Chapter 5
Irrigation Water Quality

Mohammad Zaman, Shabbir A. Shahid, and Lee Heng

Abstract The quality of irrigation waters differs in various regions, countries and locations based on how the groundwater has been extracted and used, the rainfall intensity and subsequent aquifer recharge. The use of groundwater for agriculture in hot arid countries where rainfall is scarce leads to increase groundwater salinity and limits the selection of crops for cultivation. It is therefore important to determine the irrigation water quality. The concentration and composition of soluble salts in water determines its quality for irrigation. Four basic criteria for evaluating water quality for irrigation purposes are described, including water salinity (EC), sodium hazard (sodium adsorption ratio-SAR), residual sodium carbonates (RSC) and ion toxicity. Toxicities of boron and chlorides to plants are described. More specifically the relative tolerance levels of plants to boron is tabulated for easy understanding. The most important part of this chapter is the modification of water quality diagram of US Salinity Laboratory Staff published in the year 1954, this diagram does not present EC over 2250 µS cm^{-1}, however, most of the irrigation waters present salinity levels higher than 2250 µS cm^{-1}. Therefore, to accommodate higher water salinity levels the water classification diagram is extended to water salinity of 30,000 µS cm^{-1} allowing the users of the diagram to place EC values above 2250 µS cm^{-1}. The salinity and sodicity classes are included in this chapter to provide information for crop selection and develop salinity and sodicity management options. The procedures for water salinity reduction through blending of different waters and management of water sodicity using gypsum are described by giving examples.

Keywords Irrigation · Quality · Salinity · Sodicity · Boron · Chlorides · Toxicities · Blending · Gypsum requirement

1 Introduction

Water scarcity is seen as a major constraint to intensify agriculture in a sustainable manner as an attempt to meet the food requirements of a rapidly growing human population. The ever increasing human population, climate change due to increased emissions of greenhouse gases (GHGs), and intensification of agriculture, are putting

M. Zaman et al., *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*, https://doi.org/10.1007/978-3-319-96190-3_5

severe pressure on the world's two major non-renewable resources of soil and water, and thus pose a big challenge to produce sufficient food to meet the current food demand. The present world population of 7.3 billion people is predicted to grow to over 9 billion by 2050, with the majority of this population increase occurring in developing countries, most of which already face food shortages. A 70% increase in current agricultural productivity will be required to produce sufficient food if these human population growth predictions prove to be correct. In this context, concerted efforts are being made globally to improve the effectiveness of water which will be used for enhancing the production of irrigated crops. Additionally, efforts are also being made to improve water harvesting and water conservation in rain-fed agriculture.

The injudicious use of saline/brackish water is all too often associated with the development of soil salinity, sodicity, ion toxicity, and groundwater pollution. Because of these negative effects, it is important to have a better understanding of exactly how the quality of water influences the management of irrigated agriculture, especially in arid and semi-arid regions.

Salinity, sodicity and ion toxicity are major problems in irrigation waters. In arid areas, where rainfall does not adequately leach salts from the soil, an accumulation of salts will occur in the crop's root-zone. Thus, periodic testing of soils and waters is required to monitor any change in salt content. Sodicity, the presence of excess sodium, will result in a deterioration of the soil structure, thereby reducing water penetration into and through the soil. Toxicity refers to the critical concentration of some salts such as chloride, boron, sodium and some trace elements, above which plant growth is adversely affected by those salts.

This chapter addresses several aspects of irrigation water quality and criteria to determine water quality. It will also cover management issues and soil responses to the use of irrigation water of varying quality. The information presented in this chapter is an updated and improved version of an excerpt from an earlier irrigation water quality manual (Shahid 2004).

2 Quality of Irrigation Water

The concentration and composition of soluble salts in water will determine its quality for various purposes (human and livestock drinking, irrigation of crops, etc.). The quality of water is, thus, an important component with regard to sustainable use of water for irrigated agriculture, especially when salinity development is expected to be a problem in an irrigated agricultural area.

There are four basic criteria for evaluating water quality for irrigation purposes:

- Total content of soluble salts (salinity hazard)
- Relative proportion of sodium (Na^+) to calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions – sodium adsorption ratio (sodium hazard)

- Residual sodium carbonates (RSC) – bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) anions concentration, as it relates to Ca^{2+} plus Mg^{2+} ions.
- Excessive concentrations of elements that cause an ionic imbalance in plants or plant toxicity.

In order to achieve the first three important criteria, the following characteristics need to be determined in the irrigation waters: electrical conductivity (EC), soluble anions (CO_3^{2-}, HCO_3^-, Cl^- and SO_4^{2-}) where Cl^- and SO_4^{2-} are optional and soluble cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) where K is optional. Finally, boron level must also be measured. The pH of the irrigation water is not an acceptable criterion of water quality because the water pH tends to be buffered by the soil, and most crops can tolerate a wide pH range. A detailed description of the techniques commonly employed for the analysis of irrigation water is available (USSL Staff 1954; Bresler et al. 1982).

2.1 Salinity Hazard

Excess salt increases the osmotic pressure of the soil solution, a situation that can result in a physiological drought condition. Thus, even though the soil in the field appears to have plenty of moisture, the plants will wilt. This occurs because the plant roots are unable to take up soil-water due to its high osmotic potential. Thus, water lost from the plant shoot via transpiration cannot be replenished, and wilting occurs.

