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WATER QUALITY IN AGRICULTURE: Risks and risk mitigation

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Chapter 5

Chemical risks and risk management measures of relevance to crop production with special consideration of salinity

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At least 17 chemical elements are recognized as essential nutrients for plants. Depending on the amount of nutrients that each plant needs, these elements can be categorized as macro- or micro-nutrients. Three of the most structurally important elements are carbon (C), oxygen (O) and hydrogen (H), which are provided by water and carbon dioxide. The remaining soil-derived macro-nutrients include: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S) and magnesium (Mg). Important micronutrients (or trace elements) include: iron (Fe), boron (B), manganese (Mn), zinc (Zn), copper (Cu), chloride (Cl), molybdenum (Mo) and nickel (Ni).

The challenges for plant nutrition and growth usually derive from an excessively high or low supply of specific nutrients or elements. Moreover, nutrients must be available not only in sufficient amounts but also in appropriate (soluble) form and ratios. The most common disorders are:

- Poor soil fertility resulting in crop nutrient deficiencies, which can be addressed, for example, though application of organic or chemical fertilizers; and
- Excess of salts, micro- or macro-nutrients, or potentially harmful chemicals through irrigation with contaminated water.

This chapter focuses on the second challenge: the risks related to poor irrigation water quality. Where irrigation water of low or marginal quality is used, the different chemical risks that need to be addressed can overlap, but may be categorized as follows:

- Salinity and sodicity and their effects on soils and crops (section 5.1 and sub-sections 5.1.1 and 5.1.2);
- Specific ionic effects and nutrient imbalances caused by salinity, wastewater irrigation and over-fertilization (5.1.3);
- Risks related to heavy metals (5.2);
- Risks from organic contaminants of emerging concern (CEC) such as disinfection by-products, endocrine disruptors, persistent organic pollutants (POPs), pesticides, and pharmaceuticals and personal care products (PPCP) (5.3).

The chapter ends with an extensive review of risk mitigation options for the different identified hazards (Section 5.4), applicable with site-specific adjustments to low- and middle-income countries.

5.1. Salinity and sodicity

All soils contain salts, but salinity becomes an agronomic problem affecting plant growth when certain salts concentrate in the crop's rooting zone. Aside from natural salinity of the soil and its geological parent material, a common source of salts in irrigated soils is the irrigation water itself. Salts in irrigation water stem from dissolution or weathering of rocks and soil. The salts are carried with the water and end up in systems where it is used (Ayers & Westcot, 1985). In the case of water used for irrigation, the crop extracts nearly pure water leaving most of the applied salts in the soil. Salts continue to build up in the root zone unless excess water (rain or irrigation) leaches them below the root zone. The suitability of water for irrigation is determined not only by the total amount of salts present but also by the types of salts, the salt tolerance of the crop and irrigation practices. Various soil and cropping problems develop as the total salt content in soils increases, and special management practices are required to maintain acceptable crop yields. Water quality or suitability for use is assessed based on the potential severity of problems that can be expected to develop over long-term use.

Although salt management techniques such as leaching have been recognized as essential for over a century (Hilgard, 1893), and seem straightforward, the long-term sustainability of irrigated lands remains a challenge as irrigation itself impacts other land and water resources in ways that can lower farm productivity over time, particularly in arid and semi-arid areas where most irrigation takes place (Oster *et al.*, 2012). Irrigation in these areas can also degrade the quality of water in downstream reaches, as dissolved salts enter irrigation return flows to the disadvantage of downstream farmers and communities (Wichelns & Qadir, 2015), an outcome which calls for basin-wide salinity management (see Chapters 8 and 9).

This chapter addresses (i) salinity-related water quality parameters in irrigated agriculture; (ii) sources of salts in irrigation water and their potential impacts on water quality, soil characteristics, crop growth, yield and quality; and (iii) pertinent response options based on management strategies.

5.1.1 Salinity and related impacts on soils and crops

Salinity in irrigation water is commonly represented by its electrical conductivity (EC), usually measured with an electrical conductivity meter. The EC is expressed in terms of deciSiemens per metre (dS/m), or as millimhos per centimetre (mmho/cm), both units being numerically equal. EC readings also allow to estimate the amount of total dissolved solids[1] (TDS) as shown in Equation 1a and 1b (Table 5.1).

TDS (mg/L) ≈ EC (dS/m) x 640 [1a]
(EC from 0.1 to 5 dS/m)

TDS (mg/L) ≈ EC (dS/m) x 800 [1b]
(EC > 5 dS/m)

The ratio of TDS to EC of various salt solutions ranges from 550 to 700 ppm per dS/m, depending on the compositions of the solutes in the water. For soil extracts in the EC range from 3 to 30 dS/m, the US Salinity Laboratory (1954) also used the following empirical relationship (Equation 2) between EC and the total soluble salts (TSS) concentration ($mmol_c/L$)[2].

TSS and TDS measure the amount of particles (solids) floating in water, like organic matter, silt, clay, or salts. They can be divided into those particles that are large enough to be held back by a filter which are called total suspended solids (TSS), while the particles that pass through the filter are called total dissolved solids (TDS). TSS values are often related to the turbidity (cloudiness) of water, while TDS include dissolved minerals and salts in the water and are closely related to conductivity or salinity.

[1] The majority of these solids are salts.
[2] 10 $mmol_c/L$ = 1 cmol/L Instead of mol_c we also see mol^+ or mol (eq)/L.

$TSS\ (mmol_c/L) \approx EC\ (dS/m) \times 10$ [2]

The following Equation 3 supersedes in accuracy Equation 2 for most purposes and expresses TSS and EC in terms of $mmol_c/L$ and dS/m, respectively (Marion & Babcock, 1976).

$\log TSS = 0.99 + 1.055 \ \log EC$ [3]

Table 5.1. Categories of water resources based on ambient levels of soluble salts

Water category	EC (dS/m)	Salt concentration (TDS, mg/L)	Typical water source
Non-saline	< 0.7	< 450	Drinking and irrigation water
Slightly saline	0.7–2.0	450–1500	Irrigation water; treated wastewater
Moderately saline	2–10	1500–6500	Primary drainage water and groundwater
Highly saline	10–25	6 500–16 000	Secondary drainage water and groundwater
Very highly saline	25-50	16 000–35 000	Very saline groundwater; seawater[1]
Brine	> 50	> 35 000 (or 3.5%)	Hypersaline seawater

[1] Salt concentrations of very highly saline groundwater usually fall within the lower end of this salt concentration range, while salts in seawater are close to the upper end of the salt concentration range.

Sources: Ayers, R.S. & Westcot, D.W. 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper 29, Rev. 1. Rome: FAO; Estefan, G., Sommer, R. & Ryan, J. 2013. Methods of soil, plant, and water analysis: A manual for the West Asia and North Africa region: Third Edition, Beirut: ICARDA

The relative salt tolerance of most agricultural crops is sufficiently well known to elaborate general salt tolerance guidelines. The following general conclusions can be drawn from the crop salt tolerance data (Ayers & Westcot, 1985):

- Full yield potential is typically achievable for nearly all crops when using water with a salinity content below 0.7 dS/m.
- When using irrigation water of slight to moderate salinity (i.e. 0.7-2.0 dS/m), full yield potential is still possible for most crops not sensitive to salinity, but care must be taken to achieve the required leaching fraction to maintain soil salinity within the salt tolerance limit of the crops. Treated sewage effluent commonly falls within this group.
- For higher salinity water (>2.0 dS/m), increasing leaching to satisfy a leaching requirement greater than 0.25 to 0.30 is typically not practicable because of the excessive amount of water required. In such cases, consideration must be given to replacing salt-sensitive crops with more tolerant crops that require less leaching to maintain salts in the root zone within the crop tolerance limits.

The adverse effects of excess salts in the soil solution on crop growth stems from both osmotic and specific ion mechanisms (Läuchli & Epstein, 1990). Salts reduce the osmotic potential of the soil water solution making the water less available for plants. Some crops cope better in this situation than others. If soil solution salinity surpasses crop specific thresholds, the crop yield will be reduced. Crops such as cotton, barley and sugar beet have high salinity thresholds while others such as bean, onion and strawberry have low thresholds. Salinity often affects crops without visible changes to the soil cover; however in severely affected soils, salt crystals are often found on their surface (Figure 5.1).

Figure 5.1. Salt on the soil surface

Source: www.fao.org/3/x8234e/x8234e08.htm#bm08.1.5.

Maas & Hoffman (1977) proposed a piece-wise linear[3] response equation to describe salt tolerance in crops. Two parameters obtained from this equation are: (i) the threshold soil salinity (the maximum allowable soil salinity for a crop without yield reduction), and (ii) the slope (the percentage yield decrease per unit increase in salinity beyond the threshold salinity level). The data serve only as a guideline to the relative capacities of the crops to withstand salinity as considerable variation exists among crops in terms of their ability to tolerate saline environments. The threshold salinity levels and the slope values obtained from the Maas-Hoffman equation can be used to calculate relative yield (Yr) for any given soil salinity exceeding the threshold level by using Equation 4.

$$Yr = 100 - b\,(ECe - ECt) \qquad [4]$$

Where ECt refers to the threshold saturated paste extract salinity level expressed in dS/m above which yields decline, b is the slope expressed in % per dS/m, and ECe is the average electrical conductivity of the saturated soil paste extract[4] of the root zone expressed in dS/m (for ECt and b values see Grieve, Grattan & Maas, 2012). Based on these values, the yield potential of crops can be estimated at specified salinity levels. The capacity of crops to withstand salinity is described in relative terms such as achieving the relative yield potential (Table 5.2). Further datasets on salt tolerance of additional plants and crops are available elsewhere (Grieve *et al.*, 2012; FAO & AWC, 2023, Box 5.1).

Box 5.1. FAO guidelines on brackish water use

The Guidelines on Brackish Water Use in the Near East and North Africa (NENA) Region build on country surveys conducted by the Arab Water Council (AWC). They provide country specific information and conclude with a consensus on minimum and maximum concentrations of key parameters of salt tolerance for crop protection. The guidelines address the importance of irrigation scheduling, leaching for salinity control and drainage, and how for example irrigation management (conventional vs. high frequency irrigation), reclamation leaching, and irrigation methods, including blending, cyclic and sequential reuse, influence this relationship. The guidelines further provide a range of maximum limits depending, for example, upon irrigation management, attainable leaching fractions and expected yield potential, and present related good agricultural practices (FAO & AWC, 2023).

