by weight (53 percent by value) and is growing by some 5 percent per annum. While only 4 percent of farmed fish production comes from the sea, all farmed macro algae, almost all farmed molluscs and more than 90 percent of farmed crustaceans are produced in the marine and brackish-water environments.

The fastest-growing sectors of mariculture are in high-market-value products, such as shrimp and fish, production of the former having doubled over the past five years. By contrast, farmed production of aquatic plants and molluscs has grown slowly and gradually.

References

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ANNEX 1

Survey of different brackish water standards and guidelines

A survey was conducted of the different available brackish water standards and the guidelines from Arab countries, Asian countries, Australia, Canada and United States of America (the), and, as well as those of the FAO, the FAO Guidelines (FAO 29, 1985) and the Jordan Valley Guidelines (GTZ, 2003). The 2012 FAO study "Status and New Development on the Use of Brackish Water for Agricultural Production in the Near East", including nine selected pilot countries (Algeria, Egypt, Iraq, Iran (Islamic Republic of), Jordan, KSA, Morocco, Tunisia and Yemen) was also reviewed with the aim of carrying out an assessment of brackish water resources in the region (El-Bahrawy & Halim, 2012). In addition, efforts were made to obtain information on the essential parameters and their maximum and minimum limits to be considered in the development of the NENA region brackish water guidelines.

1 Guidelines of the Arab countries

1.1 Egypt

Agricultural drainage water reuse practices in the Nile Delta began as early as the 1930s in Egypt, alongside the development of drainage projects. The reuse of agricultural drainage water has increased with the expansion of irrigated agriculture, particularly since 1950.

Over the last three decades, the drainage system in the Nile Delta has been developed extensively. The system covers all arable lands. It consists of subsurface perforated lateral pipes that discharge water into relatively wider subsurface collector pipes. The collector pipes convey the drainage water to an open drain network by gravity, which then conveys the water to disposal sites, usually by pumping. This surface and subsurface drainage systems serves the entire country and is essential to controlling waterlogging and soil salinity.

Because of the shortage of fresh water, the reuse of the drainage water for irrigation has been and will continue to be an important resource for irrigated agriculture in Egypt. Drainage water reuse is practiced in the following ways:

- Official reuse, in which the water from selected main drains is captured and mixed with the water from selected main irrigation canals. The Ministry of Water Resources and Irrigation (MWRI) manages the operation of the pumping stations and thus the reuse volume is well monitored and recorded.
- Unofficial reuse, in which individual farmers receiving insufficient fresh water for irrigation help themselves to drainage water without permission from the MWRI.

Within the official drainage water reuse system, Egypt uses an estimated 6.5 billion m^3 of drainage water for irrigation in the Nile Delta each year. Outside the official system, farmers at the end of irrigation networks reuse an estimated 2.8 billion m^3 of drainage water per year.

The salinity of the drainage water ranges between 1.3 and 4.0 dS/m. However, in some locations in the northernmost part of the Delta, parallel to the Mediterranean Sea coastal line, drainage water salinity exceeds 5 dS/m.

Law number 12/1984 establishes salinity limits for the drainage water to be blended (500 mg/l) and for the ambient drainage water (650 mg/l). No drain in the delta meets these standards. After blending the drainage water with water from the main irrigation canals, the salinity of irrigation water ranges between 800 and 1000 mg/l As per FAO regulations and the findings of the drainage water irrigation project (DWIP, 1997), with proper management, water with much higher salinity (>2000 mg/l) can be used safety.

The data collected in the Delta area for four major crops, made it possible to derive the relationship between yield decrease and soil salinity levels. This information is presented in Table A1.1.

Table A1.1: Salinity threshold values and yield decreases

Crop	Average yields up to the threshold value (tonnes/ha)	Threshold value ECe (dS/m)	Soil salinity range in which yield decreases were observed (dS/m)	Yield decreases per dS/m (tonnes /ha)
Berseem	23.54	2.5–3.0	2.5–4.0	2.71
Maize	7.50	3.0–4.0	3.0–5.5	0.75
Rice	10.00	3.5–4.0	3.5–7.5	10.4
Wheat	7.29	5.5–6.5	5.5–10.5	0.83

***Source**:* El-Gendy, S. and Nijland, H. (1989). Economic justification of drainage projects in Egypt. Final Report, Egyptian- Dutch Panel Project in Land Drainage, Drainage Research Institute (DRI), Egypt.

As long as the salinity of applied water does not exceed threshold levels, with good drainage the use of saline water will not significantly reduce yields. When drainage water salinity exceeds crop threshold level, it is advisable to blend drainage water with fresh water.

Due to the limited water resources in Egypt, water and agriculture research centres, as well as universities, are investigating the impact of irrigation water salinity on soil and on its productivity. The outcomes of major research projects are provided below.

a. NAWQAM Guidelines (NAWQAM, 2007)

The Government of Egypt and the Canadian International Development Agency (CIDA) conducted the project National Water Quality and Availability Management (NAWQAM) from 1999 to 2007. One of the NAWQAM components was drainage water reuse. The primary objective of this component was to develop operational guidelines for the environmentally safe reuse of drainage water in irrigation.

The guidelines were built on an integrated platform comprised of agricultural, environmental and socio-economic components. The views and interests of water users and stakeholders in the study areas were taken into account in developing the guidelines. The reliability and credibility of the operational guidelines are based on extensive field monitoring, data synthesis and integration, field testing, stakeholder consultation and the institutionalization of the guidelines.

Application of NAWQAM Guidelines:

The logical sequence of applying the NAWQAM guidelines is based on a stepwise manner from the inception of village development and land settlement through land reclamation and leaching of soil and finally to normal cropping. The steps of NAWQAM Guidelines application are as follows:

Step 1: Definition of beneficiary categories based on farm size, needed financial support, farmer agricultural experience, and farmer education. According to the beneficiary categories, the NAWQAM project provides social, economic, health, education and community development support services.

Step 2: Evaluation of water availability for leaching and irrigation. This is a critical step. Both the quantity and the quality of the water is assessed.

Step 3: Assessment of water quality prior to its use for leaching and irrigation. NAWQAM guidelines specify the permissible levels of the primary chemical and biological contaminants which might be found in low-quality water. These include inorganic elements (such as heavy metals), organic compounds (such as benzene and phenol) and biological parameters (such as faecal coliform and Biological oxygen Demand [BOD]).

