Water and Salinity Stress

Continually applying salt-laden irrigation water to soils can lead to soil salinization because plants leave most of the salts behind as they uptake water. Osmotic potential energy in saline soils is negative and resists the movement of water toward plant roots. According to the FAO, approximately 3 ha per minute are lost to soil salinization in the world, and 80 million ha have already been lost to soil salinization. Salinity management practices such as leaching water below the root zone are needed to prevent salt accumulation in the root zone. Leaching takes place when irrigation is increased beyond the evapotranspiration requirement. On the other hand, excess water in the soil restricts the movement of oxygen into the soil. Plants require oxygen for the roots as the conduct respiration at night. Insufficient water reduces crop evapotranspiration, and there is generally a linear relationship between percent depletion beyond the management allowed depletion and yield reduction. Crop yield reduction due to water or salt stresses can be quantified by plant stress coefficients, which reflect the plant sensitivity to stress. Water and salinity stress coefficients as well as methods to measure and control salinity are described in this chapter.

Salinity Units

Salts, in the solid phase, are composed of a metal and a ligind joined together by an ionic bond: for example, sodium (Na^+) and chloride (Cl^-). Because of differences in electronegativity, the metal loses one or more electrons and becomes a positively charged ion (cation), and the ligind gains one or more electrons and becomes a negatively charged ion (anion) when salts are dissolved. Common cations and anions in irrigation water are listed in Table 4.1. The equivalent mass of an ion is the molecular mass divided by the valence: the mass of substance required to form one mole of charge when dissolved in water.

Because ions carry electric charge, electrical conductivity of water increases with salinity. Thus, salinity can be measured with an electrical conductivity meter. Common units are decisiemens/meter (dS/m) and mmhos/cm, which equal each other. The conductivity measurement, dS/m, is multiplied by 640 in order to obtain ppm or mg/L of salts in solution. Depending on the proportion of different salts in water, the constant 640 varies from region to region.

$$C_{iw} = EC_{iw}*640 \qquad (4.1)$$

where

C_{iw} = total salinity of water, mg/L
EC_{iw} = electrical conductivity of the irrigation water, dS/m.

Saturated paste extract salinity, EC_e, is the standard measurement for soil salinity. In this test, a portion of soil is ground to a fine powder. Water is then added to the soil until it is saturated and the surface glistens. After allowing the soil to equilibrate for 1 day in a Buchner funnel, a vacuum is applied to the funnel, and soil water is extracted. Then, the electrical conductivity of the water extract is measured. Instructions on conducting a saturated paste extract test can be found in Methods of Soil Analysis, Part 1 – Physical Methods, published by the Soil Science Society of America. It is important to follow these instructions precisely in order to obtain a standardized measurement of saturated paste extract salinity.

Several unit systems are used to express salt concentration in water. The selection of the unit system generally depends on the purpose of the measurement. For example, the total mass of salts in water is expressed by mass (mg/L) whereas the quantity of carbonate that must be neutralized by acid is expressed in meq/L (moles of charge). The valence is denoted by z.

Table 4.1 Molecular mass and valence of common ions in water

	Molecular mass (g/mole)	Valence	Equiv mass (g/equiv)
Cations			
Ca^{2+}, calcium	40.1	2	20.05
Na^+, sodium	23	1	23
K^+, potassium	39.1	1	39.1
Mg^{2+}, magnesium	24.3	2	12.15
NH_4^+, ammonium	14 + 4 = 18.0	1	18.0
Anions			
Cl^-, chloride	35.5	1	35.5
SO_4^{2-}, sulfate	32 + 4 * 16 = 96	2	48
NO_3^-, nitrate	14 + 3 * 16 = 62	1	62
CO_3^{2-}, carbonate	12 + 3 * 16 = 60	2	30
PO_4^{2-}, phosphate	31.0 + 4 * 16 = 95	2	47.5
HCO_3^-, bicarbonate	1 + 12 + 3 * 16 = 61	1	61

Molarity, mol/L = moles of solute (dissolved substance)/ volume of solution

Concentration, mg/L = mass of solute/volume of solution

Equivalents/L, eq/L = (moles/L) (z)

Normality, meq/L = (moles/L) (z) (1,000)

Parts/million, ppm = g of solute/10^6 g solution (same as conc. (mg/L))

Example 4.1 Calculate the mass of calcium chloride, $CaCl_2$, dissolved in 3 liters of water, which results in chloride molarity equal to 0.15. Calculate the concentration of chloride ions.

Molarity is the number of moles of substance (calcium or chloride ions in solution) in one L of water. If the molarity of chloride ions is 0.15, then the number of moles of chloride in the water is calculated as follows: 0.15 moles/L * 3 L = 0.45 moles Cl^-.

Two moles of chloride ions are produced for every mole of calcium chloride dissolved. Thus, 0.45/2 = 0.225 moles of calcium chloride are required.

The molecular weight of calcium chloride, $CaCl_2$, is calculated as follows:

$$Ca - 40.1 \text{ g/mole}$$
$$Cl - 35.5 \text{ g/mole}$$
$$CaCl_2 - 40.1 + 2(35.5) = 111.1 \text{ g/mole}$$

Calculate the mass of $CaCl_2$ required. 0.225 moles (111.1 g/mole) = 27.8 g $CaCl_2$

Calculate the concentration of chloride in solution.

$$\left(\frac{0.15 \ moles \ Cl^-}{Liter}\right)\left(\frac{35.5 \ g}{mole}\right)\left(\frac{1,000 \ mg}{g}\right)$$
$$= 5,325 \ mg/L$$

In-class Exercise 4.1 Calculate the mass of calcium carbonate, $CaCO_3$, dissolved in 4 L of distilled water that results in carbonate molarity equal to 0.0015. Calculate the concentration of carbonate ions in the water.

Osmotic Potential Energy in Soils

Osmotic potential is caused by the fact that water with a higher concentration of salts has a lower energy (more negative) than water with a lower concentration of salts. Thus, water is driven toward the higher salinity region, or it is impeded from flowing away from the high salinity region in the case of plant water uptake. Thus, if salinity is high in the soil, then the plant has difficulty pulling water from the soil.

The osmotic potential energy in saturated soils can be calculated with the following equation:

$$\psi_s = -3.6 * EC_e \tag{4.2}$$

where

EC_e = electrical conductivity of the saturated paste extract, dS/m

ψ_s = Osmotic potential, m.