[3] The piece-wise linear model assumes no yield decline until a "salinity threshold" value and a linear decrease in yield beyond the threshold.

[4] See Sonmez *et al.* (2008) for the relation between ECe and EC in 1:1, 1:2 and 1:5 soil-water extracts under Cl- dominated conditions.

Table 5.2. Yield potentials of some grain, forage, vegetable and fibre crops as a function of average root zone salinity

Common name	Tolerance based on	Specified salinity (ECe, dS/m) to achieve 50, 80 and full yield potential[1]		
		50%	80%	100%
Durum wheat	Grain yield	19	11	<6
Barley	Grain yield	18	12	<8
Cotton	Seed cotton yield	17	12	<8
Rye	Grain yield	16	13	<11
Sugar beet	Storage root	16	10	<7
Wheat	Grain yield	13	9	<6
Sorghum	Grain yield	10	8	<7
Alfalfa	Shoot dry weight	9	5	<2
Spinach	Top fresh weight	9	5	<2
Broccoli	Shoot fresh weight	8	5	<3
Egg plant	Fruit yield	8	4	<1
Rice, paddy	Grain yield	7	5	<3
Potato	Tuber yield	7	4	<2
Maize	Ear fresh weight	6	3	<2

[1] These data serve only as a guideline to relative tolerances among crops. Absolute tolerances can vary between varieties also depending on climate, soil conditions and cultural practices.

Source: Based on the salt tolerance data of different crops and the percentage decrease in yield per unit increase in root zone salinity in terms of dS/m as reported by Maas, E.V & Grattan, S.R. 1999. Crop yields as affected by salinity. In R.W. Skaggs & J. van Schilfgaarde, eds. Agricultural drainage, pp. 55–108. Madison, WI, ASA-CSSA-SSSA.

Besides the Maas and Hoffman piece-wise linear function (Equation 4), various non-linear models have been proposed to relate crop yield to salinity (van Genuchten & Hoffman, 1984; Steppuhn *et al.*, 2005). The non-linear response functions for reduction in uptake/transpiration as a function of salinity appear to be more realistic than the linear functions created under controlled laboratory conditions, but these require more data and the exponential expressions are more complex. Under field conditions, distribution of salts is neither uniform with soil depth nor constant with time. The non-uniformity of salinity distribution is usually affected by both irrigation and leaching practices, and by the amount and distribution of rainfall (Minhas *et al.*, 2020).

5.1.2. Sodicity

Sodicity in soil or water is a measure of the relative concentration of sodium (Na) to calcium (Ca) and magnesium (Mg). It causes adverse effects on the physical and chemical properties of soil, such as changes in the ratios of exchangeable cations, the destabilization of soil structure, the deterioration of soil hydraulic properties, and an increase in susceptibility to crusting, runoff, erosion and reduced aeration. In addition, imbalances in mineral nutrition usually occur in plants grown on sodic soils, which may range from deficiencies of several nutrients to high levels of Na (Sumner, 1993; Quirk, 2001). Such chemical and physical changes have a bearing on the activity of plant roots and soil microbes, and ultimately on crop growth and yield.

Sodicity in soils is traditionally expressed in terms of the exchangeable sodium percentage (ESP). A sodic soil, by definition, contains relatively high levels of exchangeable sodium (ExNa) compared to all major exchangeable cations (i.e. calcium, magnesium, potassium and sodium) or cation exchange capacity (CExC). The exchangeable sodium percentage (ESP) is calculated as shown in Equation 5:

$$ESP = (ExNa \ / \ CExC) \times 100 \qquad [5]$$

Commonly the distinction between a saline and a sodic soil is drawn at ESP < 15 saline, and ≥ 15 sodic, unless the electrical conductivity is also high (ECe > 4 dS/m) and the soil is classified as a saline-sodic soil (US Salinity Laboratory Staff, 1954; Estefan *et al.*, 2013). In some countries, such as Australia, soils with ESP > 6 are considered as sodic soils. A possible classification of soil sodicity according to the ESP in Australia is given in Table 5.3.

Table 5.3. Classification of sodic soils under Australian conditions

	Non-Sodic	Sodic	Moderately Sodic	Strongly Sodic	Very Strongly Sodic
ESP (%)	<6	6-10	10-15	15-25	>25

Source: www.terragis.bees.unsw.edu.au/terraGIS_soil/sp_exchangeable_sodium_percentage.html.

Soil dispersion problems may occur at a higher or lower ESP depending upon clay type, soil and irrigation water salinity, and overall chemistry of irrigation water and soil. Possible ranges of ESP associated with a significant yield loss of different crops are shown in Table 5.4.

Table 5.4. Soil ESP ranges indicating about 50% yield loss

ESP range	Crop	
	Common Name	**Botanical Name**
10-15	Safflower Mash Pea Lentil Pigeon Pea Urd bean	*Carthamus tinctorius L.* *Vigna mungo (L.) Hepper* *Pisum sativum L.,* *Lens culinaris Medik.* *Cajanus cajan (L.) Millsp.* *Phaseolus mungo L.*
16-20	Bengal gram Soybean	*Cicer arietinum L.* *Glycine max (L.) Merr.*
20-25	Groundnut Cowpea Onion Pearl millet	*Arachis americana Medik.* *Vigna unguiculata (L.) Walp* *Allium cepa L.* *Pennisetum glaucum (L.) R.Br.*
25-30	Linseed Garlic Guar	*Linum usitatissimum L.* *Allium sativum L.* *Cyamopsis tetragonoloba (L.) Taub.*
30-50	Indian Mustard Wheat Sunflower Guinea grass	*Brassica juncea L. Czern.* *Triticum L.* *Helianthus L.* *Panicum maximus Jacq.*
50-60	Barley Sesbania	*Hordeum vulgare L.* *Sesbania bispinosa (Jacq.) W. Wight*
60-70	Rice Para grass	*Oryza sativa L.* *Brachiaria mutica (Forssk.) Stapf.*
70+	Bermuda grass Kallar/Karnal grass Rhodes grass	*Cynodon dactylon (L.) Pers* *Leptochloa fusca (L.) Kunth* *Chloris gayana Kunth*

Source: After Gupta, R.K. & Abrol, I.P. 1990. Salt-affected soils: Their reclamation and management for crop production. Advances in Soil Science, 11, 223–288.

Sodicity in soil solution or irrigation water is often assessed by estimating the sodium adsorption ratio (SAR), which is expressed in terms of the relative concentrations of Na to that of Ca and Mg. As shown in Equation 6, C represents concentrations in $mmol_c/L$ of the cations denoted by subscript letters (US Salinity Laboratory Staff, 1954).

$$SAR = C_{Na} / [(C_{Ca}+C_{Mg})/2]^{0.5} \qquad [6]$$

While SAR is used widely to evaluate the sodicity hazard in many arid zones of the world (see Table 3.3), it does not capture the complexity of soil chemistry. Research and practice in recent years have demonstrated that potassium (K) and Mg, in addition to Na, can have adverse impacts on the permeability of irrigated soils (Rengasamy & Marchuk, 2011; Smith, Oster & Sposito, 2015; Oster, Sposito & Smith, 2016; Qadir *et al.*, 2021).

Magnesium, for example, may cause deleterious effects on soil structure like those caused by sodium. The possibility of such magnesium effects is particularly important under conditions in which irrigation waters have magnesium-to-calcium ionic concentration ratios > 1 (Vyshpolsky *et al.*, 2008). Long-term use of irrigation water with elevated K concentrations also poses challenges to maintaining good soil structure and adequate infiltration rates (Smith, Oster & Sposito, 2015; Oster, Sposito & Smith, 2016).

Rengasamy & Marchuk (2011) have proposed a different irrigation water quality parameter: the cation ratio of structural stability (CROSS). This includes the dispersive effect of K in addition to that of Na, and differentiates the flocculating effect of Mg from that of Ca (Equation 7).

$$CROSS = (C_{Na} + 0.56C_K)/ [(C_{Ca} + 0.60C_{Mg})/2]^{0.5} \qquad [7]$$

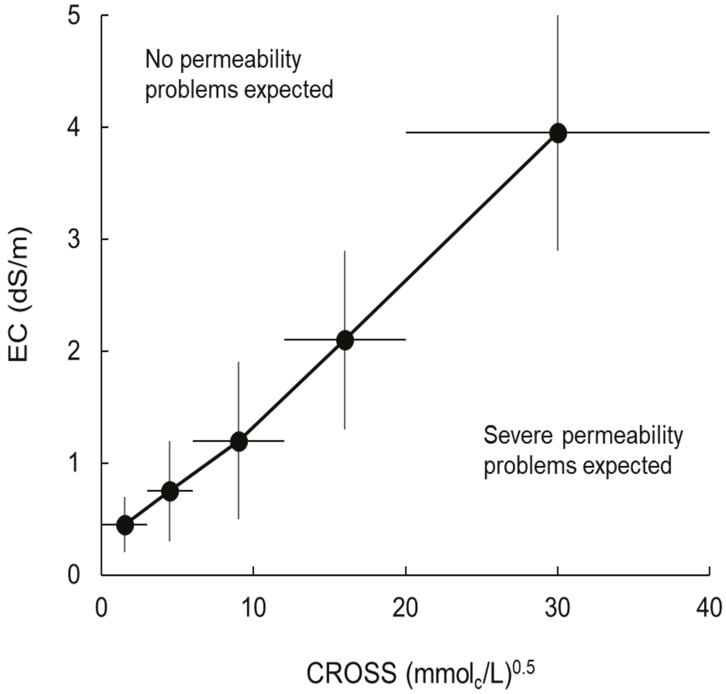
where C represents concentrations in $mmol_c/L$ of the cations. The coefficient of K (0.56) is based on the ratio of the dispersive powers (reciprocal of flocculating powers) of Na and K, and the coefficient of Mg (0.60) is based on the ratio of the flocculating powers of Ca and Mg. However, both coefficients can vary in nature (Qadir *et al.*, 2021). Nevertheless, Equation 7 addresses the over-simplification in Equation 6 (SAR), which treats Mg equal to Ca in terms of flocculating effects. In many waters, Mg concentration is low relative to Ca, although there are well-known exceptions (Oster, Sposito & Smith, 2016).