Step 4: Determination of reclamation stage is carried out by identifying three stages of reclamation and cropping based on soil salinity levels expressed as: leaching (EC>25 dS/m); leaching and some limited cropping (25>EC>4 dS/m); and normal cropping (EC<4 dS/m). NAWQAM guidelines specify the irrigation water quality parameters, namely the EC, SAR and concentrations of boron and trace elements. Crops are selected according to soil salinity and irrigation water quality. The guidelines also specify the detailed agronomic and field management practices for the reclamation and cropping stages. All the information and tables for crop selection and agricultural practices are explained in detail in the NAWQAM guidelines (2007).

b. Drainage Water Irrigation Project (DWIP) Guidelines

The Drainage Water Irrigation Project (DWIP) was a three-year project (1993–1997) funded by the African Development Bank to the benefit of the Ministry of Water Resources and Irrigation (through the National Water Research Center). The project was supported by the International Program for Technology and Research on Irrigation and Drainage (IPTRID).

The purpose of the DWIP was to investigate the effects of different irrigation water management strategies on the soil, water, crops, environment and the socio-economic well-being of farmers. Through the project, guidelines and criteria were developed for the sustainable use of drainage water for irrigating crops in the Nile Delta (in the old lands and the new lands).

DWIP guidelines enable the user to rate salinity hazard factors and suggest irrigation and crop management practices to overcome the hazards. The guidelines are organized into three matrices, one for each of three crop categories: salt-tolerant, moderately salt-tolerant and salt-sensitive. The matrices were designed to identify the relative potential hazard for crop yield reduction and soil salinization when using various types of irrigation water: fresh water (Nile river water); drainage water; mixed water (mixed fresh and drainage water) and groundwater (groundwater of varying salinity).

The irrigation water parameters considered in the DWIP guidelines are salinity and SAR, while soil quality is considered through water table depth, soil salinity at planting and potential soil particle dispersion by excessive sodium.

The DWIP guidelines also include criteria for environmental protection and public health protection. Additionally, they rates the degree of socio-economic vulnerability of the farmers involved in using drainage water in irrigation and list institutional measures designated to mitigate the risks.

Application of DWIP guidelines

Step 1: Specify the crop in the rotation

Step 2: Specify the irrigation water quality: fresh water (F), mixed water (M), drainage water (D) and groundwater (GW).

Step 3: Identify the critical factor(s) for: salt-tolerant crops, moderately salt-tolerant crops, salt-sensitive crops.

Step 4: Determine the overall rating:

- SLIGHT: no special management practices needed for soil salinization hazard (no factor is rated positive).
- MODERATE: consider practice(s) to minimize adverse effects from positive rated factors (one factor is rated positive).
- SEVERE: require change(s) in practice(s) to prevent significant yield reduction for current crop and soil degradation (two or more factors are rated positive).

According to the rating, soil, water and crop management actions are recommended. All the details and the guideline matrices are presented in DWIP (1997).

c. Law Number 12/1984: Irrigation and Drainage Law

Law 12/1984, which is implemented by the Ministry of Water Resources and Irrigation (MWRI) (Fahmy *et al.*, 2000), provides the standards for determining the suitability of drainage water for irrigation as well as regulating the use of groundwater and agricultural drainage water in irrigation. It also regulates the following:

- water rights and water ownership;
- area and sector water-use priorities;
- beneficial and harmful uses of water;
- groundwater use and administration at national, regional and local levels;
- financial and economic aspects of water resources, including state participation, water rates and charges, and reimbursement policies (especially with respect to field drainage);
- penalties for violation of the law.

The standards established by Law 12/1984 regarding the suitability of drainage water for irrigation, depending on the total dissolved salts content and SAR, are as follows:

i) Standards based on content of total dissolved salts:

- If the salinity of the drainage water is less than 0.75 dS/m at 25 °C (i.e. total dissolved salts less than 500 mg/l), it can be used in all irrigation methods directly without mixing.

- If the salinity of the drainage water is from 0.75 to 1.75 dS/m at 25 °C (i.e. total dissolved salts between 500 and 1 100 mg/l), it can be used to irrigate well drained land after mixing it with fresh water at a ratio of 1:1 if the total dissolved salts exceeds 700 mg/l.

- If the salinity of the drainage water is from 1.75 to 2.4 dS/m at 25 °C (i.e. total dissolved salts between 1 100 to 1 500 mg/l), it can be used in well drained land after mixing it with fresh water at a ratio of 1:2.

- If the salinity of drainage water is from 2.4 to 2.75 dS/m at 25°C (i.e. total dissolved salts between 1 500 to 1 750 mg/l), it can be used in well drained land after mixing it with fresh water at a ratio of 1:3.

ii) Standards based on the sodium adsorption ratio (SAR):

- If the SAR of the drainage water is less than 9, it can be used in all types of soils without permeability problems.
- If the SAR of the drainage water ranges from 9 to 15, it can be used in light texture soils without permeability problems. If it is used in other soils, gypsum should be added.
- If the SAR of the drainage water exceeds 15, it should not be used in heavy texture soils, but if used, drainage systems are necessary, suitable management should be practiced and gypsum must be added.

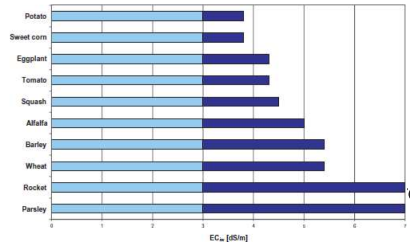
The MWRI webpage (http://www.mwri.gov.eg/irrigationlaw/1984-q.aspx) provides more details about using drainage water for irrigation.

1.2 Jordan

The guidelines for brackish water irrigation in the Jordan Valley were developed under the Brackish Water Project (BWP), which is jointly implemented by the Jordan Valley Authority (JVA) and the German Technical Cooperation (GTZ). The agricultural component of the project focuses on the use of brackish water for irrigation in the middle and southern Jordan Valley. The guidelines were developed from 2000 to 2003 to provide farmers and agricultural extension agents with practical, relevant information and know-how that can be applied in the field when using brackish water for irrigation.