As the soil dries, the salinity increases. The osmotic potential as a function of water content is

$$\psi_s = -3.6 * EC_e * \frac{\theta_{sat}}{\theta} \tag{4.3}$$

where

θ_{sat} = saturated water content (by volume), ml/ml

θ = actual water content (by volume), ml/ml

Example 4.2 Calculate osmotic potential in the soil at 25 % water content if EC_e = 1 dS/m, and saturated water content is 50 %.

$$\psi_s = -3.6 * EC_e * \frac{\theta_s}{\theta} = -3.6 * 1 * 2 = -7.2 \ m$$
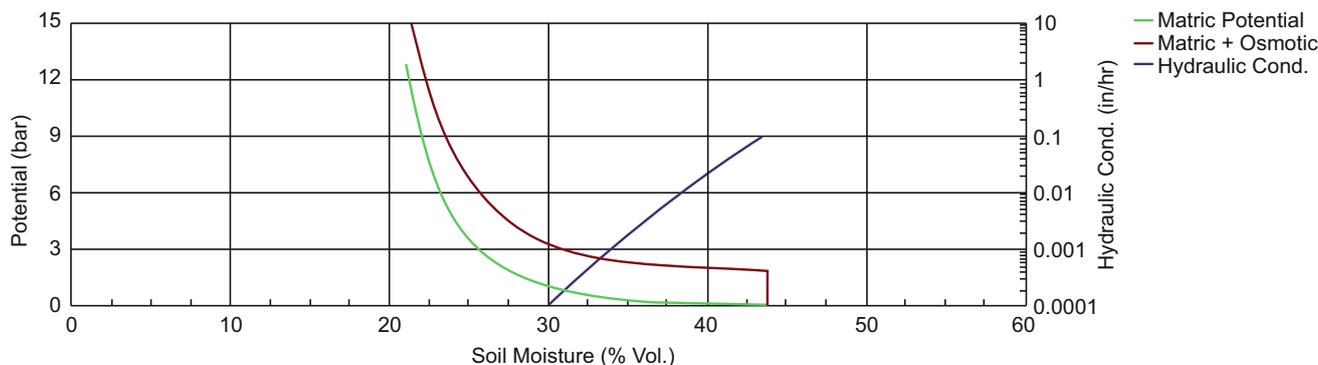$$= -0.72 \ atmospheres$$

Fig. 4.1 Effect of salinity on soil-water retention in Soil Water Characteristics Calculator

The effect of salinity in a soil can be observed in the graph at the bottom of the Soil Water Characteristics Calculator. Figure 4.1 was made in the Soil Water Characteristics Calculator for a clay loam soil and a saturated paste extract salinity of 5 dS/m. The red line represents matric + osmotic potential, and the green line represents matric potential alone. At 3 bar osmotic potential, the saline soil has 31 % water content and the nonsaline soil has 25 % water content (Fig. 4.1). If a plant can only remove water to 3 bar potential, there would be 6 % less water available to the plant in the saline soil. This difference represents the deceased availability of water for the plant. The overall effect of salinity is that it increases the permanent wilting point water content but leaves the field capacity the same. A change of 5 dS/m only decreases the water content of the permanent wilting point (15 bar) by 1 %, but there is a much greater difference at less negative matric potentials. Thus, the effect of salinity is most detrimental to salt sensitive and drought sensitive plants, which extract less water from the soil between irrigations.

Plants develop extremely negative osmotic potential energy by maintaining high solute (sugars and salts) concentration within cells. This creates an energy gradient that draws water from the soil. The osmotic potential within the plant must be significantly lower (more negative) than the combined matric and osmotic potential in the soil in order to draw water into the plant at the potential evapotranspiration rate.

Water moves through the plant from soil to atmosphere because the energy of water in the atmosphere is lower than the energy of water in the plant or the soil. The energy of water in the atmosphere is a function of the relative humidity. The energy of water is zero in the atmosphere at 100 % relative humidity, but it decreases to negative 1,000 atmospheres at 50 % relative humidity. The plant water energy, due to high sugar and salt concentration, ranges from -10 to -20 atm at midday, while the soil water energy ranges from 0 to -15 atm. Because the partial pressure of water in the atmosphere is less than that of the plant, which is less than that of the soil, water moves from the soil, through the plant, and to the atmosphere. Thus, the plant is a passive conduit that allows water to pass through based on the overall energy gradient between the atmosphere and the soil. The water column does not separate in the plant at negative energy potentials because of water's cohesive properties.

Water transpires from the roots, through the plant, and to the leaf surface through long, hollow, dead cells called xylem. Plants form sugars in the leaves through photosynthesis, and sugars are carried downward from the leaves to the roots in long, hollow, live cells called phloem. Xylem and phloem are like veins; thus, plants are referred to as vascular systems.
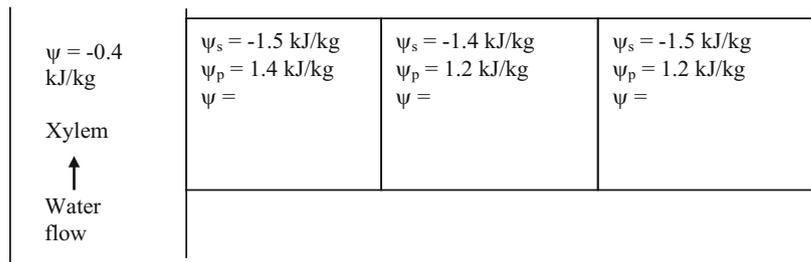
Plant cells have a selective semipermeable membrane lying just inside the cell wall. Some molecules, such as water, passively diffuse through the membrane. Other molecules are actively transported through the membrane wall by proteins that are embedded in the membrane. Thus, if the cell would like some extra sugar for dinner (for use in respiration), then it would tell the protein to pass some sugar through the membrane.

Sugars are transported from source leaves through the phloem to other locations within the plant. Phloem tissue expands as the quantities of translocated sugars increase. Unlike transpiration's one-way upward flow of water sap in the xylem, sugars in phloem sap can be transported in any direction needed so long as there is a source of sugar and a sink able to use or store the sugar. The source and sink may be reversed depending on the season, or the plant's needs. Sugar stored in roots may be mobilized to become a source of food in the early spring when the buds of trees, the sink, need energy for growth and development of the photosynthetic apparatus. Phloem sap is mainly water and sucrose; but other sugars, hormones and amino acids are also transported.

Because sugars are concentrated in the cell, the osmotic potential (chemical potential) of water in the cell is negative. The osmotic potential (Gibb's free energy) of cell water is

$$G(J/mole) = RT \ ln(C) \quad (4.4)$$

Fig. 4.2 Osmotic potential and turgor pressure in xylem and adjacent plant cells

$\psi = -0.4$ kJ/kg

Xylem

↑
Water flow

ψ_s = -1.5 kJ/kg ψ_p = 1.4 kJ/kg ψ =	ψ_s = -1.4 kJ/kg ψ_p = 1.2 kJ/kg ψ =	ψ_s = -1.5 kJ/kg ψ_p = 1.2 kJ/kg ψ =

where

C = mole fraction of water in the cell
T = temperature, °K
R = Avogadro's constant, 8.314 (kPa * L)/(mole * K)
G = Gibbs free energy, J/mole.

C (mole fraction) is found by dividing the number of moles/L of water by the total number of moles/L in the cell solution (mole fraction).

Example 4.3 Calculate the Gibb's free energy of water in a cell if the concentration of sucrose in the cell is 0.5 mole$_{sucrose}$/L water at a temperature of 27 °C. Express your answer in J/mole and J/kg (kPa).

$$mole/L \ water = \left(\frac{1,000 \ g}{L}\right)\left(\frac{mole}{18 \ g}\right)$$
$$= 55.56 \ mole/L \ water$$

mole fraction of water = $(55.56)/(55.56 + 0.5) = 0.991$

$G = RT \ \ln(C) = 8.314*300 \ \ln(0.991) = -23 \ J/mole$

Multiply by 55.56 kg/L to obtain the answer in J/kg (kPa).

$$G = RT \ln(C) = 55.56*8.314*300 \ \ln(0.991)$$
$$= -1,250 \ J/kg(kPa) = -12.5 \ atm$$

The total energy in the cell is the sum of the turgor pressure and osmotic potential

$$\psi = \psi_s + \psi_p \tag{4.5}$$

where

ψ_s = osmotic potential, J/kg
ψ_p = hydraulic pressure, J/kg
ψ = total Gibb's free energy of water in cell, J/kg.