The total soluble salts (TSS) content of irrigation water is measured either by determining its electrical conductivity (EC), reported as micro Siemens per centimeter (μS cm^{-1}), or by determining the actual salt content in parts per million (ppm). Table 5.1 prescribes the guidelines for water use relative to its salt content.

Table 5.1 Salinity hazard of irrigation water (Follett and Soltanpour 2002; Bauder et al. 2011)

	Dissolved salt content	
Hazard	ppm	EC (μS cm^{-1})
None – Water for which no detrimental effects will usually be noticed.	500	750
Some – Water that may have detrimental effects on sensitive crops.	500–1000	750–1500
Moderate – Water that may have adverse effects on many crops, thus requiring careful management practices.	1000–2000	1500–3000
Severe – Water that can be used for salt tolerant plants on permeable soils with careful management practices.	2000–5000	3000–7500

2.1.1 Modified USSL Staff (1954) Water Salinity Classification

The USSL Staff (1954) water classification diagram does not present an EC over 2250 μS cm^{-1}. However, most of the water used for irrigation purposes possesses salinity levels which are higher than 2250 μS cm^{-1}. Therefore, in order to accommodate higher water salinity levels, Shahid and Mahmoudi (2014) have modified the USSL Staff (1954) water classification diagram by extending water salinity up to 30,000 μS cm^{-1} (Fig. 5.1).

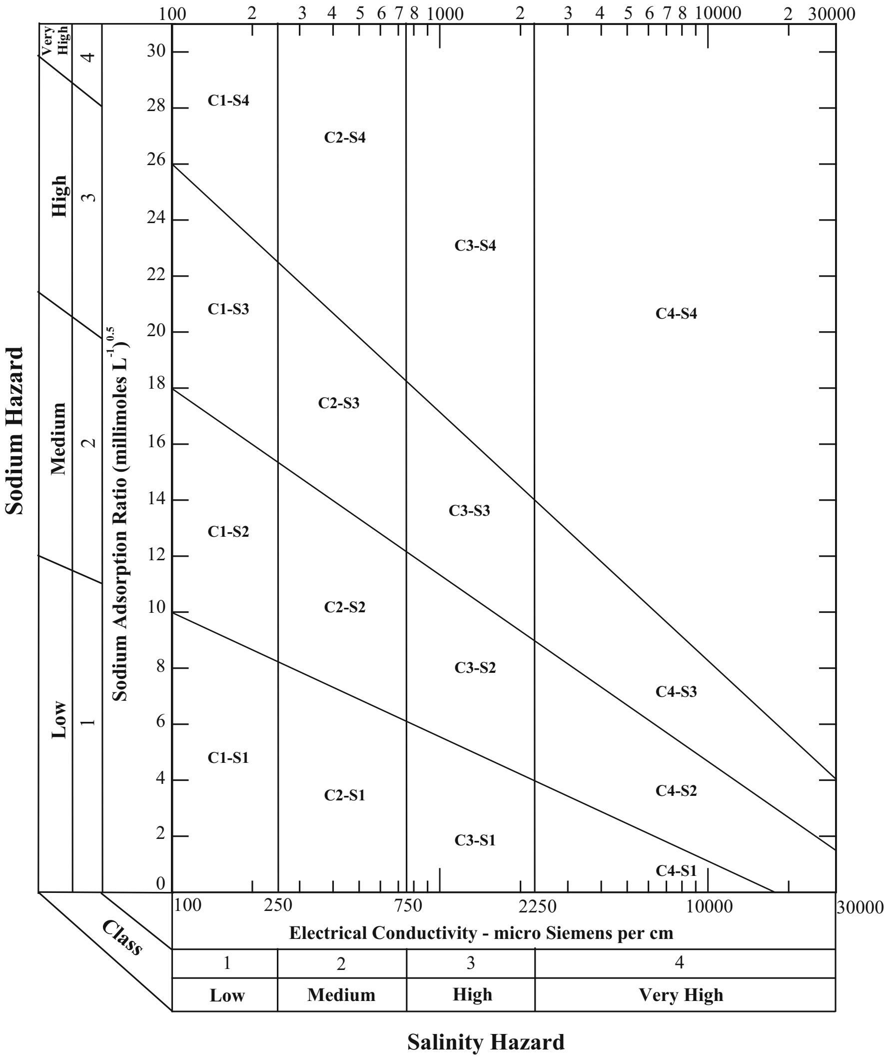

Fig. 5.1 Diagram for the classification of irrigation waters (USSL Staff 1954; modified by Shahid and Mahmoudi 2014)

2.2 Sodium Hazard

The sodium hazard of irrigation water is expressed as the 'sodium adsorption ratio (SAR)'. Although sodium contributes directly to the total salinity and may also be toxic to sensitive crops, such as fruit trees, the main problem with a high sodium concentration is its effect on the physical properties of soil (soil structure degradation). It is, thus, recommended to avoid using water with an SAR value greater than 10 (mmoles $l^{-1})^{0.5}$, if the water will be the only source of irrigation for long periods.

This recommendation holds even if the total salt content is relatively low. For example, if the soil contains an appreciable amount of gypsum, SAR value of 10 (mmoles $l^{-1})^{0.5}$ can be exceeded. The gypsum content of the soil should, thus, be determined.