The principal factor that determines the extent of adverse effects of irrigation sodicity on soil hydraulic properties is the accompanying electrolyte concentration in the soil solution, with low concentrations promoting deleterious effects under sodic environments. Infiltration problems occur due to clay swelling, the breakdown of macroaggregates into microaggregates upon wetting and/or crusting. All these processes result in a reduction in the number and size of large pores at the soil surface, reducing the infiltration of rainfall or irrigation water.

Based on the water quality data of 600 water samples representing arid and semi-arid regions around the world, Qadir *et al.* (2021) proposed revised irrigation water quality guidelines for assessing soil permeability problems (Figure 5.2). These guidelines are intended to cover a wide range of water quality conditions that occur in irrigated areas and apply to whatever combinations of K and Mg are used to calculate CROSS. The use of CROSS in place of SAR is particularly advisable for waters with EC < 4 dS/m, and where the Mg concentration exceeds the one of Ca.

The changes in the permeability of irrigated soils depend on a range of factors, such as soil texture, clay mineralogy, soil depth, presence of compacted layer(s) in the subsoil, the crop(s) to be grown, depth and quality of groundwater, methods and timing of irrigation, provision of a drainage system and its efficiency, rainfall pattern and ambient climatic conditions.

Figure 5.2. Graphic representation of the interpretation of electrical conductivity (EC) and the cation ratio of structural stability (CROSS) to assess soil permeability hazard based on Ayers & Westcot (1985) using EC and SAR.



Source: Qadir, M., Sposito, G., Smith, C.J. & Oster, J.D. 2021. Reassessing irrigation water quality guidelines for sodicity hazard. Agricultural Water Management, 255, 107054.

Another option to express the relationship between sodicity and salinity is the electrochemical stability index (ESI), which is determined by calculating the ratio of the EC of a one-part soil to five parts soil extract (EC1:5 – dS/m) and the exchangeable sodium percentage (ESP). A tentative critical ESI value for Australian cotton soil is 0.05. An economically viable response to gypsum and/or lime can be expected where ESI values are at or below this level (Hulugalle & Finlay, 2003).

5.2.3. Specific ionic effects, toxicities and nutrient imbalances

An excess of macro- or micro-nutrients can occur under saline conditions through over-fertilization and/or the use of wastewater. Depending on its source, treatment and dilution, wastewater can contain nutrients in high concentrations. Its application in combination with fertilizer application can provoke a nutrient imbalance in soils and crops, while boosting biomass production, for example, with a resulting low economic (i.e. grain) yield.

Water quality-related specific ion effects can relate to mineral-nutrition disorders and the toxicity of specific elements. Moreover, some elements such as manganese (above 0.05 mg/L) and iron (above 0.3 mg/L) can clog micro-irrigation equipment, creating a management-related risk of high element concentrations.

With reference to mineral-nutrition disorders, salts in irrigation water may cause extreme ionic ratios in the soil solution and thus can induce nutritional imbalances in crops. The uptake of certain nutrients and their accumulation by plants may decrease because of competitive processes. For example, Na-induced K or Ca deficiencies may develop in crops by excess sodium salts or a reduction in NO_3^- uptake under saline environments dominated by Cl^- salts (Grattan & Grieve, 1999; Corrado *et al.*, 2020).

As wastewater might not be the only source of nutrients, but accompany the use of chemical or organic fertilizers, good agricultural practices must be in place to avoid over-fertilization which can affect crops and the environment (see Chapter 8 on Ecology).

A toxicity problem stemming from specific ion toxicity differs from a salinity problem, which prevents the uptake of specific nutrients, in that it occurs within the plant itself. Toxicity problems occur if certain cations and anions – in saline soils often chloride, sodium or boron – present in the soil or added through irrigation water are taken up by the plant and accumulate in concentrations that are high enough to negatively affect plant growth and cause crop damage or reduced yields. In general, permanent, perennial crops (tree and vine crops) are more sensitive to specific ion toxicities than seasonal or annual crops. The initial damage to sensitive crops usually presents as marginal leaf burn and interveinal chlorosis at relatively low ionic concentrations followed by negative effects on crop growth and yield, particularly if the accumulation increases and the ionic concentrations are high enough to cause crop damage. More tolerant annual crops are usually not sensitive at low concentrations but almost all crops are damaged or completely killed if concentrations are sufficiently high (Ayers & Westcot, 1985).

Aside from salinity-related chloride (Cl), sodium or boron (B) effects, toxicity problems can derive from untreated or partially treated wastewater. The different types and amounts of chemical substances in irrigation water depend on the kind of local industry, and its environmental performance and wastewater treatment process (Rodríguez-Eugenio, McLaughlin & Pennock, 2018). Although heavy industry might be limited to coastal cities in low-income countries, textile or mining industries can represents significant inland sources of heavy metals where wastewater treatment is insufficient or absent.

Like sodium, most annual, non-woody crops are not specifically sensitive to Cl, even at higher concentrations (Grieve, Grattan & Maas, 2012). However, most woody species, as well as strawberry, bean and onion, are susceptible to chloride toxicity, but such sensitivities are largely variety and rootstock dependent. Chloride ions move readily with the 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 sodium, susceptibility to Cl toxicity is dependent upon the plant's ability to restrict its translocation from the roots to the shoot. By selecting rootstocks that restrict Cl movement within the plant, Cl toxicity can be avoided or at least delayed. The maximum Cl concentrations permissible in the soil water that do not cause leaf injury in selected fruit crop cultivars and rootstocks are shown in Table 5.5.

Table 5.5. Chloride-tolerance limits (mmol/L) of some fruit-crop rootstocks and cultivars

Crop	Rootstock or cultivar	Maximum permissible Cl^- in soil saturation extract without leaf injury[1]
Rootstocks		
Avocado (Persea americana)	West Indian	7.5
	Guatemalan	6
	Mexican	5
Citrus (Citrus sp.)	Sunki mandarin, grapefruit	25
	Cleopatra mandarin, Rangpur lime	25
	Sampson tangelo, rough lemon	15
	Sour orange, Ponkan mandarin	15
	Citrumelo 4475, trifoliate orange	10
	Cuban shaddock, Calamondin	10
	Sweet orange, Savage citrange	10
	Rusk citrange, Troyer citrange	10
Grape (Vitis sp.)	Salt Creek, 1613-3	40
	Dog ridge	30
Stone fruit (Prunus sp.)	Marianna	25
	Lovell, Shalil	10
	Yunnan, Nemagaurd	7.5
Cultivars		
Berries [2] (Rubus sp.)	Boysenberry	10
	Olallie blackberry	10
	Indian Summer raspberry	5
Grape (Vitis sp.)	Thompson seedless, Perlette	20
	Cardinal, black rose	10
Strawberry (Fragaria sp.)	Lassen	7.5
	Shasta	5

[1] For some crops, these concentrations may exceed the osmotic threshold and cause some yield reduction. Data have been adjusted from the original paper to the saturation extract. Over a wide soil textural range, the saturated water content is about twice the field capacity (FC); in other words, the Cl concentration in the saturation extract is about half of that under FC (Rhoades, 1982)

[2] Data available for one variety of each species only.

Source: Adapted from Grieve, C., Grattan, S. & Maas, E. 2012. Plant salt tolerance. In W.W. Wallender & KK. Tanji, eds. Agricultural salinity assessment and management, Second edition. pp. 405–459. Reston, VI, American Society of Civil Engineers.

Toxicity can also occur from direct absorption of the toxic ions through leaves wetted by overhead sprinklers. Sodium and chloride are the primary ions absorbed through leaves, and toxicity to one or both can present a problem for sensitive crops such as citrus. As concentrations increase in the applied water, damage develops more rapidly and becomes progressively more severe.

Although B is an essential micro-nutrient for crop plants, the concentration range of plant-available boron in the soil solution that is optimal for growth for most crops is very narrow. Above this narrow range toxicity can occur (Grattan *et al.*, 2014). Boron problems originating from irrigation water (> 0.5 mg B/L) are more frequent than those originating in the soil. Boron toxicity can affect nearly all crops but, like salinity, there is a wide range of tolerance among crops (Ayers & Westcot, 1985). Concentrations of boron in reclaimed water originate principally from household detergents and cleansing agents and, provided the concentrations are not too high, they are not expected to cause immediate harm to plants. However, boron may accumulate in the root zone through long-term use of reclaimed wastewater. Table 5.6 contains the boron tolerance limits for various crops adapted from Maas and Grattan (1999). For some crops, threshold values and slope (the percentage yield decrease per unit increase in boron beyond the threshold level) are presented such that estimated yield decline functions can be determined in the same manner as those for salinity (ECe) (see above).

Boron toxicity symptoms occur on either old or young developing tissue depending upon its mobility within the plant (Brown & Shelp, 1997). In boron immobile plants, toxicity symptoms (Figure 5.3) usually occur after boron concentrations in leaf blades exceed 250–300 mg/kg on dry mass basis, but as mentioned, not all sensitive crops accumulate boron in leaf blades. For example, stone fruits – peaches, plums and almonds – and pome fruits – apples, pears and others – are easily damaged by boron in young developing tissue, without accumulating enough boron in the leaf tissue. In such cases, leaf analysis is not a reliable diagnostic test for toxicity. With these crops, boron excess must be confirmed from soil and water analyses, tree symptoms and growth characteristics.

Figure 5.3. Boron injury on the margins of "Kerman" pistachio leaves (B-immobile species)

Source: S.R. Grattan, UC Davis.

Table 5.6. Boron tolerance limits in soil water for agricultural crops and fruits (thresholds based on boron concentration in soil

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	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	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		TT
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 and 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 lucopersi-cum (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. DW: dry weight; FW: fresh weight.
‡ 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: Adapted from Grieve, C., Grattan, S. & Maas, E. 2012. Plant salt tolerance. In W.W. Wallender & KK. Tanji, eds. Agricultural salinity assessment and management, Second edition. pp. 405–459. Reston, VI, American Society of Civil Engineers.