Cell osmotic potential remains relatively constant over the cycle of a 24-hour day; however, the turgor pressure (matric potential or hydraulic pressure, ψ_p) varies during the day and night. When the turgor pressure is just slightly higher than zero during the day, as the plant is transpiring

water, the total potential energy in plant cells is close to the osmotic potential, which is between -1 and -2 kJ/kg (-10 to -20 atm). If this total potential is more negative than the soil water potential (turgor + osmotic) , then the plant will remove water from the soil. At night, the cell turgor potential increases to between 1 and 2 kJ/kg (10–20 atm); thus, at night the total potential energy in the cell is close to zero. Thus, the plant does not remove water from the soil at night.

The hydraulic (turgor) pressure in plant cells enables the plant to maintain its shape. If water is limited, and the turgor pressure drops below zero gauge pressure, then the plant wilts. Wilting is more likely to occur when soil has high salinity because the soil osmotic potential and the total soil water potential are more negative, making it more difficult for the plant to draw water from the soil. Even if wilting does not occur, higher salinity in the soil can decrease the rate at which water enters the plant; thus, slowing water uptake → photosynthesis → plant growth.

In-class Exercise 4.2 Fill in the missing total potential values and show direction of water flow. Fill in values for total potential. Are the total potentials in Fig. 4.2 more likely to occur in the day or the night?

If the soil has a low (very negative) energy potential, whether due to osmotic or capillary potential, then it takes longer for the plant to draw water from the soil because the slope of the energy gradient is less. The plant's physiological response to water stress and salinity stress is not the same. Plants compensate for low soil osmotic potential by absorbing ions from the soil solution and manufacturing organic osmolytes within plant cells (FAO 56) in order to lower the energy potential of water in the plant. Synthesis of organic osmolytes requires expenditure of metabolic energy, so this process reduces the amount of energy directed toward crop growth and yield (FAO 56). Partial stomatal closure may also occur under high salinity conditions and thus decrease ET_c (FAO 56).

Salinity Stress

The classic book on salinity and plant stress is
Due to the decreased water uptake in the presence of soil salinity, yield decreases as salinity increases. Yield-salinity curves have been generated for many crops. Figure 4.3
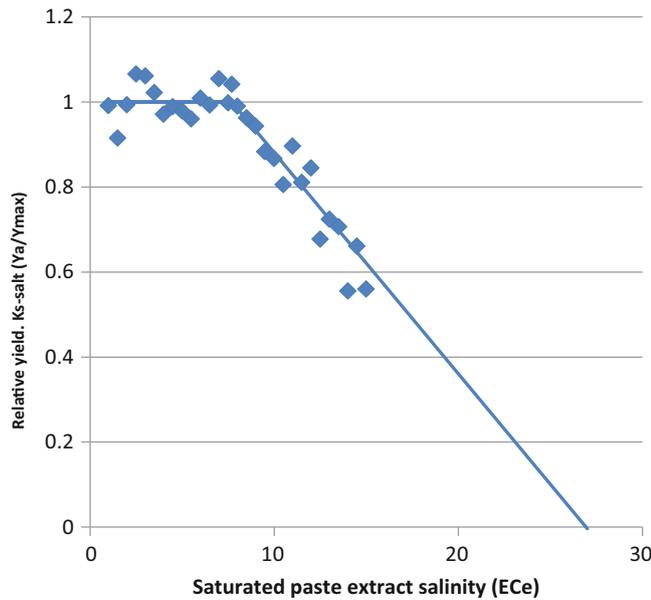
Fig. 4.3 Response of cotton to increasing saturated paste extract salinity

shows the response of cotton to soil salinity. When EC_e exceeds 7.7, the yield begins to decrease. Thus, EC_e is the salinity threshold for cotton. If saturated paste extract salinity is less than 7.7, then there is no yield decrease. Figure 4.3 shows an abrupt change in slope at the threshold with a linear relationship between soil salinity and yield above the threshold. Although recent work by Van Genuchten and others has shown that a curved line near the threshold has a closer fit to most data, this text uses the linear model in order to use standard FAO methods with linear slopes of the yield – salinity line for calculation of yield decrease as a function of salinity.

Crops that are classified as sensitive, moderately sensitive, moderately tolerant, and tolerant to salinity have no reduction in yield at EC_e = 1.0-, 3.0-, 6.0-, and 9.5-dS/m, respectively (Fig. 4.4). Vegetable crops are generally sensitive to moderately sensitive to salinity. Field crops such as cotton, wheat, and barley tend to be less sensitive to salinity. Increasing salinity is not always negative. For example, tomatoes are sometimes grown at higher salinity in greenhouse hydroponic systems to increase sugar concentration in the fruit.

The NRCS classifies irrigation salinity levels as no restriction on use (EC_{iw} < 0.7), slight to moderate restriction (0.7 < EC_{iw} < 3.0), and severe restriction (3.0 < EC_{iw}). Crops that are classified as sensitive, moderately sensitive, moderately tolerant, and tolerant to salinity have no reduction in yield at 1.0-, 3.0-, 6.0-, and 9.4-dS/m, respectively. Vegetable crops are generally classified as sensitive to moderately sensitive to salinity. Field crops (grains and fibers) tend to be less sensitive to salinity.

Table 4.2 lists b values, the slope of the line, and EC_{e-t} values, the threshold salinity, for different crops. In Eq. 4.6, b is divided by the crop sensitivity to water stress because the water stress and salinity stress equations are used together to calculate yield decrease due to both factors (Eqs. 4.9, 4.10, and 4.11). The salinity stress coefficient is equal to 1.0 if EC_e < EC_{e-t}, otherwise

$$K_{s-salt} = 1 - \frac{b}{100*K_y}(EC_e - EC_{e-t}) \tag{4.6}$$

where

b = slope of EC_e/yield line, %/(dS/m)
EC_{e-t} = threshold saturated paste extract EC_e with no yield decrease, dS/m
K_{s-salt} = salinity stress coefficient, varies from 0 to 1.

The data in Table 4.2 was acquired in crop yield – salinity stress experiments that were generally conducted with the soil near field capacity (FAO 56). Thus, the data is valid for soils with water content near field capacity. It may be possible to adjust EC in Eq. 4.6 based on water content (EC increases when water content decreases); however, FAO 56 expresses doubt that this procedure will provide accurate results.

Water Stress Coefficient

As with salinity stress, the water stress coefficient is generally calculated under the assumption that yield decreases linearly with increased percent water depletion. The threshold percent depletion, θ_t, is the water content at which yield starts to decrease. Thus, $K_{s-water}$ decreases linearly from 1 at θ_t to 0 at θ_{pwp} (Fig. 4.5), and K_s = 1 at depletion levels less than the threshold depletion. The equation can be rearranged and written in terms of threshold water content and actual water content. Threshold water content should be found with p (p is the point at which yield decreases in contrast to MAD, which is the management water depletion, which may be equal to p or less than p). The key point is that crop stress is initiated at p.

$$K_{s-water} = \frac{\theta - \theta_{pwp}}{\theta_t - \theta_{pwp}} \tag{4.7}$$

$$\theta_t = \theta_{FC} - (p/100)(\theta_{FC} - \theta_{PWP}) \tag{4.8}$$

The combined salt and water stress coefficient is the product of the two.