Continued use of water with a high SAR value leads to a breakdown in the physical structure of the soil – a situation caused by excessive amounts of adsorbed sodium on soil colloids. This breakdown in the soil physical structure, results in the dispersion of soil clay and that causes the soil to become hard and compact when dry, and increasingly impervious to water penetration (due to dispersion and swelling) when wet. Fine textured soils, those high in clay, are especially subject to this action. When the concentration of sodium becomes excessive (in proportion to calcium plus magnesium), the soil is said to be sodic. If calcium and magnesium are the predominant cations adsorbed onto the soil exchange complex, the soil can be easily tilled and will have a readily permeable granular structure.

The permissible value of the SAR is a function of salinity. High salinity levels reduce swelling and aggregate breakdown (dispersion), thus promoting water penetration. A high proportion of sodium, however, produces the opposite effect.

Regardless of the sodium content, water with an electrical conductivity (EC) less than about 200 μS cm^{-1} causes degradation of the soil structure, promotes soil crusting and reduces water penetration. Rainfall is the prime example of low salinity water and rain water will reduce the penetration of water applied subsequently into soils. It is, thus, important that both the salinity and the sodium adsorption ratio of the applied water be considered when assessing the potential effects of water quality on water penetration into soils.

2.3 Carbonates and Bicarbonates Concentration

Waters high in carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) will tend to precipitate calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), when the soil solution becomes concentrated through evapotranspiration. This means that the SAR value will increase, and the relative proportion of sodium ions will become greater. This situation, in turn, will increase the sodium hazard of the soil-water to a level greater than indicated by the SAR value.

2.4 Specific Ion Effects (Toxic Elements)

In addition to salinity and sodium hazards, certain crops may be sensitive to the presence of moderate to high concentrations of specific ions in the irrigation waters or soil solution. Many trace elements are toxic to plants at very low concentrations. Both soil and water testing can help to discover any constituents that might be toxic. Direct toxicity to crops may result from some specific chemical elements in irrigation water, e.g. boron, chloride, and sodium are potentially toxic to plants. The actual concentration of an element in water that will cause toxic symptoms varies, depending on the crop.

When an element is added to the soil through irrigation, it may be inactivated by chemical reactions. Alternatively, it may buildup in the soil until it reaches a toxic level. An element at a given concentration in water may be immediately toxic to a crop. Or, it may require a number of years to accumulate in the soil before it becoming toxic.

2.4.1 Sodium Toxicity

Sodium toxicity can occur in the form of leaf burn, leaf scorch and dead tissues running along the outside edges of leaves. In contrast, Cl^- toxicity is often seen at the extreme leaf tip. In tree crops, a sodium concentration (in excess of 0.25–0.5%) in the leaf tissue is often considered to be a toxic level of sodium. Correct diagnoses can be made from soil, water and plant tissue analysis.

Three levels of exchangeable sodium percentage (ESP) (FAO-UNESCO 1973; Pearson 1960; Abrol 1982), which correspond to three tolerance levels, are defined as: sensitive (ESP < 15), semi-tolerant (ESP 15–40) and tolerant (ESP > 40). The crops/plants listed as sensitive include, among others, beans, maize, peas, orange, peach, mung bean, mash, lentil, gram and cowpea. Semi-tolerant plants include carrot, clover, lettuce, berseem, oat, onion, radish, rye, sorghum, spinach, tomato, and tolerant plants include alfalfa, barley, beet, Rhoades grass and Karnal (Kallar) grass.

2.4.2 Boron Toxicity

Boron is essential to the normal growth of all plants, but the amount required is low. If it exceeds a certain level of tolerance depending on the crop, then boron may cause injury. The range between deficiency and toxicity of boron for many crops is narrow.

Table 5.2 Effects of boron (B) concentration in irrigation water on crops (Follett and Soltanpour 2002; Bauder et al. 2011)

Boron concentration (ppm)	Effect on crops
< 0.5	Satisfactory for all crops
0.5–1.0	Satisfactory for most crops
1.0–2.0	Satisfactory for semi-tolerant crops
2.0–4.0	Satisfactory for tolerant crops only

In order to sustain an adequate supply of boron to the plant at least 0.02 ppm of boron in the irrigation water may be required. However, to avoid toxicity, boron levels in irrigation water should, ideally, be lower than 0.3 ppm. Higher concentrations of boron will likely require that the intended crop type must first be evaluated with respect to its boron tolerance. Although boron toxicity is not a problem in most areas, it can be an important irrigation water quality parameter. Interestingly, plants grown in soils high in lime may tolerate higher levels of boron than those grown in non-calcareous soils.

Boron is weakly adsorbed by soils. Thus, its actual root-zone concentration may not vary in direct proportion to the degree that boron sourced from the irrigation water has been concentrated in the plant during growth. Symptoms of boron injury may include characteristic leaf ‘burning’, chlorosis and necrosis, although some boron sensitive species do not develop obvious symptoms. Boron toxicity symptoms first appear on older leaves as yellowing, spotting, or drying of leaf tissues at the tips and edges. The drying and chlorosis often progresses toward the center of the leaf, between the veins as boron accumulates over time (Ayers and Westcot 1985).