The guidelines are based on the evaluation and analysis of data collected in the project on local experiences and successful practices in the use of brackish water in agriculture, combined with the review of studies of international experiences and continuous scientific update. The guidelines cover nine important crops that are irrigated with brackish water in the Jordan Valley: squash, eggplant, wheat, barley, tomato, potato, sweet corn and two leaf crops. This does not imply that irrigation with brackish water is limited to these crops, but the selected crops were chosen because of their current importance and their potential for further production on farms using brackish water. The guidelines are given in detail for each of the nine crops considering their varieties, irrigation water salinity, soil texture, irrigation practices and total water supply, growing season, planting density and seeding rate, fertilization and general agricultural practices, as presented in GTZ (2003).The parameters considered in the guidelines are: salinity, chloride, sodium adsorption ratio (SAR), boron and acidity, measured as pH.

Figure A1.1 provides an overview of the irrigation practice using brackish water in the Jordan Valley, indicating the maximum value of water salinity for each crop.



ops.

Figure A1.1: Recommended threshold values of irrigation water salinity for cultivation of crops in the Jordan Valley (GTZ, 2003)

***Source**: German Technical Corporation. (GTZ). 2003. Guidelines for brackish water irrigation in the Jordan valley, brackish Water Project, Jordan Valley Authority (JVA) , (GTZ), November 2003*

1.3 Oman

In 2012, the Ministry of Agriculture and Fisheries of Oman entered into a partnership with the International Center for Biosaline Agriculture (ICBA) to prepare a strategic plan, in collaboration with relevant national partners, to combat salinity and protect water resources from pollution and salinity.

To develop the strategy, a comprehensive assessment of the current status of the agricultural systems in different governorates in Oman was conducted. The assessment included the extent of the salinity problem, distribution of water resources, productivity of different agricultural systems and the impact of salinity on farmers' income, as well as agricultural policy and legislation. The strategy also addressed socio-economic aspects and capacity-building needs at all levels. The strategy identified alternative scenarios for sustainable water resources and production systems to bring about more efficient and sustainable use of natural resources.

The assessment showed that, on 40 to 50 percent of the farms, the water used for irrigation has salinity levels over 5 dS/m, increasing soil salinity on average by 0.7 to 0.9 dS/m (Ministry of Agriculture and Fisheries and ICBA, 2012). Therefore, with the exception of a few salt-tolerant crops, such as date palm and Rhodes grass, the productivity of most crops cultivated in Oman is expected to decrease.

The guidelines propose crop varieties that tolerate soil salinity and can give good yield in salt-affected soils when employing crop management practices to counter salinity. Such crops can be grown in soils with salinity in the range of EC_{iw} 2 to 10 dS/m or 1 400 to 7 000 mg/l (~ ECe 3.5-15 dS/m or 2 500-10 000 mg/l).

For areas that have higher salinity (more than ECiw10 dS/m or 7 000 mg/l; ECe 15 dS/m or 10 000 mg/l), adaptation strategies need to be designed, mainly in terms of changing crops and cropping patterns, introduction of forage-based production systems and others.

The guidelines also provide:

- recommendations for crop selection to overcome salinity hazards;
- soil salinity classes and their impact on crop yield;
- the salt tolerance rating for the major field and forage crops cultivated in Oman;
- the leaching requirement for various crops grown with different categories of saline water.

The tables included in the guidelines and further details are provided in the Oman Salinity Strategy, Annex 2 (2012).

1.4 Guidelines of the Arab Center for Studies of Arid Zones and Dry Lands (ACSAD) on salt tolerance limits for Libya, Syrian Arab Republic and Tunisia

As presented in the report of the International Commission on Irrigation & Drainage (ICID) (2003), the Arab Center for Studies of Arid Zones and Dry Lands (ACSAD) affiliated to the League of Arab States, and the Syrian Arab Republic have studied the crop responses and yields under different salinity levels of low-quality irrigation water. The water considered in the study was blended irrigation and drainage water and saline groundwater.

Three Arab countries were considered in the study: Libya, the Syrian Arab Republic and Tunisia, and crop salt tolerance values were used as the guidelines for the use of saline water in irrigation. The considered water salinity range was as follows (ICID, 2003):

- Libya: ECiw = 3.9 to 16.7 dS/m (the maximum threshold value is 7 dS/m)
- Syrian Arab Republic: ECiw = 1.5 to 11.4 dS/m (the maximum threshold value is 8 dS/m)
- Tunisia: ECiw = 0.3 to 5.46 dS/m (the maximum threshold value is 3 dS/m)

The ICID report (2003) refers as well other parameters such as SAR, boron, chloride, and heavy metals. It also discusses the irrigation water salinity limits in other guidelines and in other countries.

2 Guidelines of Asian countries

2.1 India

Water Quality

The "India Standards" were adopted by the India Standards Institution in 1986, after they were approved by the Agricultural and Food Products Division Council. The India Standards classify irrigation water into four major classes in relation to the irrigation water salinity (expressed as electric conductivity, or EC), sodium adsorption ratio (SAR), bicarbonate ion concentration (expressed as residual sodium carbonate, or RSC) and boron concentration. Table A1.2 summarises the classification f irrigation waters in the India Standards (1987).

Table A1.2: Classification of irrigation water and related parameters, according to the India Standards

CLASS	EC dS/m	SAR	RSC (meq/l)	Boron (mg/l)
Low	Below 1.5	Below 10	Below 1.5	Below 1.0
Medium	1.5–3	10 – 18	1.5–3.0	1.0–2.0
High	3–6	18–26	3.0–6.0	2.0–4.0
Very high	Above 6	Above 26	Above 60	Above 4.0

***Source**: Indian Standard (1987). Guidelines for the quality of irrigation water, Bureau of Indian Standards, New Delhi, 1987.*

Soil Texture

The India Standard also considers soil types and provides the upper permissible limits of electric conductivity (EC), sodium adsorption ratio (SAR), residual sodium carbonate (RSC) and boron content in irrigation water for semi-tolerant and tolerant crops in different soils (see Table A1.3).