Fig. 4.4 Salinity tolerance and yield reduction of various crops in response to salinity
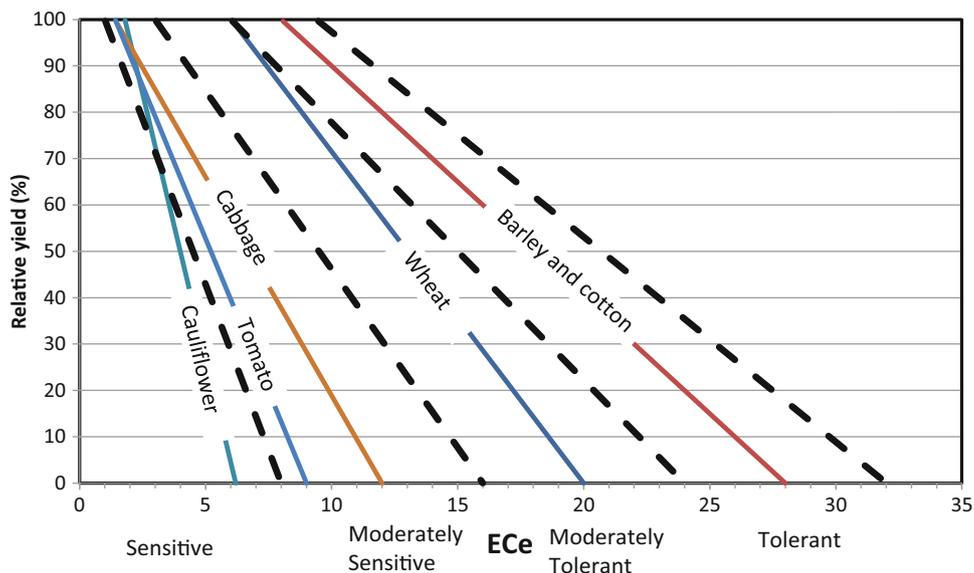

Table 4.2 Threshold EC_e and b values (from FAO 56)

Crop[1]	$EC_{e\ threshold}$[2] (dS m^{-1})[3]	b[4] (%/dS m^{-1})	Rating[5]
a. Small vegetables			
Broccoli	2.8	9.2	MS
Brussels sprouts	1.8	9.7	MS
Cabbage	1.0–1.8	9.8–14.0	MS
Carrots	1.0	14.0	S
Cauliflower	1.8	6.2	MS
Celery	1.8–2.5	6.2–13.0	MS
Lettuce	1.3–1.7	12.0	MS
Onions	1.2	16.0	S
Spinach	2.0–3.2	7.7–16.0	MS
Radishes	1.2–2.0	7.6–13.0	MS
b. Vegetables – Solanum family (Solanaceae)			
Eggplant	–	–	MS
Peppers	1.5–1.7	12.0–14.0	MS
Tomato	0.9–2.5	9.0	MS
c. Vegetables cucumber family (Cucurbitaceae)			
Cucumber	1.1–2.5	7.0–13.0	MS
Melons		–	MS
Pumpkin, winter squash	1:2	13.0	MS
Squash, Zucchini	4.7	10.0	MT
Squash (scallop)	3.2	16.0	MS
Watermelon	–	–	MS
d. Roots and tubers			
Beets, red	4.0	9.0	MT
Parsnip	–	–	S
Potato	1.7	12.0	MS
Sweet potato	1.5–2.5	10.0	MS
Turnip	0.9	9.0	MS
Sugar beet	7.0	5.9	T
e. Legumes (Leguminosae)			
Beans	1.0	19.0	S
Broadbean (faba bean)	1.5–1.6	9.6	MS
Cowpea	4.9	12.0	MT
Groundnut (peanut)	3.2	29.0	MS
Peas	1.5	14.0	S
Soybeans	5.0	20.0	MT

(continued)

Table 4.2 (continued)

Crop[1]	$EC_{e\ threshold}$[2](dS m^{-1})[3]	b[4] (%/dS m^{-1})	Rating[5]
f. Perennial vegetables (with winter dormancy and initially bare or mulched soil)			
Artichokes	–	–	MT
Asparagus	4.1	2.0	T
Mint	–	–	–
Strawberries	1.0–1.5	11.0–33.0	S
g. Fibre crops			
Cotton	7.7	5.2	T
Flax	1.7	12.0	MS
h. Oil crops			
Casterbean	–	–	MS
Safflower	–	–	MT
Sunflower	–	–	MS
i. Cereals			
Barley	8.0	5.0	T
Oats	–	–	MT
Maize	1.7	12.0	MS
Maize, sweet (sweet corn)	1.7	12.0	MS
Millet	–	–	MS
Sorghum	6.8	16.0	MT
Rice [6]	3.0	12.0	S
Wheat *(Triticum aestivum)*	6.0	7.1	MT
Wheat, semidwarf *(T. aestivum)*	8.6	3.0	T
Wheat, durum *(Triticum turgidum)*	5.7–5.9	3.8–5.5	T
j. Forages			
Alfalfa	2.0	7.3	MS
Barley (forage)	6.0	7.1	MT
Bermuda	6.9	6.4	T
Clover, Berseem	1.5	5.7	MS
Clover (alsike, ladino, red, strawberry)	1.5	12.0	MS
Cowpea (forage)	2.5	11.0	MS
Fescue	3.9	5.3–6.2	MT
Foxtail	1.5	9.6	MS
Hardinggrass	4.6	7.6	MT
Lovegrass	2.0	8.4	MS
Maize (forage)	1.8	7.4	MS
Orchardgrass	1.5	6.2	MS
Rye-grass (perennial)	5.6	7.6	MT
Sesbania	2.3	7.0	MS
Sphaerophysa	2.2	7.0	MS
Sudangrass	2.8	4.3	MT
Trefoil, narrowleaf birdsfoot	5.0	10.0	MT
Trefoil, big	2.3	19.0	MS
Vetch, common	3.0	11.0	MS
Wheatgrass, tall	7.5	4.2	T
Wheatgrass, fairway crested	7.5	6.9	T
Wheatgrass, standard crested	3.5	4.0	MT
Wildrye, beardless	2.7	6.0	MT
k. Sugar cane	1.7	5.9	MS
l. Tropical fruits and trees			
Banana	–	–	MS
Coffee	–	–	–
Date palms	4.0	3.6	T
Palm trees	–	–	T
Pineapple (multi-year crop)	–	–	MT
Tea	–	–	–

Table 4.2 (continued)

Crop[1]	$EC_{e\ threshold}$[2] (dS m^{-1})[3]	b[4] (%/dS m^{-1})	Rating[5]
m. Grapes and berries			
Blackberry	1.5	22.0	S
Boysenberry	1.5	22.0	S
Grapes	1.5	9.6	MS
Hops	–	–	–
n. Fruit trees			
Almonds	1.5	19.0	S
Avocado	–	–	S
Citrus (grapefruit)	1.8	16.0	S
Citrus (orange)	1.7	16.0	S
Citrus (lemon)	–	–	S
Citrus (lime)	–	–	S
Citrus (pummelo)	–	–	S
Citrus (tangerine)	–	'	S
Conifer trees	–	–	MS/MT
Apples	–	–	S
Peaches	1.7	21.0	S
Cherries	–	–	S
Pear	–	–	S
Apricot	1.6	24.0	S
Plum, prune	1.5	18.0	S
Pomegranate	–	–	MT
Olives	–	–	MT

S sensitive, *MS* moderately sensitive, *MT* moderately tolerant, *T* tolerant

[1]The data serve only as a guideline - Tolerance vary depending upon climate, soil conditions and cultural practices. Crops are often less tolerant during germination and seedling stage.