Irrigation water with boron >1.0 ppm may cause toxicity in boron sensitive crops. Table 5.2 describes the effects of a range of boron concentrations in irrigation water on crops (Bauder et al. 2011). The relative tolerance of plants to boron is shown in Table 5.3.

Boron levels that have developed in the soil water (saturation extract of soils) through irrigation can have a range of effects on crop yields. Wilcox (1960) presented three classes of crops with regard to boron toxicity: tolerant (2–4 ppm), semi-tolerant (1–2 ppm), and sensitive (0.3–1 ppm). Fruit crops are among the most boron sensitive, and yields of citrus and some stone fruit species are decreased by boron even at soil solution concentrations less than 0.5 ppm.

2.4.3 Chloride Toxicity

The most common crop toxicity is caused by chlorides in irrigation water. The chloride (Cl^-) anion occurs in all waters; chlorides are soluble and leach readily to drainage water. Chlorides are necessary for plant growth, though in high

Table 5.3 Relative tolerance[a] of plants to Boron concentration (ppm) in irrigation water (cf. Ludwick et al. 1990; Ayers and Westcot 1985)

Very sensitive < 0.5 ppm	Sensitive 0.5–0.75 ppm	Less sensitive 0.75–1.0 ppm	Moderately sensitive 1.0–2.0 ppm	Moderately tolerant 2.0–4.0 ppm	Tolerant 4.0–6.0 ppm	Very tolerant > 6.0 ppm
Lemon	Avocado	Garlic	Pepper, red	Lettuce	Tomato	Cotton
Blackberry	Grapefruit	Sweet potato	Pea	Cabbage	Parsley	Asparagus
	Orange	Sunflower	Carrot	Celery	Beet, red	
	Apricot	Bean	Radish	Turnip		
	Peach	Sesame	Potato	Oats		
	Cherry	Strawberry	Cucumber	Corn		
	Plum	Bean, kidney		Clover		
	Grape	Peanut		Squash		
	Walnut			Muskmelon		
	Onion					

Adapted from 'Salt Tolerance of Plants' (Maas 1987), In: CRC Handbook of Plant Science in Agriculture

[a]Maximum concentrations tolerated in soil-water or saturation extract without yield or vegetative growth reduction. Boron tolerance varies depending upon climate, soil conditions and crop varieties. Maximum concentrations in the irrigation water are approximately equal to these values or slightly less

Table 5.4 Chloride (Cl^-) levels of irrigation waters and their effects on crops (cf. Ludwick et al. 1990; Bauder et al. 2011)

Cl^- concentration		
meq l^{-1}	ppm	Effect on crops
< 2	< 70	Generally safe for all plants
2–4	70–140	Sensitive plants usually show slight to moderate injury
4–10	141–350	Moderately tolerant plants usually show slight to substantial injury
> 10	> 350	Can cause severe problems

concentrations they can inhibit plant growth, and can be highly toxic to some plant species. Water must, thus, be analyzed for Cl^- concentration when assessing water quality. Table 5.4 shows Cl^- levels in irrigation water and the effects of Cl^- on crops. In sensitive crops, symptoms occur when Cl^- levels accumulate in leaves (0.3–1.0% on a dry weight basis). Ayers and Westcot (1985) reported that Cl^- toxicity on plants appears first at the leaf tips (which is a very common symptom for chloride toxicity), and progresses from the leaf tip back along the edges as severity of the toxic effect increases. Excessive necrosis is often accompanied by early leaf drop or even total plant defoliation.

3 Classification of Irrigation Water

Shahid and Mahmoudi (2014) have modified the widely used USSL Staff (1954) salinity and sodium classification diagram for irrigation water (Fig. 5.1). This modified diagram is based on the EC (expressed in micro Siemens per cm – μS cm $^{-1}$) and the sodium adsorption ratio (SAR).

How to Use the Diagram?
The SAR as shown on y-axis (Fig. 5.1) can be calculated by using the following formula:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{1}{2}\left(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}\right)}}$$

Where, the concentrations of Na^{+}, Ca^{2+} and Mg^{2+} are expressed as milli equivalents per liter (meq l^{-1}). The values of the electrical conductivity given on the x-axis are expressed in micro Siemens per cm (μS cm^{-1}). The position of the SAR and EC points determines the quality class assigned to the water.

4 Analysis of Irrigation Water

4.1 Chemical Analyses

The ultimate in water quality data for appraisal of salinity and sodicity includes complete analyses for all major cations and anions for both irrigation and drainage waters. Major cations normally include Na^{+}, K^{+}, Ca^{2+} and Mg^{2+}. Major anions normally include CO_3^{2-}, HCO_3^{-}, Cl^{-} and also SO_4^{2-} (though see discussion below with regard to sulfate anion measurement).

When complete analyses are provided, it is possible to apply some simple tests for data consistency. For high quality water analysis, the sum of the cations in meq l^{-1} should be approximately equal to the sum of anions in meq l^{-1}. If the values are exactly equal, however, for several water samples, this suggests that some constituents have been estimated by ‘difference’. For example, recent analyses of sulfate have commonly been determined by difference because of the general unavailability of a rapid and convenient analytical procedure for measuring sulfate (Bresler et al. 1982). The SO_4^{2-} estimation is based on the difference between total soluble cations and the sum of CO_3^{2-}, HCO_3^{-}, and Cl^{-}. In fact, sulfate is not a water constituent used to measure or determine either of SAR or Residual Sodium Carbonates (RSC). Thus, sulfate measurement currently has no assigned role in water quality assessment.