5.2. Risks from heavy metals

Many potentially toxic elements are normally present in soils as well as wastewater in small amounts and, hence, are also called trace elements. Those metals with relatively high densities, atomic weights or atomic numbers are also called heavy metals. Some of these heavy metals (Zn, Cu, Fe, Ni) are important micro-nutrients when found in low doses, while others, like mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), and lead (Pb), are not, but can be found even in some phosphate and nitrate fertilizers (Rodríguez-Eugenio, McLaughlin & Pennock, 2018).

During wastewater treatment, some of these elements may be (at least partially) removed, but others can persist and could present phytotoxic problems. Wherever irrigation water might be affected by effluent from industrial or mining activities, it is recommended not to use it for food production, unless laboratory analysis can verify its safety, based for example on phytotoxic threshold levels (Table 5.7). The same applies to sewage sludge, which can contain accumulated levels of harmful chemicals, and should not be used for food crops, even if treated for pathogens, unless a detailed risk assessment based on laboratory data is possible (Box 5.2). As different chemical elements have varying mobility in soils, the risk assessments might also vary, for example with soil texture and soil acidity (pH), as indicated in Table 5.7. In contrast to sewage sludge, the risk assessment can be different for septic sludge from on-site sanitation systems.[5]

The recommended maximum concentration (RMC) is based on a water application rate of 10 000 m^3/ha/yr. If the water application rate greatly exceeds this, the maximum concentrations should be adjusted downward accordingly. No adjustment should be made for application rates of less than 10 000 m^3/ha/yr. The values given are for water used on a long-term basis at one site.

RMC levels are established based mainly on concerns about soil protection, as irrigation with contaminated water can lead to long-term accumulation of potentially toxic compounds. However, there are distinct differences in the mobility and bioavailability of heavy metals (trace elements) and thus their risks for crops and humans. They can be divided roughly into four groups depending on their soil retention and translocation within the plant (Table 5.8). In brief, group 1 elements are poorly soluble and hardly taken up by plants; group 2 elements are in part taken up but remain in the roots; group 3 elements accumulate in and kill the plant before the concentration reaches values which can affect humans; and group 4 elements are easily transferred and can accumulate in the plant without damaging it, and thus pose the highest risk for consumers (Chaney, 1980).

Cadmium has been identified as the main heavy metal of concern in wastewater, as compared to other metals it is more available to plants and can be found in the edible parts of crops. Although not usually toxic to plants, it can present great risks to human health. However, as heavy metals can accumulate in soils over long periods, it is necessary to control not only irrigation water but also soils and metal concentrations in the crop. However, permissible limits for heavy metals in soil-plant systems vary significantly for soils based on their characteristics, as well as on the type of crop and sampled crop component (e.g. root, shoot, older/younger leaves, fruit/seeds) over the growing season (Shahid, 2017).

[5] Septic sludge (septage), for example, from backyard septic tanks or pit latrines is considered a safer product than sewage sludge from a chemical perspective, but requires pathogen control (Nikiema, Cofie & Impraim, 2014).

Table 5.7. Recommended maximum concentrations (RMC) of selected metals and metalloids in irrigation water

Element	RMC mg/L	Remarks
Aluminium	5.00	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate any toxicity.
Arsenic	0.10	Toxicity to plants varies from 12 mg/L for Sudan grass to less than 0.05 mg/L for rice, as mobility is higher in flooded soils.
Beryllium	0.10	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans.
Cadmium	0.01	Toxic at concentrations as low as 0.1 mg/L in nutrient solution for beans, beets and turnips. Conservative limits are recommended due to the risk of accumulation in plants and soils.
Chromium	0.10	Not generally recognized as an essential plant growth element. Conservative limits are recommended.
Cobalt	0.05	Toxic to tomato plants at 0.1 mg/Lin nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Copper	0.20	Toxic to several plants at 0.1 to 1.0 mg/L in nutrient solution.
Iron	5.00	Non-toxic to plants in aerated soils (pH > 5), but can contribute to soil acidification and loss of availability of phosphorus and molybdenum.
Lithium	2.50	Tolerated by most crops up to 5 mg L. Mobile in soil. Toxic to citrus at low concentrations with a recommended limit of < 0.075 mg/L.
Manganese	0.20	Toxic to a number of crops at a few-tenths to a few mg/L in acidic soils (pH < 5).
Molybdenum	0.01	Non-toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Nickel	0.20	Toxic to a number of plants at 0.5 to 1.0 mg/L. Reduced toxicity at neutral or alkaline pH.
Lead	5.00	Can inhibit plant cell growth at very high concentrations.
Selenium	0.02	Toxic to plants at low concentrations and toxic to livestock if forage is grown in soils with relatively high levels of selenium.
Zinc	2.00	Toxic to many plants at widely varying concentrations. Reduced toxicity at pH ≥ 6.0 and in fine textured or organic soils.

Source: WHO. 2006. Guidelines for the safe use of wastewater, excreta and greywater. Volume II, Wastewater use in agriculture. WHO-UNEP-FAO, based on Ayers, R.S. & Westcot, D.W. 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper 29, Rev. 1. Rome, FAO, and Pescod, M. 1992. Wastewater treatment and use in agriculture. Irrigation and Drainage Paper No. 47. Rome, FAO.

Table 5.8. Trace elements classified in groups according to their potential risk to the food chain through absorption by soil-plant transfer

Group	Metal	Soil adsorption	Phytotoxicity	Food chain risks
1	**Ag, Cr, Sn, Ti, Y and Zr**	Low solubility and strong retention in soil	Low as limited or no uptake	Low risks because they are not taken up by plants
2	**Hg and Pb**	Strongly absorbed by soil colloids	Plant roots may adsorb elements but not translocate them to shoots; generally not phytotoxic except at very high concentrations	Pose minimal risks to human health Risks to grazing animals (or humans) if contaminated soils are ingested
3	**B, Cu, Mn, Mo, Ni and Zn**	Less strongly absorbed by soil than groups 1 and 2	Readily taken up by plants and phytotoxic at concentrations that pose little risk to human health	Conceptually, the "soil-plant barrier" protects the food chain from these elements
4	**As, Cd, Co, Mo, Se and Tl**	Least absorbed by the soil of all metals (plant uptake likely)	Pose human or animal health risks to plant tissue concentrations that are not generally phytotoxic	Bioaccumulation through the soil-plant-animal food chain. Soils contaminated with As* or Cd pose the most widespread risks to the food chain.

* Arsenic (As) in groundwater used for drinking is a major health concern in Asia. Continuous build-up of As in the soil through irrigation can affect crop roots and reduce yields. The risk for humans through eating As-exposed crops requires more research (Heikens, 2006). Other sources of As in soils include agrochemical compounds (pesticides, herbicides) and mining and smelting activities.

Source: Rodríguez-Eugenio, N., McLaughlin, M. & Pennock, D. 2018. Soil pollution: A hidden reality. Rome, FAO; based on Chaney, R.L. 1980. Health risks associated with toxic metals in municipal sludges. In G. Bitton *et al.* (eds.) Sludge: Health risks of land application. Ann Arbor, MI, Ann Arbor Science, pp. 59–83

Box 5.2. Heavy metal-related guidelines for sewage sludge application in agriculture

EU Directive 86/278/EEC encourages the use of sewage sludge in agriculture for its nutrient value, but regulates its use to prevent harmful effects on soil, surface and groundwater, plants, animals and people. Sludge should not exceed the values outlined in Table 5.9 (to be analysed at least every six months) and its application should not surpass the concentration defined for selected heavy metals in soils (Table 5.10). To avoid pathogenic risks, the guidelines refer in general to treated sludge (septage and sewage sludge) which has undergone biological, chemical or heat treatment, long-term storage or any other appropriate process, so as to significantly reduce possible health hazards resulting from usage. Under certain conditions, the use of untreated sludge can be permitted if there is no risk to human or animal health, for example if it is injected or worked into the soil. Restrictions may also be less stringent for sludge from small sewage treatment plants which treat primarily domestic waste.

Sludge must not be applied to soil in which fruit and vegetable crops are growing or grown (with the exception of fruit trees), or less than ten months before fruit and vegetable crops are to be harvested. Grazing animals must not be allowed access to grassland or forage land less than three weeks after the application of sludge.

Table 5.9. EC limits for heavy metal concentrations in sludge for use in agriculture (mg/kg of dry matter)

Parameters	Limit values
Cadmium	20 to 40
Copper	1 000 to 1 750
Nickel	300 to 400
Lead	750 to 1 200
Zinc	2 500 to 4 000
Mercury	16 to 25
Chromium (1)	1000

(1) Value from France; the EC did not define a Cr limit as of end 2022

Source: European Commission. 1986. Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. Official Journal of the European Union, 181, 4.7.1986, pp. 6–12

Table 5.10. EC limits for concentrations of heavy metals in soils with a pH of 6 to 7 (mg/kg of dry matter). Land spreading is not authorized if the soil pH is below 5.

Parameters	Limit values (1)
Cadmium	1 to 3
Copper (2)	50 to 140
Nickel (2)	30 to 75
Lead	50 to 300
Zinc (2)	150 to 300
Mercury	1 to 1.5
Chromium (3)	150

(1) EC member States may permit the limit values they set to be exceeded if e.g. commercial food crops are being grown exclusively for animal consumption, without human or environmental risk.
(2) EC member States may permit the limit values they set to be exceeded by max 50% in respect of these parameters on soil with a pH consistently higher than 7, and no risk in particular for groundwater.
(3) Value from France; The EC did not define a Cr limit as of end 2022.