[2]ECe, threshold means average root zone salinity at which yield starts to decline

[3]Root zone salinity is measured by electrical conductivity of the saturation extract of the soil, reported in deciSiemens per metre (dS m-1) at 25°C

[4]b is the percentage reduction in crop yield per 1 dS/m increase in ECe beyond ECe threshold

[5]Ratings are: T = Tolerant, MT = Moderately Tolerant, MS = Moderately Sensitive and S = Sensitive

[6]Because paddy rice is grown under flooded conditions, values refer to the electrical conductivity of the soil water while the plants are submerged
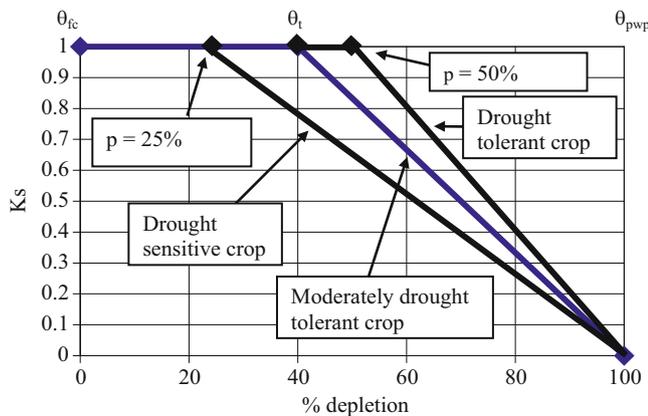
Fig. 4.5 Ks versus water content curve (after FAO 56)

The relationship between yield decrease and combined stress is

$$1 - \left(\frac{Y_a}{Y_{max}}\right) = K_y(1 - K_s) \qquad (4.10)$$

where

K_y = crop sensitivity to water stress.
Y_a = actual yield, kg/ha
Y_{max} = maximum potential yield, kg/ha.

Equation 4.10 can be rearranged to solve for actual yield

$$Y_a = \left(1 - K_y(1 - K_s)\right)Y_{max} \qquad (4.11)$$

Crop sensitivity to water stress, K_y, for different crops is tabulated in Table 4.3.

$$K_s = (K_{s-salt})\ (K_{s-water}) \qquad (4.9)$$

where

K_s = combined salt and water stress coefficient.

Table 4.3 Crop sensitivity to water stress, K_y (FAO 56)

Crop	K_y	Crop	K_y
Alfalfa	1.1	Potato	1.1
Banana	1.2–1.35	Safflower	0.8
Beans	1.15	Sorghum	0.9
Cabbage	0.95	Soybean	0.85
Citrus	1.1–1.3	Spring Wheat	1.15
Cotton	0.85	Sugarbeet	1.0
Grape	0.85	Sugarcane	1.2
Groundnet	0.70	Sunflower	0.95
Maize	1.25	Tomato	1.05
Onion	1.1	Watermelon	1.1
Peas	1.15	Winter wheat	1.05
Pepper	1.1		

Example 4.4 Calculate actual yield for cotton for a growing season if average salinity during the growing season is 10.4 dS/m, and average water content is 14 %. $\theta_{fc} = 20$ %, $\theta_{pwp} = 10$ %. $K_y = 0.85$. Max yield = 1,285 kg/ha. MAD = 50 % (set equal to p from FAO56, but don't worry about this). Threshhold EC_{et} is 7.7 dS/m and b is 5.2.

$$\theta_t = \theta_{FC} - (MAD/100)(\theta_{FC} - (\theta_{PWP})$$
$$\theta_t = 20 - (0.5)(20 - 10) = 15\%$$

$$K_{s-water} = \frac{\theta - \theta_{pwp}}{\theta_t - \theta_{pwp}} = \frac{0.14 - 0.10}{0.15 - 0.10} = 0.8$$

Calculate K_{s-salt}

$$K_{s-salt} = 1 - \frac{b}{100*K_y}(EC_e - EC_{e-t})$$

$$= 1 - \frac{5.2}{100*0.85}(10.4 - 7.7) = 0.83$$

Calculate total K_s

$$K_s = K_{s-water}K_{s-salt} = 0.80*0.83 = 0.67$$

Calculate yield

$$Y_a = (1 - K_y(1 - K_s))Y_m = (1 - 0.85(1 - 0.67))1,285$$
$$= 924 \ kg/ha$$

Example 4.5 Calculate the yield reduction for sugar beets. Assume 80 cm is applied and 100 cm is required. $Y_{max} = 40$ tons/ha.

From Table 4.3, $K_y = 1.0$. The yield based on the FAO K_y slope is calculated as follows:

$$Y_a = \left(1 - K_y\left(1 - \frac{ET_{c-adj}}{ET_c}\right)\right)Y_m$$

$$= \left(1 - 1.0\left(1 - \frac{80}{100}\right)\right)40 = 32 \ t/ha$$

Modeling Soil Salinity

The basis for the salinity model is the conservation of mass equation. Salts may change from liquid to solid phase or be removed from the soil by plant uptake. Although different salts are taken up by plants in different proportions, have different absorption potentials, and different solubilities, a simple model of root zone salinity is often used, which lumps all salts into one salinity term and ignores precipitation to the solid phase, adsorption, plant uptake, and dissolution. Hillel (1998) presented the following equation with all of the possible terms for overall salinity within the liquid phase in the root zone.

$$\begin{aligned}
&\left[\rho_w\left(V_rC_r + V_iC_i + V_gC_g\right) + M_s + M_a\right] \\
&- \left(M_p + M_c + \rho_w V_d C_d\right) \\
&= \Delta M_{sw}
\end{aligned} \tag{4.12}$$

where

ρ_w = density of water, 1,000 mg/L
V_r = volume of rainwater entering the soil, L
C_r = salinity concentration in rainwater, mg/L
V_i = volume of irrigation water entering the soil, L
C_i = salinity concentration in irrigation water, mg/L
V_g = volume of ground water entering the soil, L
C_g = salinity concentration in ground water, mg/L
M_s = mass of salt dissolved from the soil, mg
M_a = mass of salt from agricultural inputs, mg
M_p = mass of salt precipitated (turned to solid), mg
M_c = mass of salt removed by the crop, mg
V_d = volume of water removed from the soil by drainage, L
C_d = concentration of salts in drainage water
ΔM_{sw} = change in mass of salt in the soil's liquid phase.