The data from above measurements are, thus, used to calculate the SAR in order to assess the sodicity hazard of the irrigation water, e.g. by use of Fig. 5.1 to obtain the water's sodicity (S) class. The EC, expressed in μS cm^{-1}, will then be used to obtain the conductivity (C) class of salinity. In addition, Residual Sodium Carbonate (RSC) can also be measured. These measurements are briefly described below.

4.1.1 EC and Total Salt Concentration

The most important water quality parameter from the standpoint of salinity is the total concentration of dissolved salts. It is different from 'total dissolved solids (TDS)', a term which carries some ambiguity. The measurement of TDS is much more tedious than measuring the EC – which is the preferred measure of salinity (Bresler et al. 1982). A simple meter is used to measure the electrical conductivity (EC) of both irrigation and drainage waters. Total salt concentration can then be obtained by using the following relationship for water having EC values between 0.1 and 10 milli Siemens per cm (mS m^{-1}) or dS m^{-1} (Bresler et al. 1982):

$$\text{Total cations or anions}\ \left(\text{meq l}^{-1}\right) = 10 \times \text{EC}\ \left(\text{mS cm}^{-1}\text{or dS m}^{-1}\right)$$

Thus, once the concentrations of total cations or anions are known, the sum of cations or anions represents concentration of total salts contained within any solution.

4.1.2 Sodium Adsorption Ratio (SAR)

The tendency of salt solution to produce excessive exchangeable sodium in a soil must also be considered. A useful index for predicting this tendency is the Sodium Adsorption Ratio (SAR).

An SAR less than 8 (mmoles $l^{-1})^{0.5}$ is considered to be a 'low sodium' water class, i.e. the use of the irrigation water with SAR less than 8 is rated as being safe with regard to causing sodicity. That said, the prolonged use of class 8 SAR water for irrigation, when water drainage and leaching is restricted, may cause soils to develop sodicity. The detrimental effect of SAR also depends on the EC value, and in Pakistan an SAR of 10 is considered safe level (Kinje 1993).

Adjusted SAR

The significance of SAR_{adj} is that under field conditions, and in normal conditions of irrigation management, the exchangeable sodium percentage (ESP) value in top soil is very nearly equal to the adjusted SAR, where pHc is calculated as the pH used in the Langelier Index of the irrigation water. Ayers and Westcot (1985) presented the term adjusted SAR (SAR_{adj}) as:

$$SAR_{adj} = SAR_{IW}[1 + (8.4 - pHc)]$$

The Langelier index is based on calculation of the pH which given water would achieve when in equilibrium with solid-phase calcium carbonates at average CO_2 values. This pH, when compared to the initial pH of the water, can be used to predict whether $CaCO_3$ should precipitate from or be dissolved by the waters as it passes through calcareous soil (Balba 1995). The pHc is the theoretical pH that water could have in equilibrium with $CaCO_3$.

4.1.3 Residual Sodium Carbonates (RSC)

There is another approach which is empirical in nature (Eaton 1950). It has been widely used to predict the additional sodium hazard which is associated with $CaCO_3$ and $MgCO_3$ precipitation, and involves a calculation of the residual sodium carbonates (RSC). This approach is based on the equation:

$$RSC\left(meq\ l^{-1}\right) = \left(CO_3^{2-} + HCO_3^{-}\right) - \left(Ca^{2+} + Mg^{2+}\right)$$

Where, all the concentrations are in meq l^{-1}. The ranges of RSC in meq l^{-1} with respect to water suitability for irrigation are shown in Table 5.5.

5 Conductivity Classes (USSL Staff 1954)

There are four salinity classes, low, medium, high and very high, as presented in Table 5.6.

5.1 Low Salinity Water (Salinity Class C1)

It can be used for irrigation of most crops on most soils with little likelihood that soil salinity will develop. Some leaching will be required for salinity Class C1 water, but

Table 5.5 Residual sodium carbonates (RSC) and suitability of water for irrigation (Eaton 1950; Wilcox et al. 1954)

RSC (meq l^{-1})	Suitability of water for irrigation
< 1.25	Safe
1.25–2.50	Marginal
> 2.5	Unsuitable

Table 5.6 Salinity classes of irrigation waters (USSL Staff 1954)

Salinity of irrigation water – EC (μS cm^{-1})	Salinity class	Salinity hazard
100–250	C1	Low
250–750	C2	Medium
750–2250	C3	High
> 2250	C4	Very high

this occurs under normal irrigation practices, except for soils with extremely low permeability.

5.2 *Medium Salinity Water (Salinity Class C2)*

It can be used if a moderate amount of leaching can occur. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

5.3 *High Salinity Water (Salinity Class C3)*

It cannot be used on soils which possess restricted drainage and, thus, poor leaching abilities. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should always be selected.

5.4 *Very High Salinity Water (Salinity Class C4)*

It is not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances. Here, the soils must be permeable, drainage must be adequate to good and irrigation water must be applied in excess in order to provide considerable leaching. Only very salt tolerant crops should be selected.