Source: https://ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_disposal2a.pdf

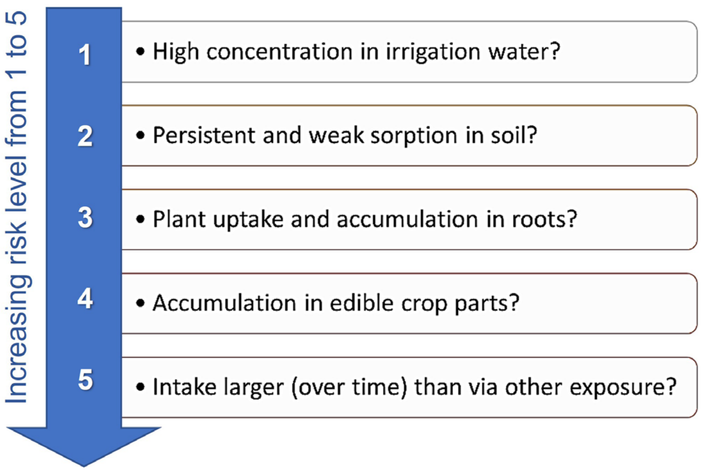
5.3. Risks from organic contaminants of emerging concern (CEC)

A wide range of organic contaminants can be present in industrial or municipal wastewaters, including pesticides, healthcare products, persistent organic pollutants, micro-plastics, pharmaceutical and personal care products, or residues of any of these. These contaminants are commonly referred to collectively as contaminants of emerging concern (CEC). Most are released into the environment as a result of human activities and might not be removed through conventional wastewater treatment. The presence of this type of organic compounds can be of relevance for agricultural wastewater use, although a comprehensive risk assessment for agro-food systems is still limited by multiple factors, not least the sheer number of CEC and their diverse structures and environmental behaviour.

Soil serves as the initial recipient of CEC when agricultural fields are irrigated or amended with biosolids (treated faecal sludge). Sorption to soil and degradation in soil play an important natural role in controlling the availability of CEC for plant uptake. While most of these substances come only in small concentrations, many CEC are taken up by roots. Uptake varies with the physical and chemical properties of the organic contaminant, the biological characteristics of the plant as well as soil physical and chemical characteristics. Once CEC enter plant roots, the chemicals can potentially translocate to different organs where they may be transformed by the plant metabolism. Uptake and accumulation of CEC in edible crops present a potential route for human exposure via dietary ingestion. Based on observations to date, CEC are accumulated in edible fruits, leaves or roots, typically within a very small range. Under field conditions, the estimated dietary consumption of a pharmaceutical by-product, for example, would be several orders of magnitude less than any prescribed daily dose for such a pharmaceutical. However, there is little knowledge pertaining to long-term human health effects, or synergistic effects of the combination of various compounds, and as a result regulatory standards or guidelines are only slowly emerging. In comparison with pathogenic health risks, the presence of organic chemical levels on irrigated vegetables, even if elevated, is considered to be of secondary importance in view of human health in low-income countries (WHO, 2006; Amoah *et al.*, 2006). In comparison, fish grown in CECs polluted water could present a higher human health risk (Meador, Yeh & Gallagher, 2018).

Figure 5.4 summarizes a theoretical flow chart from low to high risk. Access to the required data and information to follow such a guiding framework could be a challenge (Fu *et al.*, 2019).

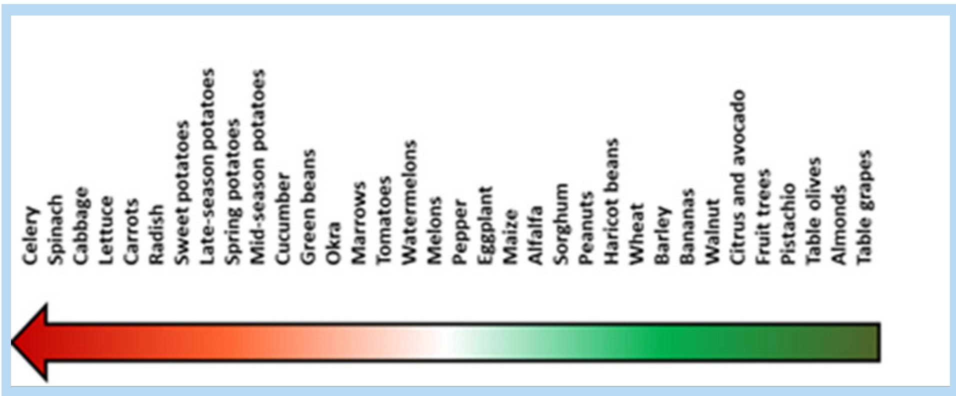
Figure 5.4. Contaminants of emerging concern risk chart



Source: Modified from Fu, Q., Malchi, T., Carter, L.J., Li, H., Gan, J., & Chefetz, B. 2019. Pharmaceutical and Personal Care Products: From Wastewater Treatment into Agro-Food Systems, Environmental Science & Technology 2019 53 (24), 14083-14090

Some guidance on differences between crops in view of their CEC uptake potential is provided in Figure 5.5. In general, crops with a high transpiration rate are expected to have a higher absorption potential for CEC when grown in warm and dry conditions following the order of: Leafy vegetables > root vegetables > cereals and fodder crops > fruit vegetables.

Figure 5.5. Increasing potential of CEC uptake by different plant species



Source: Christou, A., Papadavid, G., Dalias, P., Fotopoulos, V., Michael, C., Bayona, J. M., Piña, B. & Fatta-Kassinos, D. 2019. Ranking of crop plants according to their potential to uptake and accumulate contaminants of emerging concern. Environmental Research, 170, 422–432.

The World Health Organization (WHO, 2006) has published numerical limits to define the maximum permissible concentrations of a selected group of organic contaminants in agricultural soils (Table 5.11). The values relate to the levels at which contaminants can be transferred to humans through the food chain. However, for most of these organic contaminants, the possibility of accumulating in the soil is small due to their typically low concentrations in wastewater.

Table 5.11. Maximum tolerable concentrations of selected pesticides and other organic chemicals in soils exposed to wastewater or treated sludge applications

Contaminant	Soil concentration (mg/kg)	Contaminant	Soil concentration (mg/kg)
Aldrin	0.48	Methoxychlor	4.27
Benzene	0.14	PAHs (as benzo[a]pyrene)	16.00
Chlordane	3.00	PCBs	0.89
Chloroform	0.47	Pentachlorophenol	14.00
2,4-D	0.25	Pyrene	41.00
DDT	1.54	Styrene	0.68
Dichlorobenzene	15.00	2,4,5-T	3.82
Dieldrin	0.17	Tetrachloroethane	1.25
Dioxins	0.00012	Tetrachloroethylene	0.54
Heptachlor	0.18	Toluene	12.00
Hexachlorobenzene	1.40	Toxaphene	0.0013
Lindane	12.00	Trichloroethane	0.68

Source:WHO. 2006. Guidelines for the safe use of wastewater, excreta and greywater. Volume II: Wastewater use in agriculture. Paris, WHO-UNEP-FAO

WHO and FAO have jointly developed the Codex Alimentarius Commission which reviews and updates regularly food safety and quality standards including the maximum residue level of pesticides, heavy metals, and so on in crops based on the acceptable daily intake[6].

5.4. Options for risk reduction

Sustainability of agriculture irrigated with low-quality water will require a comprehensive approach to soil, water and crop management based on risk assessments and risk mitigation. In contrast to the usually invisible risks from pathogens or chemicals in wastewater, farmers are well aware of common salinity problems and receptive to training programs in addressing these challenges. Case study 2 in the annex describes such an example from Bangladesh.

5.4.1. Risk assessments

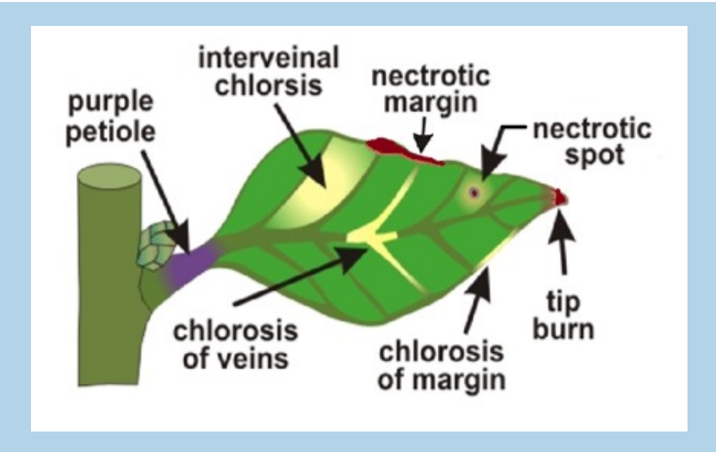
In most cases, risk assessments require a chemical analysis of the irrigation water, the soil and/or the crop, in order to identify pollution or nutritional stress, or imbalances, compared with control sites and local or international standards (see above). Sampling should consider spatial and temporary variability, which will require a variety of samples and separate sample analysis. Comprehensive guidelines for water, soil and plant sampling and analyses have been compiled by Estefan, Sommer & Ryan (2013) among others.

[6] For pesticides, see for example, www.fao.org/fao-who-codexalimentarius/codex-texts/dbs/pestres/pesticides/en

For some abiotic risks, such as salinity, sodicity or specific ion toxicities, laboratory analysis of soils and plant tissue should be accompanied by field observations indicating typical salinity or ion toxicity symptoms (Figure 5.1), or nutritional disorders (Figure 5.3). This is particularly important for situations where no laboratory is available, and visual identification of crop nutrient disorders on crop leaves can provide insights into potential problems (Bergmann, 1992). Field guides, for example, for rice are readily available from the International Rice Research Institute, for wheat from CIMMYT and so on. Online guides in regard to particular nutrient deficiencies are also available for multiple crops from IPI, YARA and others.

Common terms for describing typical foliar symptoms of nutritional disorders are shown in Figure 5.6.

Figure 5.6. Terminology of common leaf abnormalities



Source: http://flairform.com/growers-guide/ (modified)

Risk prevention or mitigation strategies vary with the hazard. In contrast to pathogenic risks (see Chapter 4), which can be addressed through various (low-cost) wastewater treatment processes, and a range of improved water fetching, irrigation, and post-harvest practices (Amoah *et al.*, 2011), the best option for chemical contaminants is risk prevention and tertiary wastewater treatment at source, not mitigation at the farm level (Simmons, Qadir & Drechsel, 2010; Fu *et al.*, 2019). Conversely, for challenges such as salinity, researchers have developed a variety of farm-based options over many decades. Table 5.12 provides a simplified overview and the following sub-sections detail the risk mitigation options, in particular in relation to salinity.