Table A1.3: Suitability of irrigation water for semi-tolerant and tolerant crops in different soil types

SOIL TEXTURAL CLASS	Upper permissible limit							
	BORON		SODICIT Y				SALINITY	
	EC (dS/m)		SAR		RSC (meq/l)		B (mg/l)	
	S. T.*	T.†	S. T.*	T.†	S. T.*	T.†	S. T.*	T.†
Above 30 percent clay (sandy clay, clay loam, silty clay loam, silty clay, clay)	1.5	2	10	15	2	3	2	3
20-30 percent clay (sandy clay loam, loam, silty loam)	4	6	15	20	3	4	2	3
10-20 percent clay (sandy loam, loam, silty loam)	6	8	20	25	4	5	2	3
Below 10 percent clay (Sand, loamy sand, sandy loam, silty loam, silt)	8	10	25	30	5	6	1	2

**Semi-tolerant crops.*

†Tolerant crops.

***Source**:* Indian Standard (1987). Guidelines for the quality of irrigation water, Bureau of Indian Standards, New Delhi, 1987.

These limits are for specific conditions where rainfall is below 600 mm/annum, no other source of water is available, and drainage and water table are not a serious limitation.

Using irrigation water of 4 dS/m salinity and above is confined to winter season crops. It should not be used during the summer season. Even during emergencies, not more than one or two protective irrigations are given to the autumn season crops.

Other guidelines from India

In 1992, guidelines for using saline and alkaline water in irrigation in India were recommended by Minhas and Gupta (1992). These consider factors such as water quality, soil texture, crop tolerances and rainfall (Table A1.4). These guidelines are based on field experiences and the results of long-term experimentation and they have a wider applicability in different agro-ecological zones of India (Minhas & Gupta, 1992).

Although the guidelines were developed for the monsoonal climate, they can also be applied to areas with seasonal rainfall. For meeting site-specific water quality objectives, the following recommendations have been added to these guidelines:

- Use gypsum for saline water with SAR >20 and/or Mg/Ca>3 and rich in silica.

- Fallow during the rainy season when SAR>20.
- Apply additional phosphorous, especially when Cl/SO_4>2.0.
- Use canal water preferably at early growth stages.
- Include pre-sowing irrigation for conjunctive use with saline waters.
- Increase the seed rate by 20 percent and apply early post-sowing irrigation (within 2–3 days) to help better germination when EC_w<EC_e (0–45 cm soil at harvest of spring crops).
- Use saline water irrigation just before the onset of monsoons to lower soil salinity and raise the antecedent soil moisture for greater salt removal by the rain.
- Use organic matter in saline environment to improve crop yield for soils having (i) shallow water table within 1.5 m in autumn, and (ii) hard subsoil layers.

Table A1.4: Guidelines for using saline irrigation waters in India

		EC_{iw} (ds/m) Limit for rainfall region (mm)		
Soil texture (% clay)	Crop tolerance	<350	350–550	>550
	(a) Saline waters (RSC <2.5 meq/l)			
Fine (>30)	Sensitive	1.0	1.0	1.5
	Semi-tolerant	1.5	2.0	3.0
	Tolerant	2.0	3.0	4.5
Moderately fine (20–30)	Sensitive	1.5	2.0	2.5
	Semi-tolerant	2.0	3.0	4.5
	Tolerant	4.0	6.0	8.0
Moderately coarse (10–20)	Sensitive	2.0	2.5	3.0
	Semi-tolerant	4.0	6.0	8.0
	Tolerant	6.0	8.0	10.0
Coarse (<10)	Sensitive	--	3.0	3.0
	Semi-tolerant	6.0	7.5	9.0
	Tolerant	8.0	10.0	12.5

	(b) Alkali waters (RSC> 2.5, EC_{iw} <4.0 ds/m)		
	Upper limit of		Remarks
Soil texture (% clay)	SAR	RSC	1. Limits pertain to kharif fallow-rabi crop rotation when annual rainfall is 350–550 mm. 2. When the waters have Na <75%, Ca + Mg <25%, or rainfall is >550 mm, the upper limit of the RSC range is safe. 3. For double cropping, RSC neutralization with gypsum is essential based on the quantity of water used. During rabi season: grow less-water –requiring crops, and during kharif: avoid growing rice.
Fine (>30)	10	2.5–3.5	
Moderately fine (20–30)	10	3.5–5.0	
Moderately coarse (10–20)	15	5.0–7.5	
Coarse	20	7.5–10.0	

Note: Kharif crops are those grown in the rainy season during the summer while rabi crops are those grown in the winter.

***Source**:* Minhas, P.S. and Gupta, R.K. (1992). Quality of irrigation water – Assessment and management, p. 123, ICAR, New Delhi.

2.2 Pakistan

Water quality

The Water and Power Development Authority (WAPDA) of Pakistan, which is responsible for land reclamation projects, applies the guidelines presented in Table A1.5 for land reclamation and irrigation. (Further details can be found in the ICID report [2003]).

Table A1.5: Guidelines for using saline water in Pakistan

Class	ECiw (ds/m)	SAR	RSC (meq/l)
Usable (fit to be used as such or no dilution with canal water)	0–1.5	0–10	0–2.5
Marginal (to be used after mixing with canal water in 1:1 ratio)	1.5–3	10–18	2.5–5
Hazardous (to be used after higher dilution with canal water or with amendments)	> 3	> 18	> 5

***Source**:* ICID (2003). Saline water management for irrigation, New Delhi, India, August 2003.

Soil salinity

Javed Akhter *et al.* (2002) considered the soil salinity guidelines as the salt-tolerant limits for different crops at 50 percent relative crop yield, where the maximum soil salinity reaches 22 dS/m for grasses, 38 dS/m for some tree types and 19.5 dS/m for some vegetables such as Brassica napus (rapeseed).

2.3 Iran (Islamic Republic of)

As presented in the Iran (Islamic Republic of) Assessment Country Report (2012), the use of brackish water for crop production has a long history in Iran (Islamic Republic of), although there are a limited number of reports of such experiences. Management practices employed by the farmers in using brackish water are similar to those used with non-saline water. In general, crop production is based on using high inputs of seeds, fertilizer and water. Agronomic practices such as land preparation, irrigation methods and crop rotation are suboptimal.

When rainfall is normal or above normal, good yields are obtained with the use of brackish waters since rainfall, in addition to inefficient irrigation, leaches the salt below the root zone. However, under drought conditions, crop yields drop sharply and are lower than average yields with non-saline irrigation.