Crops only remove a negligible amount of salt (Hillel 1998). For a steady state model, assuming constant salinity concentration during the season and the year, and assuming that in-situ precipitation (liquid to solid) and dissolution (solid to liquid) of salt is negligible in the case of a steady-state model, then the salt balance becomes (Hillel 1998)

$$V_iC_i + V_rC_r = \left(V_d - V_g\right)C_d \tag{4.13}$$

If precipitation and irrigation water salinity are averaged so that C_{in} is the average weighted salinity of the two water sources, and if water movement upward into the root zone from a water table is negligible, then Eq. 4.13 becomes

$$V_{in}C_{in} = V_{out}C_{out} \tag{4.14}$$

Water volume can be replaced by water depth.

$$d_{in}C_{in} = d_{out}C_{out} \tag{4.15}$$

Leaching Fraction

The strategy for keeping soil salinity within an acceptable range is leaching the soil: applying extra water and leaching salts below the root zone. Although the steady state leaching fraction equation described in this section are inferior to transient analysis (Letey et al. 2011), it is the most common method of calculating the leaching fraction. The *WINDS* model is used to compare transient analysis of salinity leaching to the steady state equations in Chapter 26. The leaching fraction, LF, is the leached depth or seepage depth divided by the applied depth where i in Eq. 4.16 includes precipitation as well as irrigation if C_{in} is the average salinity of both.

$$LF = \frac{d_{out}}{d_{in}} = \frac{d_{seepage}}{i} \qquad (4.16)$$

where

LF = leaching fraction, dimensionless.

Substitute Eq. 4.16 into Eq. 4.15 in order to solve for the leachate concentration

$$d_{in}C_{in} = LF*i\,C_{out}$$

$$C_{out} = \frac{C_{in}}{LF} \qquad (4.17)$$

Because EC is proportional to the concentration, C, the leachate salinity for uniform water application can be written as (Ayers and Westcott 1985).

$$EC_{dw} = \frac{EC_{iw}}{LF} \qquad (4.18)$$

where

EC_{dw} = electrical conductivity of drainage water (leachate or seepage), dS/m.
EC_{iw} = electrical conductivity of irrigation water, dS/m.

Depth of drainage water is equal to the irrigation water minus d_{ET}. Substitute into Eq. 4.16

$$d_{out} = i - d_{ET} \quad LF = \frac{i - d_{ET}}{i} \qquad (4.19)$$

The maximum allowable EC_e can be calculated based on crop sensitivity to salinity stress; and the required leaching fraction can be calculated based on the maximum allowable EC_e. Equation 4.20 an empirical equation based on field experiments conducted with low frequency irrigation systems. It has been a standard method for calculation of leaching fraction, although updated methods are often recommended in it place. Nevertheless, the equation is reliable within normal ranges of salinity and leaching fraction.

$$LF = \frac{EC_{iw}}{5*EC_e - EC_{iw}} \qquad (4.20)$$

Example 4.6 Irrigation water salinity (EC_{iw}) = 1 dS/m. Applied water depth (d_{in}) = 1176 mm/season. Crop water demand (ET_c) = 1,000 mm/season. Assume that plants extract 40 %, 30 %, 20 %, and 10 % of their water from the upper quarter, 2nd quarter, 3rd quarter, and lowest quarter of the root zone, respectively. First, determine the leachate salinity treating the root zone as a single layer. Next, determine the seepage salinity from each of 4 layers and the average salinity for the 4 layers (from Ayres and Westcott 1985).

Treating the entire root zone as a single layer, calculate seepage salinity.

$$LF = \frac{i - ET}{i} = \frac{1,176 - 1,000}{1,176} = 0.15$$

$$EC_{dw} = \frac{EC_{iw}}{LF} = \frac{1}{0.15} = 6.7 \ dS/m$$

Use the same equations to determine soil salinity at the bottom of each of the four quarters of the root zone.

$$LF_1 = \frac{1,176 - 0.4*ET}{1,176} = \frac{1,176 - 0.4*1,000}{1,176} = 0.66$$

$$EC_1 = EC_{iw}/LF_1 = 1/0.66 = 1.5 \ dS/m$$

$$LF_2 = \frac{776 - 0.3*ET}{776} = \frac{776 - 0.3*1,000}{776} = 0.61$$

$$EC_2 = EC_1/LF_2 = 1.5/0.61 = 2.5 \ dS/m$$

$$LF_3 = \frac{476 - 0.2*ET}{476} = \frac{476 - 0.2*1,000}{476} = 0.58$$

$$EC_3 = EC_2/LF_3 = 2.5/0.58 = 4.3 \ dS/m$$

$$LF_4 = \frac{276 - 0.1*ET}{276} = \frac{276 - 0.1*1,000}{276} = 0.64$$

$$EC_4 = EC_3/LF_4 = 4.3/0.64 = 6.7 \ dS/m$$

The calculated seepage salinities, treating the soil as a whole and in layers, agree: 6.7 dS/m.

The average soil salinity is the average of the irrigation water salinity and the salinities at the bottom of the 4 layers.

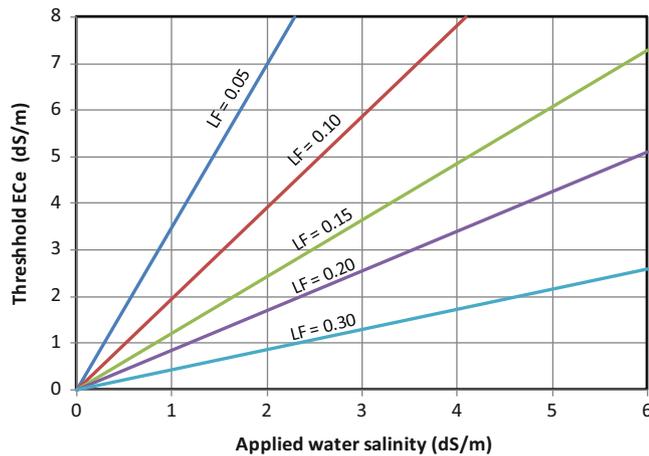$$EC_{ave} = (1/2 + 1.5 + 2.5 + 4.3 + 6.7/2)/4 = 3.0 \ dS/m.$$

Fig. 4.6 Recommended leaching fractions from Hoffman and Ven Genuchten equation where EC_a is salinity of irrigation water and C_v is saturated paste extract EC

Soil water salinity is greater than the saturated paste extract salinity, because, during the saturated paste extract test, distilled water is added to the soil until saturation is reached. If the water content in the soil is at field capacity, and the field capacity is approximately 50 % of saturated water content (porosity), then, the average EC_e in the soil, based on Eq. 4.3, is

$$EC_{e\ (sat)} = EC_{ave}*(\theta_{FC}/\theta_{sat}) = 3.0*(0.5) = 1.5\ \text{dS/m}$$

Rhoades (1974) recommended the following leaching fraction equation for high frequency sprinkler or trickle irrigation; however, the need for this equation has been questioned by some. It results in higher recommended leaching fractions for high frequency irrigation.

$$LF = EC_{iw}/(2\ EC_e) \tag{4.21}$$

Hoffman and Van Genuchten (1983) developed the following theoretical equation for LF. In most cases, Eq. 4.22 yields similar results to Eq. 4.20, but because it is based on theory, it has a wider range of salinity parameters for which it is accurate. Hoffman and Van Genuchten developed Fig. 4.6 based on Eq. 4.22.

$$\frac{EC_e}{EC_{iw}} = \left(\frac{1}{LF} + \frac{\delta}{Z*LF}\ln\left(LF + (1-LF)e^{-z/\delta}\right)\right) \tag{4.22}$$

where

Z = root zone depth
δ = empirical constant set to 0.2 Z.