Table 5.12. Options for addressing chemical (non-pathological) threats from low-quality irrigation water

Risk mitigation options / Risks caused by irrigation	Salinity	Sodicity	Boron or Chloride toxicity	Heavy metals	Organic contaminants	Macro-nutrient over-supply
1. Primary and secondary wastewater treatment	Salinity can increase in pond based systems due to evaporation					
2. Tertiary wastewater treatment (reverse osmosis)						
3. Crop/variety restrictions for those capable of withstanding the hazard						
4. Irrigation methods reducing water volume (e.g. drip irrigation, furrows)	Drip clogging possible					
5. Irrigation in excess of crop water requirements to support leaching				Accumulation of less soluble contaminants possible		
6. Irrigation in conjunction with freshwater (cyclic applications, blending)						
7. Good agronomic practices (soil nutrient and water management)				Limited impact if any		
8. Soil amelioration (with limestone, gypsum, etc. to influence soil pH or counter nutrients in excess)						
9. Phytoremediation					To be determined	

Legend: Useful | Very useful

Source: Authors' own elaboration

5.4.2. Crop diversification, restrictions and field trials

A pertinent selection of plant species capable of withstanding ambient levels of salinity and/or sodicity and producing adequate yields is crucially important when using saline, sodic or saline-sodic waters for irrigation. Such restrictions are generally limited to the possibility of access to a replacement crop (or variety) with financially viable market value.

The approach is also applicable to crops able to withstand high levels of boron or chloride, for example. While there exist tables on crop tolerance levels (see Table 5.11), the salt or specific ion tolerance of a crop should be valued in context because optimal selection depends on several soil, crop and climatic factors. The best approach for farmers is to use guidelines such as these to narrow down the choice of crops and then test several on the farm with the available soil and water before making a final selection.

Where the potential for chemical contamination in the area is high (e.g. downstream of a mining, car repair/wash, or an industrial area), and upstream wastewater treatment capacities are unknown or limited, changing food crops to others with lower uptake might not be the safest option, especially where laboratory data are missing. In such cases, a switch to non-food crops is highly recommended, such as forage or bio-energy crops.

The same applies to high salinity. As high-quality forages for cattle and sheep are in short supply in many parts of the world, using salt-tolerant forage grass and shrub species in a forage-livestock system could increase the availability of quality feed, and thus meat and milk outputs. Promising forage species as reported by different researchers include, but are not limited to, Tall wheatgrass, Kallar grass or Australian grass, Para grass, Bermuda grass, Kochia, sesbania, purslane, and shrub species from the genera Atriplex and Maireana (Barrett-Lennard, 2002; Robinson *et al.*, 2003).

The cultivation of bio-energy crops on salt-affected waste lands offers an opportunity to put otherwise unproductive land into production and ensures simultaneously that no natural ecosystems or food-producing agricultural production areas need be converted into systems for renewable energy production. Studies have shown that a range of plant species can be used for renewable energy production on salt-affected environments. Jatropha, toothbrush tree, Russian olive and sweet-stem sorghum are promising examples (Qadir *et al.*, 2010).

Several fruit-tree species have shown promising results under saline environments. Prominent fruit trees for saline environments are date palm, olive, chicle, guava, Indian jujube and karanda (Qureshi & Barrett-Lennard, 1998). Tolerance varies between cultivars but is not the only factor to consider. The water and nutrient requirements of olive, for example, are lower than most other tree species, which represents an advantage in salt-affected areas characterized by low nutrient availability or accessibility to plants.

Studies on establishing rapidly growing tree plantations can offer an opportunity to use salt-affected lands to provide fire wood under saline environment for example, using a variety of indigenous and exotic tree species (Qadir *et al.*, 2008; Qureshi & Barrett-Lennard, 1998). The selection of tree species for salt-affected lands usually depends on the cost of inputs and the subsequent economic and/or on-farm benefits. Planting salt-tolerant nitrogen-fixing trees on salt-affected lands enhances the nitrogen availability and organic matter content in these soils, which are otherwise characterized as deficient of nutrient elements (Kaur, Gupta & Singh, 2002).

5.4.3. Irrigation methods reducing crop exposure to salts

There are different ways to irrigate crops, such as surface or flood irrigation, furrow irrigation, sprinkler irrigation, and micro-irrigation such as drip or trickle irrigation. Table 5.13 presents several parameters for the evaluation of commonly used irrigation methods in relation to the reduction of risks from salts. Some irrigation methods are more suitable for saline water or other types of marginal- or low-quality water than others (Simmons, Qadir & Drechsel, 2010). Drip irrigation systems, for example, have the advantage of reducing the amount of water lost, while decreasing the impacts of salinity. However, clogging of drippers through salt accumulation between emitters may limit the use of drip irrigation systems for saline waters (see chapter 3).

Managing salinity and water stress simultaneously is a complex challenge. Experimental and modelled results regarding leaching efficiency and irrigation frequency can reach contradictory conclusions, depending also on soil and crop characteristics. One often overlooked fact is that salt-stressed plants use less water than non-stressed plants. Thus, irrigating a salt-stressed plant more frequently may not be more beneficial.

Table 5.13. Parameters for evaluating commonly used irrigation methods in relation to risk reduction

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

Source: Simmons, R.W., Qadir, M. & Drechsel, P. 2010. Farm-based measures for reducing human and environmental health risks from chemical constituents in wastewater. In P. Drechsel et al. (eds.) Wastewater irrigation and health: Assessing and itigating risks in low-income countries, pp. 209–238. London, Earthscan-IDRC-IWMI; after Pescod, M. 1992. Wastewater treatment and use in agriculture. Irrigation and Drainage Paper No. 47. Rome, FAO.

Regardless of how plants respond to integrated stress, they presumably do better when grown on saline soils if water deficit stress is minimized. However, salt-stressed crops might not respond positively to increasing irrigation frequency unless 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 oxygen deficit or root disease (Maas & Grattan, 1999).

Several benefits of high frequency irrigation do exist, however, regardless of salinity. These include increased water availability for root uptake, more root activity and improved nutrient management options. Mineral nutrition has been shown to reduce specific toxicity of salts, and thus proper high frequency fertigation could be particularly beneficial for saline conditions (Silber, 2005). Increased frequency is especially favourable for horticultural crops on shallow or coarse-textured soils (Lamm & Trooien, 2003).

5.4.4. Salt management in the root zone

As salts are added to irrigated soils with each irrigation event, it is important to maintain the salinity in the root zone at acceptable levels. Maintenance of salinity can only be achieved by leaching excess salts below the root zone. The leaching frequency depends on the salinity status in water or soil, the salt tolerance of the crop, rainfall and other climatic conditions. Adequate soil drainage is considered as an essential prerequisite to achieve leaching requirement vis-à-vis salinity control in the root zone (Ayars & Tanji, 1999). Natural internal drainage alone may be adequate if there is enough storage capacity in the soil profile, or a permeable subsurface layer occurs that drains to a suitable outlet. An artificial system must be provided if such natural drainage is not present where a perched water table can encroach within the root zone. Besides adequate soil drainage, land levelling and an adequate depth of groundwater are also basic components to maintain salinity in the root zone at a specific level.

If impermeable layers in the soil cause perched water tables that prevent adequate drainage, then drainage water collection systems must be installed and the drainage water disposed of or reused to avoid on-site and off-site salinity effects. To achieve adequate leaching, the volume of irrigation water applied needs to exceed the crop water requirement unless rainfall is adequate to leach excess salts from the root zone.

The leaching requirement (LR) is the minimum leaching fraction needed to control soil salinity to an acceptable level – typically, the full yield potential of the crop. This value varies with both the crop type and the salinity of the irrigation water. The LR can be estimated as follows (Equation 8):

$$LR = ECw / [5 \times (ECe) - (ECw)] \qquad [8]$$

where LR refers to the leaching requirement needed to control the salinity in the root zone within the salt tolerance level of a specific crop by surface irrigation, ECw is the electrical conductivity of applied irrigation water and ECe refers to the average soil salinity (determined from the extract of saturated soil paste) in the root zone that can be tolerated by the crop under consideration (Table 5.2). These values also provide information on yield loss by these crops as the salinity of the soil increases. The identification of the leaching requirement is also important for determining the total water requirement (AW) of the crop (Equation 9; Ayers & Westcot, 1985).

$$AW = ET / (1 - LR) \qquad [9]$$

where AW refers to the depth of applied water per unit area on a yearly or seasonal basis (mm/year or m^3/ha), ET is the annual or seasonal crop water consumption expressed as evapotranspiration (mm/year or m^3/ha) and LR is the leaching requirement expressed as fraction of 1. The leaching required to maintain salt balance in the root zone may be achieved either by applying enough water at each irrigation to meet the LR, or by applying, less frequently, a larger leaching amount sufficient to remove the salts accumulated from previous irrigations.

Guidelines based on such steady-state equations have shown to provide an acceptable approximation, especially in frequently irrigated systems where irrigation is given at a constant ratio to potential crop ET. However, they also tend to overestimate the LR, which can lead to the application of excessive amounts of irrigation water and increased salt loads in drainage systems or underlying aquifers (Corwin & Grattan, 2018).

Furthermore, standard guidelines for managing salinity and irrigation, as described by the equations above, were mostly designed with the goal of maintaining root zone salinity at a level that avoids any reductions in crop growth or yield. However, due to the diminishing availability of good quality water for irrigation, it is increasingly important that irrigation and salinity management tools be able to target at least submaximal crop yields and support the use of marginal quality waters (Skaggs *et al.*, 2014).

More advanced models can serve this purpose and address technical shortcoming by simulating dynamic systems where crop production responds to changing input parameters, including weather conditions or soil hydraulic properties, under consideration of the sensitivity of specific crops to salinity. Such transient state models enable users to relate crop water use and crop yield to dynamic changes in soil salinity and soil water content in the root zone resulting from variations in irrigation water salinity, amounts of applied water, salination due to upward movement of salts from shallow groundwater levels, rainfall and climate.