At present, no guidelines are available for practical application in the field. In developing such guidelines, local factors such as the soil physical and chemical properties, climate and management practices should be considered. Guidelines should also be based on the experiences and scientific knowledge accumulated in the country from the use of brackish water. Table A1.6 provides the classification of water quality in Iran (Islamic Republic of) and general recommendations for its use in irrigation.

Table A1.6: Classification of water quality in Iran (Islamic Republic of)

Group	Salt Concentration mg/l	Electrical Conductivity dS/m	Consideration and Recommendations
Fresh	<500	<0.7	For all soil types and all crops. In dry seasons. winter leaching is recommended.
Slightly Salineto Marginal	500-1500	0.7-2.5	Safe to use with light- and medium-textured soils. In clay soils, leaching and drainage is needed.
Brackish	1500-5000	2.5-8	In light soils winter leaching is needed. In medium and heavy soils leaching with every irrigation is required. During germination, irrigation with non-saline or slightlysaline water is recommended.
Saline	5OOO-8OOO	8-12	Should not be used with sensitive crops in clay soil. During germination.Non-saline and slightly saline water should be used. Not suitable for soils with poor internal drainage.
Very Saline	8000-13000	12-20	Only in exceptional cases (tolerant crops and tight soil with good drainage) or in emergency (drought) in limited numbers is allowed
Hyper Saline	>13000	>20	Not allowed for irrigation

Source: Yekom Consulting Engineers (2008)

Table A1.7 provides crop classification in relation to EC_e, crop yield sensitivity and soil groups as adopted in Iran (Islamic Republic of) (ICID, 2003)

Table A1.7: The main crops classification related to salinity rate (electrical conductivity) saturated extract and crop yield adopted in Iran (Islamic Republic of)

Electrical conductivity (Ece) ds/m	Crop yield sensitivity to salinity	Soil groups related to salinity
0 to 2	Soil salinity effect on crops is negligible	Non-saline
2 to 4	Performance of crops sensitive to salinity may be limited	Low-saline
4 to 8	Performance of crops sensitive to salinity will be limited	Moderately-saline
8 to 16	Crops tolerant to salinity will have acceptable performance	Strongly-saline
< 16	Just a few crops which are extremely tolerant to salinity will have acceptable economic performance	Extremely-saline

Source: ICID (2003). Saline water management for irrigation, New Delhi, India, August 2003.

According to Seyed Ali Mohammad Cheraghi, Senior Researcher and Head of Salinity Division at the Fars Agricultural and Natural Resources Research Center in Iran (Islamic Republic of), new findings suggest that water salinities higher than those recommended by the earlier guidelines could be used (Letey *et al.*, 2011).

For the NENA region, higher water salinity limits are recommended as given in Table A1.8.

Table A1.8: Recommended minimum and maximum water salinity limits in NENA region*

Parameter	Min.	Max.	Crop restriction
ECiw (dS/m)	< 1.0		Crops sensitive to salinity
	1.0	2.5	Moderately sensitive crops
	2.5	5	Moderately tolerant crops
	5	7	Tolerant crops
	7	13	Tolerant and moderately tolerant crops with 50% reduction in crop yield
		>13	Usable only in exceptional cases

**__Source__: Compiled data from selected countries in NENA region involved the preparation of the present Guidelines. Author's own elaboration.*

The above proposed limits are based on the following rationales:

1. Full yield potential may not be the economically optimum yield. This is particularly true when only saline waters are available and potential maximum yields are not possible.
2. Salt precipitation (calcite) reduces salt concentration in the root zone.
3. Rainfall could significantly moderate the consequence of irrigation with saline water.
4. Higher yielding and more salt-tolerant crop varieties are available now, compared to varieties used in most studies conducted decades ago.

Considering the above rationale and taking into account the values for 90 percent yield potential for different crops from the crop tolerance tables, the above water salinity limits are recommended.

3 Guidelines from United States of America (the)

Water quality

Soil scientists from Colorado State University and the Colorado Water Institute use the following categories to describe the effects of irrigation water on crop production and soil quality:

- salinity hazard - total soluble salt content (EC);
- sodium hazard - relative proportion of sodium to calcium and magnesium ions (SAR);
- pH - acid or basic;
- alkalinity - carbonate and bicarbonate;
- specific ions: chloride, sulphates, boron and nitrate.

All the details and the maximum limits of each category are discussed in Fact Sheet No. 0.506, Irrigation Water Quality Criteria, developed by Colorado State University, U.S. Department of Agriculture (Bauder *et al.*, 2011).

Also, Fipps (2003) from Texas A&M University, discussed the classification of irrigation water using several different measurements to classify the suitability of water for irrigation, including ECiw, total dissolved solids and SAR. Permissible limits for classes of irrigation water ranged from excellent (175 mg/l) to doubtful (2 100 mg/l), while over 2 100 mg/l is unsuitable for use in irrigation. Additionally, the sodium hazard of water based on SAR values is ranked from low (ranging from 1 to 10) to high (ranging from 18 to 26 and generally unsuitable for continuous use), while higher than 26 is unsuitable for irrigation.

Boron is a major concern in some areas where high boron levels cause plant toxicity. Irrigation water classification relative to crop tolerance to boron ranges from excellent (boron equal to 0.33 mg/l for sensitive crops and to 1 mg/l for tolerant crops), to unsuitable (from 1.25 mg/l for sensitive crops to 3.75 mg/l for tolerant crops).

Soil Quality

As to soil quality, Fipps (2003) presented soil salinity tolerance levels for different crops for relative crop yields of 100 percent, 90 percent, 75 percent and 50 percent. For barley, for instance, the maximum soil salinity allowed is 28 dS/m for barley, while the maximum soil salinity for tall wheat grass is 32 dS/m. Fipps also listed the soil chloride tolerance of a number of agricultural crops, with maximum chloride concentrations without loss in yield ranged between 350 and 2 800 mg/l.

Different agricultural practices, including subsurface drainage, seed placement, salinity management techniques, chemical amendments, irrigation types and schedules are also presented by Fipps (2003).

4 Guidelines from Canada

The Canadian Environmental Quality Guidelines for use in Alberta were developed by the Science and Standards Branch, Alberta Environment, in 1999 and modified in 2013. The guidelines (presented in tables) were compiled from new and previous Alberta guidelines, from the guidelines of the Canadian Council of Ministers of the Environment (CCME), and from criteria developed by the United States Environmental Protection Agency (USEPA).