6 Sodicity Classes (USSL Staff 1954)

The classification of irrigation waters with respect to sodium adsorption ratio (SAR) is based primarily on the effects which exchangeable sodium accumulation has on the physical conditions of the soil. However, it should be kept in mind that sodium sensitive plants may still suffer injury (as a result of sodium accumulation in plant tissues) even when exchangeable sodium values in soil-water are too low to bring about a deterioration of the physical condition of the soil.

6.1 Low Sodium Water (Sodicity Class S1)

It can be used for irrigation on almost all soils with little danger of the soil developing harmful levels of exchangeable sodium. However, sodium sensitive crops such as stone fruit trees and avocados may accumulate injurious concentrations of sodium.

6.2 Medium Sodium Water (Sodicity Class S2)

It will present an appreciable sodium hazard in fine textured soils which have high cation exchange capacity, especially under low leaching conditions, unless gypsum is present in the soil. Sodicity class S2 water may be used in coarse textured or organic soils with good permeability.

6.3 High Sodium Water (Sodicity Class S3)

It may produce harmful levels of exchangeable sodium in most soils. Its use will require special soil management methods, good drainage, a high leaching ability and high organic matter conditions. Gypsiferous soils, however, may not develop harmful levels of exchangeable sodium from such waters. Management methods may require use of chemical amendments which encourage the replacement of exchangeable sodium. That said, use of those amendments may not be feasible with waters of very high salinity.

6.4 Very High Sodium Water (Sodicity Class S4)

It is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity. Specifically, where the soil water solution is rich in calcium or the use of gypsum or other soil amendments may make the use of sodicity class S4 irrigation water feasible. Irrigation water sodicity classes and their hazards are given in Table 5.7.

Table 5.7 Sodicity classes of irrigation water (USSL Staff 1954)

SAR of irrigation water (mmoles $l^{-1})^{0.5}$	Sodicity class	Sodicity hazard
< 10	S1	Low
10–18	S2	Medium
18–26	S3	High
> 26	S4	Very high

Sometimes the irrigation water may dissolve sufficient calcium from calcareous soils to decrease the sodium hazard appreciably, and this should be taken into account using salinity class C1 – sodicity class S3 and salinity class C1 – sodicity class S4 irrigation waters. For calcareous soils with high pH values, or for non-calcareous soils, the sodium status of irrigation water in salinity class C1 – sodicity class S3, salinity class C1 – sodicity class S4, and salinity class C2 – sodicity class S4 may be improved by the addition of gypsum through lining of irrigation channels with gypsum stones or the sodium hazard may be countered by applying gypsum to the soil periodically. This is especially applicable when salinity class C2 – sodicity class S3 and salinity class C3 – sodicity class S2 irrigation water is used.

7 Improvement of Irrigation Water Quality

There are a number of ways to improve water quality, with regard to salinity and sodicity hazards, prior to using for irrigation purposes. Most commonly used practices are described below.

7.1 Blending Water

The saline/brackish water quality can be improved if an alternate source of good quality water is available. The desired water salinity level, depending upon the crop to be irrigated, can be derived by a standard calculation procedure.

Example
A blend is made with 50% fresh water (EC 0.25 dS m^{-1}) with 50% brackish water (EC 3.9 dS m^{-1}). The resulting EC of the blended water would be:

$$\begin{aligned}&\text{EC(blended water)} = (\text{EC of fresh water} \times \text{mixing ratio}) +\\&(\text{EC of brackish water} \times \text{mixing ratio}) = (0.25 \times 0.50) + (3.90 \times 0.50)\\&= 0.125 + 1.95 = 2.075 \text{dS m}^{-1}\end{aligned}$$

7.2 Blending Water to Achieve a Desired Salinity

The desired water salinity can be achieved (by mixing two waters of known salinity) to irrigate a specific crop based on the threshold salinity. In this case, it is necessary to know what ratio of the two waters will be used to achieve the desired salinity.

Example
A blend is to be made of two waters, fresh (0.25 dS m^{-1}) with brackish (20 dS m^{-1}). Thus, we need to know 'in what ratio these two waters are to be mixed' to achieve a desired resultant water salinity of 8 dS m^{-1}.

Let us assume that we need to develop a final volume of 2 liters of the resultant water with a salinity of 8 dS m^{-1}.

$$\text{A standard formula can be used : C1V1} = \text{C2V2}$$

Where,

C1 = 20 dS m^{-1}
V1 = unknown volume of the brackish water
C2 = 7.75 dS m^{-1} or desired water salinity (8–0.25 = 7.75)
V2 = 2 liters or 2000 ml of desired final volume

Using the formula,

$$\text{C1V1} = \text{C2V2}$$
$$20 \times \text{V1} = 7.75 \times 2000\ \text{ml}$$
$$\text{V1} = (7.75 \times 2000\ \text{ml})/20 = 775\ \text{ml}$$

Thus, 775 ml of the brackish water will be required to raise EC of the fresh water from 0.25 to 8 dS m^{-1}. The resulting blending ratio will be (1:2.58, i.e. the ratio of brackish water added to fresh water).

8 Water Sodicity Mitigation

Water sodicity can be mitigated through the judicious use of calcium-containing amendments such as gypsum ($CaSO_4.2H_2O$). Relative to other amendments, gypsum is cheap and easy to handle, and by far the most suitable amendment to bring down irrigation water sodicity (the ratio of sodium to calcium + magnesium). The quantity of gypsum needed for adding to irrigation water depends upon the quality of water (RSC and SAR levels) and the quantity of water required for irrigation during the growing season of the crop.