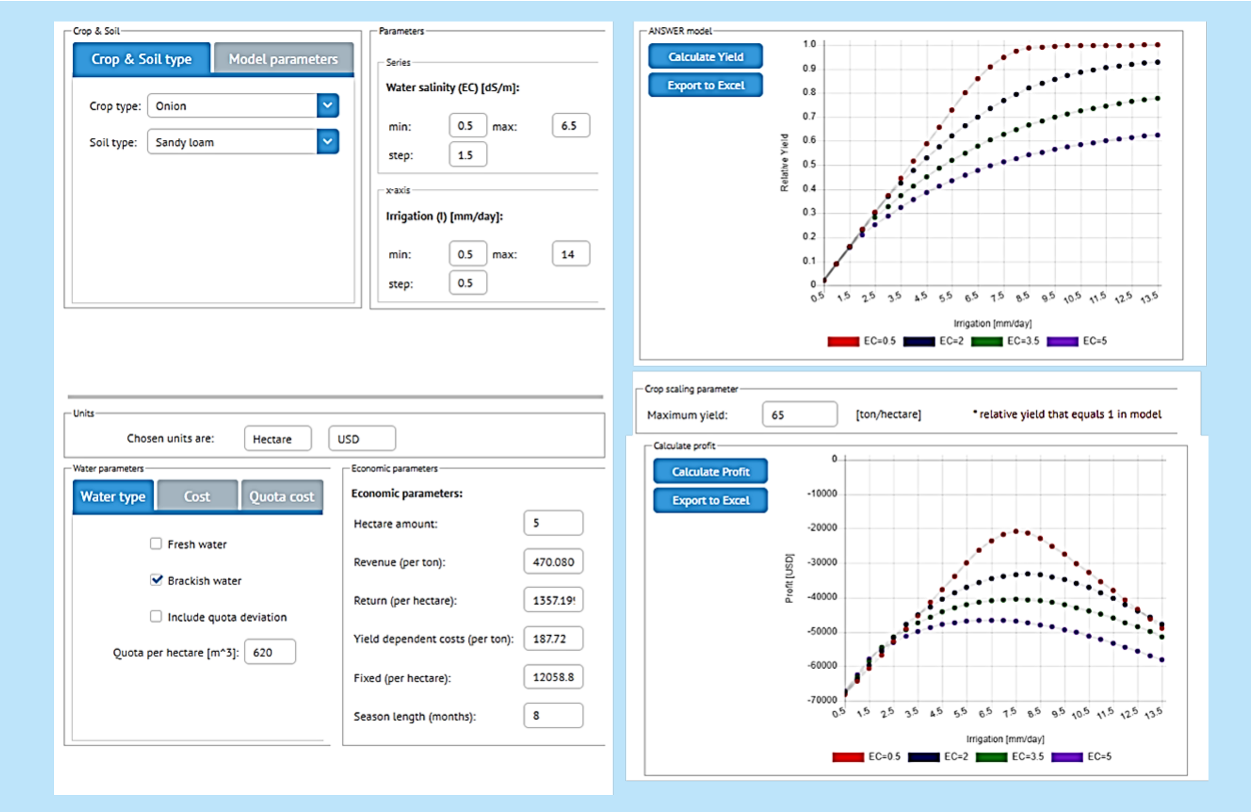
A variety of computer programs and packages developed for modelling water movement in two or three dimensions are freely available and are continuously updated. The popularity of transient state models such as HYDRUS, which serves different irrigation systems under salinity and sodicity, or related models such as STANMOD, RETC, UNSATCHEM and HP1, is growing rapidly, especially in developed countries (Šimůnek, van Genuchten & Šejna, 2016). While able to solve site specific, complex situations, these models are handicapped by the expertise and large number of parameters required for execution (Shani *et al.*, 2007). Further improvements will increase the adaptability of these models to more data-scarce conditions. Until then, the more user-friendly, steady-state models, despite being more conservative than transient models, remain valuable as means to generate a first, quick approximation of the suitability of water for irrigation (Oster *et al.*, 2012). If the water is suitable for irrigation for a particular crop in a particular location, a more rigorous assessment may not be necessary (Corwin & Grattan, 2018).

Less data-intensive models have been presented, for example, by Shani *et al.* (2007, 2009) and Skaggs *et al.* (2014). These "intermediate" models can provide good results as long as irrigation is frequent and regular. The models are easy to use and can calculate plant response to water and salinity, determine LRs and the environmental burden through the quantity of leached salts. Moreover, they can be coupled with a cost-benefit analysis (Figure 5.7) as presented in Kaner *et al.* (2018), or a model implemented by the California State Water Resources Control Board under the framework of the Central Valley Salinity Alternatives for Long-term Sustainability (CV-SALTS) for predicting crop yield and profitability response to saline irrigation water (Nicolas & Kisekka, 2022), based on an analytical approach for steady-state conditions of soil water, plant water uptake and salinity in the root zone (Shani *et al.*, 2007, 2009).

5.4.5. Irrigation in conjunction with freshwater

Saline, sodic and saline-sodic waters can be used for irrigation in conjunction with freshwater (or reclaimed wastewater), if available, through cyclic (temporal alternating) and in-situ blending approaches. Both options are possible: stretching supplies of freshwater by adding saline water, and blending saline water with freshwater. Blending saline waters with good-quality irrigation waters has been a common practice in several water-short regions of Australia, India, Pakistan, Spain and the United States (Tanji and Kielen, 2002; Oster, Sposito & Smith, 2016; Minhas, Qadir & Yadav, 2019). Case study 3 in the annex presents such an example from Spain. Another example of combining water sources to fit different situations is provided in Box 5.3. In all cases, it is important to follow the guidelines for interpretation of the combined effects of salinity and sodicity of blended water used for irrigation on soil physical properties, particularly infiltration rate (Figure 5.2, above).

Figure 5.7. User interface of the ANSWER economic-crop irrigation decision support application



Source: https://app.agri.gov.il/AnswerApp/; Kaner *et al.* (2018), based on Shani *et al.* (2007) analytical soil-water-salinity crop response model.

In an irrigation strategy consisting of cyclic use of saline water and freshwater, the crop rotations may include both moderately salt-sensitive and salt-tolerant crops. Typically, freshwater is used early on to reduce soil salinity in the upper profile, facilitating germination and permitting crops with lesser tolerances to salinity to be included in the rotation. Saline water is used for more salt-tolerant crops or for more salt-sensitive crops later in the season (Minhas, Qadir & Yadav, 2019). The cyclic strategy requires a crop rotation plan that can make best use of the available good quality water and saline water, and considers the different salt sensitivities among the crops grown in the region, including changes in salt sensitivities of crops at different stages of growth.

The advantages of the cyclic strategy include: (i) soil salinity is kept lower over time, especially in the topsoil during seedling establishment; (ii) a broad range of crops, including those with high economic-value and moderate salt sensitivity, can be grown in rotation with salt-tolerant crops; and (iii) conventional irrigation systems can be used. Studies addressing the cyclic use of saline waters (Minhas, Qadir & Yadav, 2019) have shown that this strategy is sustainable for cotton, rice, wheat, safflower, sugar beet, tomato, cantaloupe and pistachio, provided the problems of crusting or poor aeration are dealt with through optimum management.

In the Indian Sub-continent, the soil salinity levels are managed satisfactorily by monsoon rains and the extent of salt leaching depends on the total amount of monsoon rainfall and subsurface drainage. Therefore, problems may arise where there is insufficient rainfall to induce effective leaching. Under such conditions, salinity build-up at the end of the irrigation season may not be ameliorated by rainfall, thus requiring additional water for reclamation leaching.

Box 5.3. Blending of different water qualities in Israel

In Israel, to meet domestic and industrial freshwater demands under limited overall supply, the fraction of natural freshwater used for irrigated agriculture was decreased from about two-thirds (in the 1990s) to currently about one-third. This was accomplished by increasing irrigation water use efficiency and promoting the blending of irrigation water with alternative water sources. Drip irrigation, for example, is used today in Israel at rates higher than anywhere else in the world. The utilization of low-quality water has been encouraged (compensated) through a water for irrigation pricing structure, where the cost to farmers goes down as irrigation water salinity increases. Today, some 60 percent of the irrigation water supply comes from treated wastewater (up to 40 percent) and brackish groundwater. Overall, around 85 percent of all domestic wastewater is reused. However, the salinity levels of the recycled wastewater (between ca. 1 and more than 3 dS/m) and the management of water quality variations can represent a significant burden for the farmer.

Israel's move towards desalination of seawater to ensure national municipal water security has fortunately also reduced the salinity of the recycled wastewater released for irrigation. However, irrigation with pure desalinated water has resulted in crop damage as the reverse osmosis treatment process also removes useful crop nutrients. Thus, the blending of different water sources remains a good strategy, while research is moving towards alternatives to reverse osmosis, in order to selectively remove problematic elements while leaving agricultural desirable crop nutrients in the water (Yermiyahu *et al.*, 2007; Raveh & Ben-Gal, 2015; Tal, 2016; Cohen, Lazarovitch & Gilron, 2018).

5.4.6. Good agronomic practices

Where wastewater treatment is limited, undiluted wastewater might carry a significant nutrient load. This makes crop fertilization and nutrient management a complex task (Janssen *et al.*, 2005) as it requires information on nutrient levels in water, soils and plants. Such data might not be readily available to poor farmers or relevant government departments. Additionally, following strictly local fertilizer application guidelines might not help unless they consider the additional nutrient input from the water. To avoid nutritional disorders, farmers can select crops that are less sensitive to high nutrient levels or which can take advantage of high amounts of P and N. Higher N levels are thus more welcome in farms specializing in leafy crops than fruits or grains. In addition, fodder grass is well suited to absorb N and P applied via wastewater. Where farmers do not have the option to grow crops that benefit from high N or P levels, the irrigation water might first pass through farm-based filter systems to transform part of its nutrient load into biomass. This could take the form of an on-farm pond covered with duckweed (a good fodder) or a wetland system.

5.4.7. Seed placement

Various good agronomic practices exist to mitigate salinity challenges, such as sowing seed on relatively less saline parts of ridges, raising seedlings with freshwater and their subsequent transplanting, mulching of furrows to minimize salinity build-up and maintain soil moisture for longer period, or increasing plant density to compensate for possible decrease in growth.