The guidelines are divided into three sets of surface water quality guidelines: Surface Water Quality Guideline for the Protection of Aquatic Life, Water Quality Guidelines for Agriculture and Surface Water Quality Guidelines for Recreation and Aesthetics. The details of the Water Quality Guidelines for Agriculture, including the different parameters, categories, limits and conditions are presented in the Environment and Sustainable Resource Development report published by the Government of Alberta (2013).

5 Guidelines from Australia

The Waterlines Report Series Number 66 (2011), published by the Australian and New Zealand Environment Conservation Council, presents irrigation water-quality guidelines. The guidelines (summarised in Table A1.9) act as a general guide for applying saline irrigation waters for relatively salt-tolerant crops. The guidelines also include the upper limits for certain heavy metals and elements, refer to crop species such as barley and cotton, and discuss crop management for saline areas and risk assessment for irrigation using brackish water with conductivity from less than 1 000 µS/cm to 4000 µS/cm. All the details and guideline tables are presented in the Waterlines Report Series Number 66 (2011).

Table A1.9: Irrigation water-quality guidelines for relatively salt-tolerant plants

Parameter	Irrigation water guidelines				Comments
	Moderately tolerant		Very tolerant		
Salinity	3 000 µS/cm–5 000 µS/cm	Zucchini, beets, olive, dates, wheat, millet, sunflower, oats, kikuyu, fescue.	4 000 µS/cm–	Barley, canola, cotton, Japanese millet, couch, Rhodes grass, buffalo, rye grass, phalaris, berseem clover, puccinellia.	Some salts are plant nutrients (phosphates and nitrates). When brines have a significant concentration of nutrients, the contribution of these to salinity can be discounted.

Alkalinity			7 000 µS/cm		High carbonates cause calcium and magnesium ions to form insoluble minerals, leaving sodium as the dominant ion in solution. Alkaline water could intensify sodic soil.
pH	6.5–8.5	Most crops and plants	>8.5	Salt-tolerant plants usually grown in high pH soils.	
Chloride—leaf damage	355 –710 mg/l	Alfalfa, barley, corn, cucumber	>710 mg/l	Cauliflower, cotton, safflower, sesame, sorghum, sugar beet, sunflower	Drip or subsurface irrigation and irrigation at night will minimise risks.
Chloride—in water	710–960 mg/l	Grapes			
Sodium (SAR)	18–46	Clover, oats, tall fescue, rice.	46–102	Wheat, lucerne, barley, tomatoes, beets, most grasses	
Boron	2.0–4.0 mg/l	Lettuce, cabbage, celery, turnip, bluegrass, oat, corn, artichoke, tobacco, mustard, clover, squash.	4.0–6.0 mg/l	Sorghum, tomato, alfalfa, parsley, beets, asparagus	

Source: ANZECC (1992). Australian water quality guidelines for fresh and marine waters. National Water

6 FAO GUIDELINES

In 1985, FAO published general guidelines for evaluating water quality for irrigated crop production. The document (FAO Irrigation and Drainage Paper 29) classified irrigation water into three groups based on salinity, sodicity, toxicity and miscellaneous hazards. These general water quality classification guidelines help identify potential crop production problems associated with the use of conventional water sources. The guidelines are equally applicable to evaluate water of marginal quality for irrigation purposes in terms of its chemical constituents, such as dissolved salts, relative sodium content and toxic ions. Several basic assumptions were used to define the range of values in the guidelines. Detailed information is provided in the document.

7 SURVEY CONCLUSIONS

The survey of the different guidelines from various countries and regions of the world showed that the parameters considered in the different guidelines reflect the hazards of using brackish water in agriculture as:

- salinity hazard: Water with high salinity is toxic to plants and poses a salinity hazard. Water salinity is usually measured in TDS (total dissolved solids) or in EC (electric conductivity).
- sodium hazard: Irrigation water containing large amounts of sodium is of special concern due to sodium's effects on the soil and poses a sodium hazard. Sodium hazard is usually expressed in terms of SAR (sodium adsorption ratio).
- specific ion hazard: Certain ions (sodium, chloride and boron) from soil or water accumulate in a sensitive crop to concentrations high enough to cause crop damage and reduce yield.

Therefore, most of the guidelines consider salinity, SAR, boron and chloride as important parameters for assessing the suitability of brackish water for use in agriculture. The different conditions of each country (such as climate, soil and groundwater conditions) affect the upper limits of these parameters in each of the guidelines. Some of the guidelines consider only one or two parameters. This is the case in Oman's guidelines, which consider only water salinity, and in Egypt's Law 12/1984, which considers only salinity and SAR. The guidelines reviewed also consider other important parameters affecting the use of brackish water in agriculture. These additional parameters differ from one country to another. Pakistan's guidelines, for instance, consider RSC (residual sodium carbonate or bicarbonate ion concentration) as an important parameter; the guidelines from Colorado State University, in United States of America (the), consider the parameters of pH and alkalinity; and the FAO Irrigation and Drainage Paper 29 (1985), consider various additional parameters, including nitrogen (NO_3 - N), bicarbonate (HCO_3) and pH.

The parameters that were considered in the development of these guidelines for brackish water use in irrigation in the NENA region are the most common parameters in the surveyed guidelines: salinity, SAR, boron and chloride. Table A1.10 details the limits of these parameters in the different guidelines.

Table A1.10: Limits of the most common parameters of irrigation water salinity according to the guidelines surveyed

Parameter		EC (dS/m)	SAR	Boron (mg/l)	Chloride
Egypt	Law 12/1984	2.75	15	-	-
	DWIP	6	13	-	-
	NAWQAM	6	15	3	-
FAO		3	9	3	10 meq/l
Jordan		7	9	3	10 meq/l
Syrian Arab Republic		8	-	-	-
Libya		7	-	-	-
Tunisia		3	-	-	-
Oman		10	-	-	-
Iran (Islamic Republic of)		12.5	-	-	-
India		15	30	3	-
Pakistan		3	18	-	-
Canada		5.6	10	6	700 mg/l (20 meq/l)
United States of America		3	9	6	350 ppm (10 meq/l)
Australia		7	18	6	960 mg/l (27.8 meq/l)

Source: compiled from surveyed guidelines mentioned in this chapter for brackish water use in other countries, some case studies and success stories are presented (Annex 2) from Denmark, Egypt, Greece, Italy, Spain, Syrian Arab Republic and Türkiye . Author's own elaboration.