8.1 Gypsum Requirement Using the Residual Sodium Carbonates (RSC) Concept

Example 1
Irrigation water has an RSC 8.5 meq l^{-1} and it needs to be reduced to 2.5 meq l^{-1}. The water required for irrigation is 800 mm per hectare for the complete growing period of the sorghum crop. How much gypsum will be required for adding to the water that is needed to irrigate one hectare, that water having the desired RSC of 2.5 meq l^{-1}?

- 1equivalent per liter of Na^+ will require 1 equivalent per liter of Ca^{2+} which is equal to 86.06 grams of gypsum per liter of solution
- Therefore, 1 meq l^{-1} of Na^+ will require 1 meq l^{-1} of Ca^{2+} which is equal to 0.08606 grams of gypsum per liter of solution
- Thus, 6 meq l^{-1} of Na^+ will require 6 meq l^{-1} of Ca^{2+} which is equal to 0.51636 grams of gypsum per liter of solution
- Total water required to irrigate one hectare of sorghum crop = 800 mm × 10 = 8000 M^3 (Where, 1 mm of water in 1 hectare is equal to 10 M^3)
- 8000 M^3 of water is equal to 8000 × 1000 = 8,000,000 liters of irrigation water across the entire growing season
- Total gypsum requirement = 8,000,000 × 0.51636 = 4.13 metric tons of 100% pure gypsum
- If the gypsum purity is 70%, then 5.90 tons of gypsum will be required to neutralize 6 meq l^{-1} of Na^+ in 8 million liters of irrigation water

To amend the water RSC, it is best to place the gypsum in the water channels. Then, the flowing irrigation water will dissolve the gypsum, reducing the Na^+:(Ca^{2+} + Mg^{2+}) ratio prior to entering the agricultural field.

Example 2
A farmer is using saline water with an EC of 3 dS m^{-1} for irrigating a sorghum crop. He is facing problems with irrigation water infiltrating into his field soil and has decided to use gypsum. A laboratory analysis has shown that he needs an increase of 5 meq l^{-1} of calcium in the irrigation water. How much gypsum would be required to irrigate one-hectare area with a crop water requirement for the entire growing period as 800 mm?

- EC of water = 3 dS m^{-1}
- Cropped area = 1 ha
- Gypsum purity = 70%

Total water requirement = 800 mm × 10 = 8000 M^3 = 8,000,000 liters.

- 1 meq l^{-1} of Na^+ will require 1 meq l^{-1} of Ca^{2+} which is equal to 0.08606 grams of gypsum per liter of solution.

Table 5.8 The chemical analyses of well water

Water	EC dS m^{-1}	Ion concentrations (meq l^{-1})								SAR (mmoles $l^{-1})^{0.5}$
		Na^+	K^+	Ca^{2+}	Mg^{2+}	CO_3^-	HCO_3^{2-}	Cl^-	SO_4^{2-}	
Well water	4	25	2	7	6	0	0	20	20	9.805
Resultant water	1	6.25	0.5	1.75	1.5	0	0	5	5	4.903

- 5 meq l^{-1} of Na^+ will require 5 meq l^{-1} of Ca^{2+} which is equal to 0.4303 grams of gypsum per liter of solution.
- Total water required to irrigate one hectare of sorghum crop = 800 mm or 8000 M^3
- 8000 M^3 of water is equal to 8000 × 1000 = 8,000,000 liters.
- Total gypsum requirement = 8,000,000 × 0.4303 = 3.44 metric tons of 100% pure gypsum
- If gypsum purity is 70%, then 4.92 metric tons of gypsum will be required to neutralize 5 meq l^{-1} of Na^+ in 8 million liters of water.

Thus, 4.91 tons of gypsum of about 10 mesh size (2 mm) will be required for the irrigation water application across the entire growing season.

8.2 *Determining the SAR of Blended Water to Be Used for Irrigation*

Example 1
Water from a well has the composition (Table 5.8) and this well water will be diluted in a1:3 ratio with desalinated water. What will be the resultant SAR of the blended water? Assume that the desalinated water has negligible EC and Na^+, Ca^{2+}, Mg^{2+} contents.

After blending with a ratio of 1:3 (well water:desalinated water), the SAR of the resultant blended water is reduced to half. However, it should be noted that the EC is reduced to one-quarter of the well water. Therefore, care should be taken to understand such conversions.

Example 2
A canal water (EC = 1.0 dS m^{-1}) source is available to irrigate a crop. However, the volume of water is insufficient. The farmer has decided to blend well water with a ratio of 20% well water (5 dS m^{-1}) with 80% of canal water (1 dS m^{-1}). What will be the SAR of the resultant water? Following are the water analyses of canal, well and blend waters (Table 5.9).