Since most crops are salt sensitive at the germination/emergence stage, it is important to avoid the use of saline and sodic waters during this critical growth period. Under field conditions, this can be achieved through modification of planting practices to minimize salt accumulation around the seed and improve the stand of crops. For example, double row planting on flat beds can be practised with lettuce, onion, and in certain cases other field crops. Seeds are planted on the edges of the beds where salt accumulation is minimal (Rhoades, 1999). For larger seeded crops, the seeds can be planted in furrows. The seed is placed in a wet and less saline zone, as during the preparation of ridges more saline surface soil goes to the ridges and pre-sowing irrigation helps to leach the salts from furrow soil more efficiently than those of the ridge soil. The beneficial effects of furrow planting in mustard and sorghum over flood irrigation with saline water have been reported (Minhas, Qadir & Yadav, 2019). The practice of furrow planting has also been utilized for creating a favourable environment for the establishment of tree plantations where saline water was the source of irrigation.

Other interventions in addition to planting techniques include pre-sowing irrigation to leach the salts from seeding zone, raising seedlings with freshwater and their transplanting and subsequent irrigations with saline water, the use of mulches to maintain soil moisture for longer periods, and an increase in the seed or seedling rate per unit area (plant density) to compensate for a possible decrease in growth or plant density (Tanji & Kielen, 2002) (e.g. using 25 percent extra seed rate to achieve an expected 10-15 percent improvement in grain yield).

5.4.8. Soil amelioration

Specific soil ameliorants can alter the crop availability of micro-nutrients and heavy metals. Liming with $CaCO_3$, for example, can increase soil pH from 5.5 to 7.0, resulting in a significant reduction in Cadmium uptake among many crops (Gray *et al.*, 1999; Zhu *et al.*, 2016). Other materials, such as organic waste, sawdust or biochar, can absorb heavy metals from irrigation water. A key challenge is to obtain such materials in sufficient quantity and to finance the required laboratory analyses needed to monitor the success of the intervention. Collaborations with universities are recommended if the agricultural extension service has no access to such capacities.

In the case of irrigation with sodic waters or management of soils with a high ESP, there is a need to provide a source of free calcium (Ca^{2+}) to mitigate the effects of sodium and in certain cases of magnesium on soils and crops. Gypsum is the most commonly used source of calcium in this situation, and the amount required can be estimated through simple analytical tests, before being added to the soil or applied with irrigation water. Gypsum application techniques have been refined in the form of "gypsum beds", the use of which improves solubility and application efficiency and reduces the costs of application. Although this method produces significantly higher crop yields than any control, there may be constraints in many developing countries due to (i) the low quality (impurities) of available gypsum; (ii) restricted availability of gypsum in absolute terms or when actually needed; and/or (iii) increased costs due to competing demand (Qadir *et al.*, 2007).

Another low-cost source of calcium is phosphogypsum, which can be used as an amendment for managing high-magnesium waters and soils. Phosphogypsum is a major co-product of the production of fertilizer from phosphate rock. Where phosphate rock is available and mined, phosphogypsum offers additional value as it also supplies some phosphorus and sulfur needed for plant growth (Vyshpolsky *et al.*, 2008). Another calcium-supplying chemical amendment could be calcium chloride, unless chloride-sensitive crops are cultivated on the ameliorated land.

As with contaminants, crop residues, municipal waste compost, manure or biochar can also be useful in ameliorating the effects of soil and irrigation water sodicity. Organic matter left in or added to the field can improve the chemical and physical conditions of the soils irrigated with sodic wastewater by supporting the dissolution of calcite caused by enhanced CO_2 production from microbial breakdown of organic matter (Leogrande & Vitti, 2019).

However, the availability of sufficient quantities of organic material is usually limited in semi-arid climates where salinity problems are most common. Another challenge is the difficulties inherent in recommending an optimal dose of compost or other organic amendments to be applied for saline/sodic soil recovery. Several authors found that successful doses can range from 10 to 50 t/ha of different organic amendments to improve the physical, chemical and biological properties of soils affected by severe problems of salinity and/or sodicity (e.g. ECe > 10 dS/m and/or ESP > 20%). However, high rates of organic amendments (greater than 50 t/ha), even if useful to reduce soil Na content, in many cases increased soluble salt concentrations and provoked the accumulation of undesirable elements (e.g. heavy metals or organic pollutants). This last aspect becomes particularly relevant in coarse-textured soils, characterized by high permeability and low cation exchange capaciity where salts and other organic compounds can be easily leached and may consequently contaminate the subsoil and/or groundwater (Leogrande & Vitti, 2019).

5.4.9. Phytoremediation

Phytoremediation could be a good option for amending soils in developing countries as it is inexpensive and easily scalable. This technique is based on the use of living green plants to fix, adsorb or dissolve contaminants or salts. The application of phytoremediation often remains limited, however, due to the unavailability of suitable plant species, the low biomass production of alternative species and the long growing seasons required.

Phytoremediation might refer to a process internal or external to the plant, namely: the ability of plant roots to absorb particular ions for the plant to accumulate; or chemical changes in the root zone (partial pressure of carbon dioxide increase influencing the dissolution rate of calcite), resulting in enhanced levels of Ca^{2+} in the soil solution to possibly replace Na^{+} in the cation exchange complex depending on the respective available amounts (Qadir *et al.*, 2007).

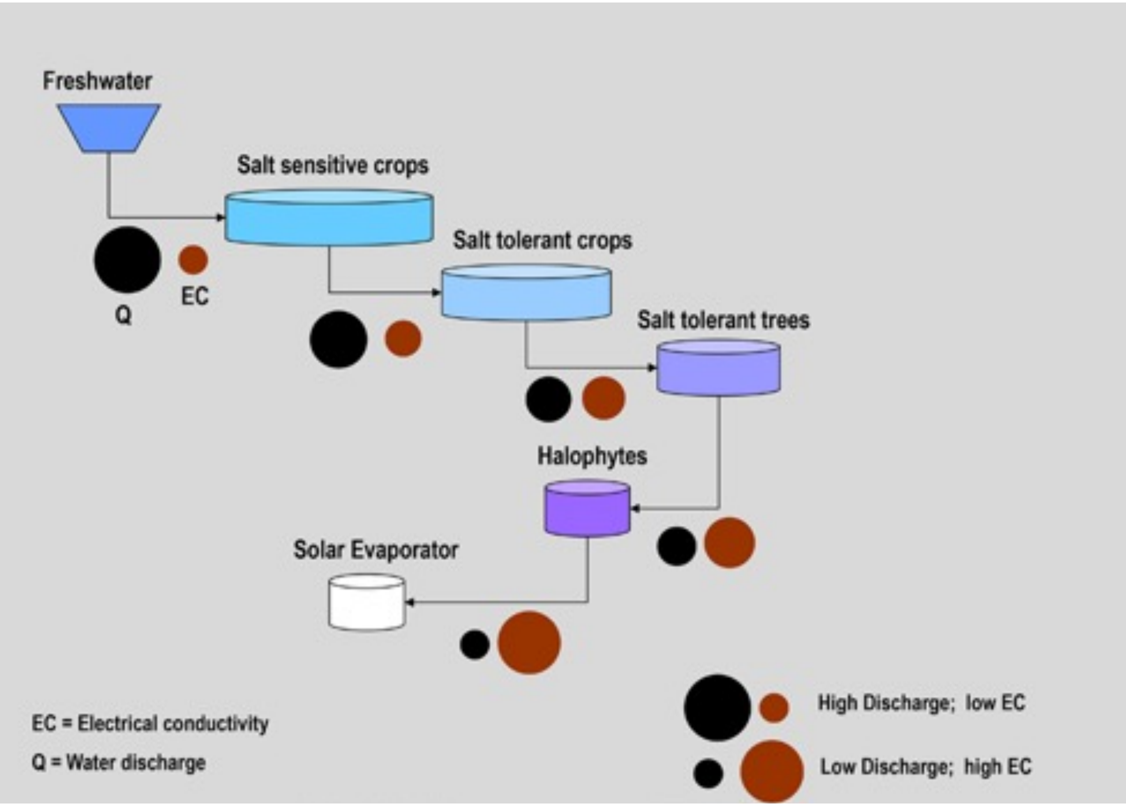
While the first option is more popular in terms of trace elements and some heavy metals (see Chapter 5), the second option can be effective when used on moderately saline sodic and sodic soils if soluble calcite and appropriate plant species are available. However, the efficiency of different plant species used in phytoremediation of sodic and saline-sodic soils has been found to be highly variable. In general, phytoremediation appears to work on moderately sodic and saline-sodic soils, provided: (i) irrigation is performed in excess of the crop water requirement to facilitate adequate leaching, and (ii) the excess irrigation was applied when the crop growth, and hence the partial pressures of carbon dioxide, were at their peak. On such soils, the performance of phytoremediation (e.g. with Para grass or Sesbania) was comparable with soil application of gypsum. On highly sodic and saline-sodic soils, use of chemical amendment is likely to outperform phytoremediation treatments (Qadir *et al.*, 2007).

5.4.10. Off-site salinity management

When setting-up drainage systems, it is essential to consider the possible impacts of the drainage waters on agricultural fields downstream as well as the environment. Thus, it is important to evaluate the suitability of the potential disposal site(s) for the drainage water and the salt it contains.

Two generic options for local management of saline drainage waters are (i) disposal to evaporation basins for regional storage, and (ii) reuse for irrigation of crops able to withstand the levels of salinity and sodicity in the drainage water and its receiving soils (Grattan *et al.*, 2014). The first option represents a missed opportunity to productively utilize saline drainage waters, and such an approach should only be considered where the productive use of these waters is deemed to be economically unsuitable (Qadir *et al.*, 2015). With the second option, the reuse of drainage water to directly irrigate downstream crops (Figure 5.8) by traditional irrigation methods is less sustainable than the original irrigation water as the drainage water contains higher concentrations of salts than the applied irrigation water. Thus, an irrigation cascade relying on drainage water, requires on all steps over-irrigation with the final plants to be likely halophytes (UN Water, 2020). Although sequential reuse is conceptually attractive, caution is advised for those estimating the rate of salt movement through the sequential system, particularly if steady-state assumptions are used (Grattan *et al.*, 2014). See also case study 4 from California in the annex.

Figure 5.8. Schematic representation of a sequential drainage water reuse system



Source: UN Water. 2020. Analytical brief on unconventional water resources. Geneva.

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