ANNEX 2

Guidelines for brackish water use for agricultural production in rainy countries (> 200 mm/year) of the NENA region

Soil Texture (% clay)	Crop tolerance	Soil salinity (dS/m)	Cultivated Crops	EC_{iw} (dS/m)			SAR_{iw}
				R* <200 mm/year	R* = 200-400 mm/year	R* >400 mm/year	
Fine soil (clay % >30)	Sensitive		Green beans, strawberry , onion, apricot, avocado, clementine, orange, peach, almond, prune, cherry, citrus, carrot, bean, okra, apple, plum, bean, medlar, gumbo, mulberry	0.5 - 1	1.0 - 2	1.0 - 3	5 - 7
	Moderate	0.46 – 17.0	Lettuce, tomato, potato, cauliflower, cucumber, maize, melon, water melon, pepper, zucchini, eggplant, fava bean, turnip, carrot, berseem, grape, olive tree, vine, corn, spinach, celery, broccoli, broad bean, artichoke, oats, beet, fig tree, pomegranate, triticale	1.0 – 3.5	1.8 – 4	2.0 - 5	6.8 - 9
	Tolerant	0.46 – 17.15	Red beet, spinach, artichoke, asparagus, olive, fig tree, pomegranate, date palm, barley, sugar beet, durum wheat, cotton, barley, asparagus	1.5 - 3	2.5 - 5	3.5 - 8	6.8
Moderately fine soil (clay % 20-30)	Sensitive		Green beans, strawberry, onion, apricot, avocado, clementine, orange, peach, almond, prune, cherry, citrus, carrot, bean, okra, apple, plum, bean, medlar, gumbo, mulberry	0.5 - 1	1.0 - 2	1.0 - 3	6 - 7
	Moderate	0.6 - 5	Lettuce, tomato, potato, cauliflower, cucumber, maize, melon, water melon, pepper, zucchini, eggplant, fava bean, turnip, carrot, berseem, grape, vine, corn, spinach, celery, broccoli, broad bean, artichoke, oats, beet, fig tree, pomegranate, triticale	1.0 -3	2.0 - 4	3.0 - 5	7 - 8
	Tolerant	0.6 - 5	Red beet, spinach, artichoke, asparagus, olive, fig tree, pomegranate, date palm, sugar beet, durum wheat, barley, date palm, cotton, asparagus	2 – 5	4 - 6	5 - 8	8 - 10
Moderately coarse soil (clay % 10-20)	Sensitive		Green beans, strawberry onion, apricot, avocado, clementine, orange, peach, almond, prune, cherry, citrus, carrot, bean, pear, medlar, gumbo, mulberry	1.0	2.0	3.0	6 - 8
	Moderate	0.6- 3	Lettuce, tomato, potato, cauliflower, cucumber, maize, melon, water melon, pepper, zucchini, eggplant, fava bean, turnip, carrot, berseem, grape, Alfalfa, broccoli, broad bean, artichoke, oats, beet, fig tree, pomegranate, triticale	2 - 8	3.5	4.5 - 5	6.7-10.3
	Tolerant	1 - 5	Red beet, spinach, artichoke, asparagus, olive, fig tree, pomegranate, date palm, sugar beet, durum wheat, barley, asparagus	1.5 - 5	5	6 - 7	6.7-10.3
Coarse soil (clay % <10)	Sensitive		Green beans, strawberry onion, apricot, avocado, clementine, orange, peach, almond, prune, cherry, citrus, carrot, bean, pear, medlar, gumbo, mulberry	1.5	2.5	3.5 - 4	8 - 10
	Moderate	3	Lettuce, tomato, potato, cauliflower, cucumber, maize, melon, water melon, pepper, zucchini, eggplant, fava bean, turnip, carrot, berseem, grape, broccoli, broad bean, artichoke, oats, beet, fig tree, pomegranate, triticale	2.5	4.5	5 – 6.5	8 - 10
	Tolerant	4 - 5	Red beet, spinach, artichoke, asparagus, olive, fig tree, pomegranate, date palm, sugar beet, durum wheat, barley, asparagus	4-5	6.0 - 7	7- 8	8 - 10

* *R = Rainfall*

Guidelines for brackish water use for agricultural production in non-rainy countries (<200 mm/year) of the NENA region

Soil texture (% clay)	Soil Salinity (dS/m)	Crop tolerance	Cultivated crops	EC_{iw} (dS/m) R* <200 (mm/year)	SAR_{iw}
Fine soil (clay %>30)	1 – 1.7	Sensitive	All crops	<1.5	3 - 5
	1.2 - 6	Moderate	Citrus, vegetables, rice , berseem, squash, potato, tomato, alfalfa, eggplant, olive, pomegranate, date palm	1.5 - 7.5	3.3 – 7.5
	1.2 - 10	Tolerant	Cereals, date palm, barley, wheat, cotton, sorghum, pistachios, sugar beet	2 -14	7.5 -10
Moderately fine soil (clay % 20-30)	1 – 1.7	Sensitive	Bean, potato, maize, sugar cane, citrus, grape	<1.5	5 - 7
	Up to 11	Moderate	Tomato, potato, rice, alfalfa, olive, pomegranate, date palm	2.8 - 12	7 - 9
	2.5 - 10	Tolerant	Wheat, barley, date palm, cotton, sorghum, pistachios, sugar beet	2 – 14	8 - 10
Moderately coarse soil (clay % 10-20)	3 – 3.5	Sensitive	Pepper, bean, okra, potato, maize, sugar cane, citrus, grape	1-3	7
	2 -11	Moderate	Tomato, barley, potato, cauliflower, cucumber, maize, pepper, eggplant, lettuce, squash, sorghum grain, sorghum fodder, cow pea, alfalfa	3 - 12	8 - 9
	4 - 12.5	Tolerant	Wheat, cotton, sorghum, millet, sugar beet, barley, date palm, pistachios	3 - 6	8 -10
Coarse soil (clay % <10)	1 – 1.9	Sensitive	Cucumber, cauliflower, cabbage, potato, maize, sugar cane, citrus, grape, bean, okra	0.8 - 4	7
	2 - 6	Moderate	Tomato, wheat, corn, potato, pepper, cucumber eggplant, squash, alfalfa, olive, pomegranate, date palm	1.5 - 6	9 - 10
	1.2 - 11	Tolerant	Barley, date palm, garlic, onion, tomato, squash, olive, wheat	2 – 8*	9 - 10

Note: *The Irrigation Water Chloride and Boron contents for the NENA region brackish water are not included in Table 4.8 (a & b) as they are commonly agreed to be*

27 meq/l and 3 mg/l respectively for all countries.