Table 5.9 The chemical analyses of the canal, well and the resultant (blended) waters

Water	EC (dS m^{-1})	Ion concentrations (meq l^{-1})								SAR (mmoles $l^{-1})^{0.5}$
		Na^+	K^+	Ca^{2+}	Mg^{2+}	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	
Canal water	1.0	6.25	0.5	1.75	1.5	0	0	5.0	5.0	4.903
Well water	5.0	32.0	2.5	9.0	8.0	0	0	25.0	25.0	10.98
Blended water	1.8	11.4	0.9	3.2	2.8	0	0	9.0	9.0	6.58

Composition of blended water:

EC	= (1.0 × 0.8) + (5.0 × 0.20)	= 0.8 + 1.0	= 1.8 dS m^{-1}
Ca^{2+}	= (1.75 × 0.8) + (9.0 × 0.2)	= 1.4 + 1.8	= 3.2 meq l^{-1}
Mg^{2+}	= (1.5 × 0.8) + (8 × 0.2)	= 1.2 + 1.6	= 2.8 meq l^{-1}
Na^+	= (6.25 × 0.8) + (32.0 × 0.2)	= 5.0 + 6.4	= 11.4 meq l^{-1}
K^+	= (0.5 × 0.80) + (2.5 × 0.20)	= 0.4 + 0.5	= 0.9 meq l^{-1}
Cl^-	= (5.0 × 0.80) + (25.0 × 0.2)	= 4.0 + 5.0	= 9 meq l^{-1}
SO_4^{2-}	= (5.0 × 0.80) + (25.0 × 0.2)	= 4.0 + 5.0	= 9 meq l^{-1}
SAR	= $Na^+/[(Ca^{2+} + Mg^{2+})/2]^{0.5}$	= $11.4/[(3.2 + 2.8)/2]^{0.5}$	= 6.58 (mmoles $l^{-1})^{0.5}$

Blending should, thus, be done with an objective. If the objective is to reduce SAR, but with the condition that adequate canal/fresh water is not available to irrigate the crop, then blending is desirable. If, however, a sufficient volume of canal water is available, then simply replacing well water with the canal's fresh water for irrigation is a good option. Other farm conditions must also be considered, e.g. infiltration problems due to high SAR. Addition of gypsum as described above should also be considered.

9 Cyclic Use of Water

Where fresh water is also available, but not sufficient to offset the full water requirement of the crop, there is always a need to find alternate source of water, which is usually the groundwater and is often saline or saline-sodic. Under such conditions, it is recommended to use fresh water at early stage of crop when the young seedlings are not able to tolerate high salinity level. Once the seedlings are well established, at this stage there are two options to use these waters: (i) to use saline water for some time and then leach the salts with fresh water, and (ii) use saline water first and then use fresh water (cyclic use) to irrigate the crop. This way both fresh and saline waters are used.

References

Abrol IP (1982) Technology of chemical, physical and biological amelioration of deteriorated soils. Panel of experts meeting on amelioration and development of deteriorated soils in Egypt 2–6 May 1982, Cairo, pp 1–6

Ayers RS, Westcot DW (1985) Water quality for agriculture. FAO irrigation and drainage paper 29 rev 1. Food and agriculture organization of the United Nations, Rome, Italy, 174 pp
Balba AM (1995) Management of problem soils in arid ecosystems. CRC/Lewis Publishers, Boca Raton, 250 pp
Bauder TA, Waskom RM, Sutherland PL, Davis JG (2011) Irrigation water quality criteria. Colorado State University Extension Publication, Crop series/irrigation. Fact sheet no. 0.506, 4 pp
Bresler E, McNeal BL, Carter DL (1982) Saline and sodic soils. Principles-dynamics-modeling. Advanced Series in Agricultural Sciences 10. Springer-Verlag, Berlin/Heidelberg/New York, 236 pp
Eaton FM (1950) Significance of carbonates in irrigation waters. Soil Sci 69:123–133
FAO/UNESCO (1973) Irrigation, drainage and salinity. An International source book. Unesco/FAO, Hutchinson & Co (Publishers) Ltd, London, 510 pp
Follett RH, Soltanpour PN (2002) Irrigation water quality criteria. Colorado State University Publication No. 0.506
Kinje JW (1993) Environmentally sound water management: Irrigation and the environment. Proceedings of the International Symposium on Environmental Assessment and Management of Irrigation and Drainage Projects for Sustained Agricultural Growth, 24–28 October 1993, Lahore, Pakistan, pp 14–44
Ludwick AE, Campbell KB, Johnson RD, McClain LJ, Millaway RM, Purcell SL, Phillips IL, Rush DW, Waters JA (eds) (1990) Water and plant growth. In: Western Fertilizer Handbook – horticulture Edition, Interstate Publishers Inc, Illinois, pp 15–43
Maas EV (1987) Salt tolerance of plants. In: Christie BR (ed) Handbook of plant science in agriculture. CRC Press, Boca Raton, pp 57–75
Pearson GA (1960) Tolerance of crops to exchangeable sodium. USDA Information Bulletin No 216, 4 pp
Shahid SA (2004) Irrigation water quality manual. ERWDA Soils Bulletin No 2, 29 pp
Shahid SA, Mahmoudi H (2014) National strategy to improve plant and animal production in the United Arab Emirates. Soil and water resources Annexes
USSL Staff (1954) Diagnosis and improvement of saline and alkali soils. USDA Handbook No 60. Washington DC, USA 160 pp
Wilcox LV (1960) Boron injury to plants. USDA Bulletin No 211, 7 pp
Wilcox LV, Blair GY, Bower CA (1954) Effect of bicarbonate on suitability of water for irrigation. Soil Sci 77:259–266