One of the key factors in leaching fraction calculations is the leaching efficiency. In some soils, there are mobile and immobile zones. There may be very little mixing of irrigation water and the majority of soil water in immobile zone, with most of the infiltrated water leaching through the soil without mixing with the immobile water. For example, the leaching efficiency may be only 20 % in a clay soil with most soil water between clay particles, so the soil water salinity after leaching is much higher than calculated with the assumption that leaching efficiency is 100 %.

Example 4.7 Calculate the leaching fraction with no reduction in yield for cotton and corn if irrigation water salinity is 960 ppm. Compare results from Eqs. 4.20, 4.21, and Fig. 4.6 (Eq. 4.22).

$$\text{Irrigation water salinity} = 960\ \text{ppm} = 960/640\ \text{dS/m}$$
$$= 1.5\ \text{dS/m}$$

Cotton

Max. soil salinity in the saturated paste extract (Table 4.2) for cotton with no yield reduction = 7.7 dS/m.

Equation 4.20 $LF = \dfrac{EC_{iw}}{5(EC_e) - EC_{iw}} = \dfrac{1.5}{5(7.7) - 1.5} = 0.04$

Equation 4.21 $LF = EC_{iw}/(2*EC_e) = 1.5/(2*7.7) = 0.10$

From Fig. 4.6, with $ECa = 1.5$ and $Cv = 7.7$, LF = 0.04

Corn

Max. soil salinity in the saturated paste extract (Table 4.2) for corn with no yield reduction = 1.7 dS/m.

Equation 4.20 $LF = \dfrac{EC_{iw}}{5(EC_e) - EC_{iw}} = \dfrac{1.5}{5(1.7) - 1.5} = 0.21$

Equation 4.21 $LF = EC_{iw}/(2*EC_e) = 1.5/(2*1.7) = 0.44$

From Fig. 4.6, with $ECa = 1.5$ and $Cv = 1.7$, LF = 0.16

As expected Eq. 4.20 and Fig. 4.6 had similar results, and Eq. 4.21 estimated a higher leaching fraction.

With drip irrigation systems, salts may be concentrated at the edge of the wetted zone, leaving a ring of salts around the emitters on the soil surface. Similarly, salts may be pushed to the midpoint between furrows and concentrate at the centers of beds. If this is the case, then it may be beneficial to plant crops at an offset position on the bed.

If water is less expensive in winter, then growers can leach the soil during the winter, and use less water in summer. However, transient changes in soil salinity concentration can occur quickly during the growing season. In fact, soils can become salinized within one growing season if there is no leaching and high salinity in irrigation water. Plants are most sensitive to salinity during germination, so it is most important to control salinity at the beginning of the season.

Irrigation Application Depth and Leaching Fraction

If the goal is to maintain salinity within an acceptable range during the entire growing season, then the depth of irrigation water that should be applied during any one

Table 4.4 Maximum acceptable salinity in irrigation water as a function of soil type, rainfall per year, and crop sensitivity to salinity (After Rao et al. 1994)

Soil texture (percent clay)	Crop tolerance	Annual rainfall		
		<350 mm	350–500	550–750
Fine (>30 %)	Sensitive	1	1	1.5
	Semi-tolerant	1.5	2	3
	Tolerant	2	3	4.5
Moderately fine (20–30 %)	Sensitive	1.5	2	2.5
	Semi-tolerant	2	3	4.5
	Tolerant	4	6	8
Moderately coarse (10–20 %)	Sensitive	2	2.5	3
	Semi-tolerant	4	6	8
	Tolerant	6	8	10
Coarse (<10 %)	Sensitive	–	3	3
	Semi-tolerant	6	7.5	9
	Tolerant	8	10	12.5

irrigation event is the RAW divided by the irrigation efficiency and (1-LF).

$$IR = \frac{100}{IE(1 - LF)}RAW \qquad (4.23)$$

where

IR = irrigation requirement during single irrigation event, cm
IE = irrigation efficiency, percent.

Example 4.8 Calculate the depth of irrigation water required (average for the field), IR, for melons based on Eq. 4.23. The MAD is 45 %, the irrigation system efficiency is 70 %, the irrigation water EC_{iw} is 1.09 dS/m, and the TAW is 24 cm.

Max. soil salinity in the saturated paste extract (Table 4.2) for melons with no yield reduction = 2.2 dS/m.

$$LF = \frac{EC_{iw}}{5(EC_e) - EC_{iw}} = \frac{1.09}{5(2.2) - 1.09} = 0.11$$

$$IR = \frac{100}{IE(1 - LF)}RAW = \frac{100}{70(1 - 0.11)}(0.45*24 \ cm)$$
$$= 17 \ cm$$

Project Planning and Salinity

Irrigation water salinity is the primary factor in determining the susceptibility of a region to salinization. Irrigation water with a salinity lower than 450 mg/L ($EC_{iw} = 0.7$) does not present a hazard for irrigation salinity. Irrigation water with salinity in excess of 2,000 mg/L ($EC_{iw} = 3$) presents a hazard for many crops. However, rainfall, soil type, and crop sensitivity to salinity are critical factors in determining the salinity hazard from irrigation water. Rao et al. (1994) developed Table 4.4 that specifies the maximum acceptable salinity of irrigation water as a function of these three factors.

Sodicity

Excess sodium reduces water availability because it leads to breakdown of clay particle structure (dispersion), and these particles can clog the soil and reduce infiltration rate to nearly zero. The reason that sodium causes clay particle dispersion is that sodium molecules, with a valence of 1 (Na^+), are loosely attracted to negatively charged clay layers, and they maintain a hydration shell of approximately ten water molecules. The other major cation in water, calcium, is attracted much more strongly to the clay particles because they have a charge of +2. As a result, they are positioned very close to the clay particle surface, and they have a much smaller shell of water hydration (Fig. 4.7). If too many sodium molecules, with their large shell of hydration, are in the soil water solution, then they will be the primary ion in the interlayer between clay particles, and the shells of hydration will force the clay layers apart and break down the soil structure.

Equation 4.24 calculates the sodium adsorption ratio (SAR), which can be used to determine the sodium hazard associated with irrigation water.
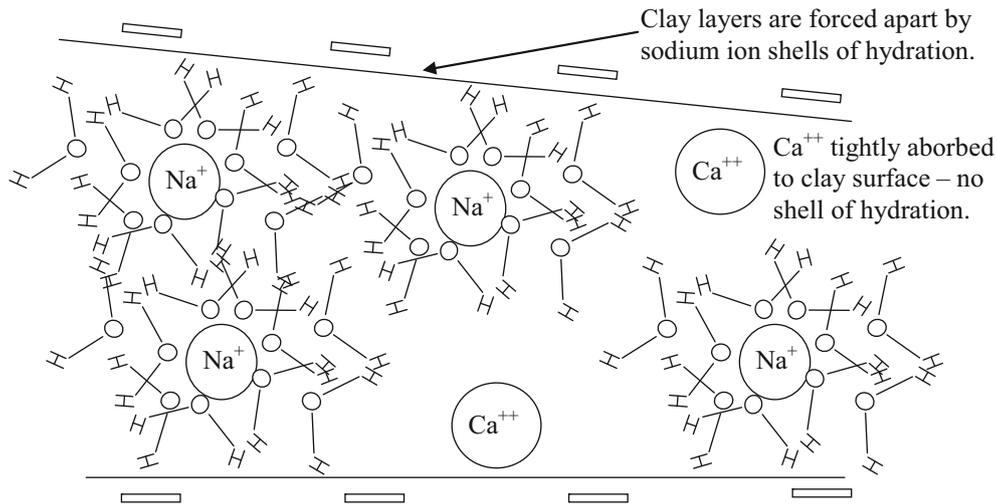
Fig. 4.7 Sodium hydration shell and calcium ions between clay layers

Table 4.5 Sodicity hazard to soils as a function of irrigation water sodicity and salinity

SAR	EC_{iw}		
	None	Slight to moderate	Severe
0–3	>0.7	0.7–0.2	<0.2
3–6	>1.2	1.2–0.3	<0.3
6–12	>1.9	1.9–0.5	<0.5
12–20	>2.9	2.9–1.3	<1.3
20–40	>5.0	5.0–2.9	<2.9

$$SAR = \frac{|Na^+|}{\sqrt{\frac{|Ca^{++}|+|Mg^{++}|}{2}}} \qquad (4.24)$$

where

SAR = sodium absorption ratio, dimensionless
Na^{++} = sodium normality, meq/L
Ca^{++} = calcium normality, meq/L
Mg^{++} = magnesium normality, meq/L.