** It is expected to have higher EC_{iw} values, yet the values in this table are based on actual field data obtained from the pilot NENA countries, where this range is the maximum water salinity used in countries with coarse soils.*

ANNEX 3

Guidelines for alfalfa crop cultivation under brackish water irrigation in NENA countries

ECiw	EC_e	Drainage system	Fertilizers	Planting procedures	Irrigation system	Irrigation intervals	No. of irrigation applications per season	LF%	Irrigation quantity	Crop productivity
2.2–8 dS/m	0.6–8 dS/m	For high saline soil Heavy clay: Surface drainage with spacing 10 m and 80 cm depth. Clay soil: Surface drainage with spacing 10 m and 80 cm depth. Loam soil: Surface drainage with spacing 10–15 m and 80 cm depth. Sandy clay loam: Surface drainage with spacing 20 m and 80 cm depth. Mole drainage is recommended at 1.5 m spacing and 45–60 cm depth. For lower salinity soil: Subsurface drainage about 50 m spacing and 1.5 m depth	375 kg/ha superphosphate at soil preparation. 125 kg/ha potassium sulphate at soil preparation. Alfalfa is a legume and is able to fix nitrogen, therefore, small amount of N fertilizers can be added for nourishing crop establishment 125 kg ammonium nitrate at first irrigation, in addition to 125 kg/ha ammonium nitrate after each cutting. Inoculation does not succeed in saline soil	1. Cultivation should start on wet soil to maintain relatively low salinity on surface. 2. Deep plough to 20 cm depth for shallow water table. Plough to 40 cm for deep water.	Surface and sprinkler irrigation	Once every 15 days according to climatic conditions	52–365 irrigations according to irrigation system applied	25–30% depending on water and soil salinities	1600–1800 mm	10–23 ton/ha

ANNEX 4

Guidelines for cultivation of trees under brackish water irrigation in NENA countries

Crops	ECiw (dS/m)	EC_e (dS/m)	Agricultural practices	Fertilizers (kg/ha)			Irrigation practices					Productivity (ton/ha)
				N	P	K	LF%	Quantity (mm)	Numbers	Intervals (days)	System	
Atriplex halimus	6–12	8	Soil preparation takes place only before the planting	Urea (46%) 100	P_2O_5 (45%) 50	K_2O_4 (50% K_2O) 100	25–30	600	26	15	Drip/ sprinkle r	273–283 ton/ha
Sesbania	7.43–11.71 (grains) 41.92–38.24 (Biomass)		Ploughing, planning and bedding					374.5	7	11	Drip/ sprinkler	4.34–5.04 ton/ha grain and 41.92–38.24 ton/ ha above ground biomass

ANNEX 5

Guidelines for sugar beet cultivation under brackish water irrigation in NENA countries

ECiw	EC_e	Drainage system	Fertilizers	Planting procedures	Irrigation system	Irrigation intervals	No. of irrigation applications per season	LF%	Irrigation quantity	Crop productivity
3.45 dS/m	0.46–17.5 dS/m	For highly saline soil Heavy clay: Surface drainage with spacing 10 m and 80 cm depth. Clay soil: Surface drainage with spacing 10 m and 80 cm depth. Loam soil: Surface drainage with spacing 10–15 m and 80 cm depth. Sandy clay loam: Surface drainage with spacing 20 m and 80 cm depth. Mole drainage is recommended at 1.5 m spacing and 45–60 cm depth. For low saline soil: Subsurface drainage about 50 m spacing and 1.5 m depth.	Nitrogen Ammonium nitrate (33% of N), Urea (46%) 280 kg/ha for irrigated areas, 140 kg/ha for rainfed areas. Potassium: Potassium sulphate (50% of K_2O), potassium nitrate (39% of K_2O) 180 kg/ha for irrigated areas, 90 kg/ ha for rainfed areas. Phosphate: Mono ammonium phosphate (55% of P_2O_5), Simple superphosphate (18% of P_2O_5), Triple superphosphate (45% of P_2O_5) 140 kg/ha for irrigated areas, 70 kg/ha for rainfed areas Note: Amount of fertilizers can be changed according to the soil texture and conditions.	1. Land preparation, using short furrows within basins, plough, disk, Land levelling. 2. Ploughing should be deep enough to promote leaching (30 cm). 3. Deep ploughing combined with deep fertilization is essential. 4. Superficial harrowing (10 cm). 5. Cultivation should start on wet soil to maintain relatively low salinity on soil surface. For lower soil salinity: Addition of organic matter at 50 ton/ha before planting sugar beet is recommended.	Surface and sprinkler irrigation	Once every 15 days according to climatic conditions	11 irrigations according to climatic conditions	20% depending on water and soil salinities	600 mm	68 ton/ ha (root)

ANNEX 6

Guidelines for sorghum fodder cultivation under brackish water irrigation in NENA countries

ECiw	EC_e	Drainage system	Fertilizers	Planting procedures	Irrigation system	Irrigation intervals	No. of irrigation applications per season	LF%	Irrigation quantity	Crop productivity
3 dS/m	4 dS/m	Not applicable	Organic fertilizers at 500 kg/ha. 500 kg/ ha of 30-15-50 NPK	1. Traditional land preparation, using short furrows within basins, plough, disk, land levelling, 2. Ploughing should be deep enough to promote leaching (30 cm) 3. Deep ploughing combined with deep fertilization is essential. 4. Superficial harrowing (10 cm) 5. Cultivation should start on wet soil to maintain relatively low salinity on soil surface.	Surface and sprinkler irrigation	10 days according to climatic conditions	12 according to climatic conditions	Not available	- 650 mm (brackish water) 80 mm fresh water	10 ton/ha

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