The hazard level of sodium is a function of both the SAR and the overall salinity (Table 4.5). Higher salinity in the soil water decreases the osmotic potential (more negative) of water in the soil water solution, and, as such, decreases the amount of water in the hydration shells around the sodium ions in the interlayer between clay particles. Thus, it may be very detrimental to irrigate with low salinity water in a field that was previously irrigated with high salinity and sodicity water.

Example 4.9 Irrigation water has 460 mg/L sodium (Na^+), 40.1 mg/L calcium (Ca^{++}), and 24.3 mg/L magnesium (Mg^+). If irrigation water salinity is 1,280 ppm, then what level of hazard is presented by sodicity?

Equivalent masses are given in Table 4.1. Calculate meq/L for each cation.

460 mg/L Na^+/23 mg/meq = 20 meq/L Na^+
40.1 mg/L Ca^{++}/20.05 mg/meq = 2 meq/L Ca^{++}
24.3 mg/L Mg^{++}/12.15 mg/meq = 2 meq/L Mg^{++}

$$SAR = \frac{|Na^+|}{\sqrt{\frac{|Ca^{++}|+|Mg^{++}|}{2}}} = \frac{20}{\sqrt{\frac{2+2}{2}}} = \frac{20}{\sqrt{2}} = 7$$

The EC_{iw} of the irrigation water is 1,280 ppm/640 dS/m/ ppm = 2. From Table 4.5, there is no possible hazard due to sodicity from this water.

Specific Ion Toxicity

Specific ion toxicity is also generally not quantified by crop stress coefficients; however, it can also lead to yield loss when certain salts (ions) become toxic at high concentration in soils. Table 4.6 lists specific ion toxicity levels of sodium, chloride, and boron. Certain crops are more susceptible to specific ions than others. Not even the most sensitive crops are susceptible to specific ion toxicities at levels less than those list in the "none" column. Nearly all crops are affected at the severe level.

Table 4.6 Specific ion toxicity (Credit NRCS)

Element	Irrigation type	Units	Degree of restriction on use		
			None	Slight to moderate	Severe
Sodium	Sprinkler irrigation	meq/L	<3	3–9	>9
Sodium	Surface irrigation	meq/L	<3	>3	
Chloride	Sprinkler irrigation	meq/L	<4	4–10	>10
Chloride	Surface irrigation	meq/L	<3	>3	
Boron		meq/L	<0.7	0.7–3.0	>3.0

Questions

1. What is the molecular mass (g/mole) of calcium carbonate ($CaCO_3$)?
2. What is the molarity and ppm of Na^+ and Cl^- if 0.02 g NaCL is dissolved in 4 L of water?
3. What is the concentration of salts (mg/L) in water with $EC_{iw} = 2.4$ dS/m?
4. What is the soil salinity (mg/L) at saturation if the saturated paste extract EC_e is 4 dS/m?
5. How many moles of sodium chloride "NaCl" are required in 4 L of water to develop a solution that has 1,000 mg/L sodium? What is the concentration of chloride in the water?
6. How many grams of NO_3 are dissolved in 4 L of water with a nitrate concentration of 20 mg/L?
7. Calculate the mass of ammonium nitrate NH_4NO_3 dissolved in 200 L water to obtain a nitrate concentration of 30 mg/L in water.
8. If saturated paste extract EC_e is 2 dS/m, then what is the osmotic potential ψ_s of the water if the water content θ is 15 % and the saturated water content θ_s is 45 %?

9. Explain Fig. 4.1.
10. Explain the function of the xylem and the phloem in the plant.
11. Calculate the Gibb's free energy of water "G" in a cell if the concentration of sucrose in the cell is 0.3 mole sucrose/L water at a temperature of 20 °C. Express your answer in J/mole and J/kg (a.k.a. kPa).
12. Calculate yield for cotton for a growing season if average values of EC_e and water content during the growing season are 12 dS/m and 13.5 %, respectively. $\theta_{fc} = 0.2$, $\theta_{pwp} = 0.1$. $K_y = 0.85$. Max yield = 1,000 kg/ha. MAD = 0.55. Threshold EC_e is 7.7 dS/m and b is 5.2. $K_y = 0.85$ for cotton
13. Why does high sodium ruin some soils? What types of soils are most vulnerable?
14. Irrigation water has 230 mg/L sodium (Na+), 60.15 mg/L calcium (Ca++), and 24.3 mg/L magnesium (Mg++). If irrigation water salinity is 1,000 ppm, then what level of hazard is presented by sodicity?
15. Fill in the missing total potential values and show direction of water flow. Are these total potentials more likely to occur in the day or the night?

$\psi = -1.1$ kJ/kg Xylem ↑ Water flow	$\psi_s = -1.5$ kJ/kg $\psi_p = 0.5$ kJ/kg $\psi =$	$\psi_s = -1.4$ kJ/kg $\psi_p = 0.6$ kJ/kg $\psi =$	$\psi_s = -1.5$ kJ/kg $\psi_p = 0.7$ kJ/kg $\psi =$

16. Determine the leachate salinity. Irrigation water salinity (EC_{iw}) = 2 dS/m. Applied water depth (d_{in}) = 1,250 mm/season. There is no precipitation during the growing season. Crop water demand (ET_c) = 1,000 mm/ season. Average soil moisture content is the same at the beginning and end of the growing season.
17. Irrigation water salinity (EC_{iw}) = 2 dS/m. Applied water depth (d_{in}) = 1300 mm/season. Crop water

demand (ET_c) = 900 mm/season and assume that plants extract 40 %, 30 %, 20 %, and 10 % of their water from the upper quarter, next quarter, next, and lowest quarter of the root zone, respectively. Calculate the salinity at the bottom of the root zone by treating the root zone as a whole and calculate salinity at the bottom of each of the 4 layers. Calculate the average salinity in the root zone by assuming that the field capacity is half of the saturated water content (divide average salinity in half for EC_e). Then calculate the leaching fraction that would be required to have this average salinity in the root zone with Eq. 4.20 and compare with the leaching fraction in this problem.

18. Calculate the depth of irrigation water required (average for the field), IR, for cotton based on Eq. 4.23. The MAD is 50 %, the irrigation system efficiency is 60 %, the irrigation water EC_{iw} is 2 dS/m, and the TAW is 20 cm.

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