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In irrigated agriculture, the hazard of salt water is a constant threat. Poor-quality irrigation water is generally more concerning as the climate changes from humid to arid conditions. Salinity is not normally a threat where precipitation is a major source of salt-free water for crop production. Water entering the soil which is not stored or consumed by evapotranspiration moves through the crop root zone, eventually reaching the water table. This percolating process flushes (leaches) soluble salts. Less rainfall means smaller amounts of precipitation available to leach salts. In Nebraska, rainfall decreases from 30 inches in the east to 15 inches in the west. Therefore, salinity is more likely a problem in the western portion of the state. If the amount of water leaching through the soil is too low to remove salts, the soil's salt content increases and crop yields may decrease. In such situations, the soil is said to be salt-affected.

The three major types of salt problems are salinity, sodicity and toxicity. Salinity refers to the total concentration of dissolved salts in the soil or water. Salinity causes reduced crop growth and yield loss because the plant must redirect energy from growing to extracting pure water from the saline water in its root zone. This additional energy expenditure is called osmotic stress. It is similar in impact to drought stress. Sodicity, the presence of excess sodium, deteriorates soil structure and reduces water penetration into and through the soil. Like drought and salinity, excess proportions of sodium, in comparison to calcium and magnesium, reduce water availability to the crop. The term, sodicity, has replaced the term "alkali" when referring to the effects of excess sodium in the soil. Toxicity refers to specific salt constituents, such as chloride, boron, sodium and some trace elements which are toxic to certain crops at relatively low concentrations. Trees and other woody crops are frequently sensitive to these potentially toxic elements.

Origins of Salts

Salt-affected soils and waters are part of the ongoing geochemical processes. Soluble salts originate from the disintegration (weathering) of minerals and rocks. Normally, salts move from weathering sites into the groundwater system, move into streams and then into oceans. The present day location of salt is primarily determined by the amount of water which has passed through each point of the hydrologic cycle. If rainfall is high, as in humid climates, most salts have been transported into oceans or to deep groundwater systems. In arid environments where rainfall is limited, salts are frequently present in the soil. Society can alter these geological processes and create salinity hazards in many ways, including irrigation, mining, processing plants and other activities.

Salts may accumulate in landscapes with particular relief and geologic conditions. Because salts move with water, saline conditions are linked to lowlands or depressions where water naturally drains and accumulates. This situation is often associated with restricted internal soil drainage which leads to high water table conditions. Another major factor is whether the landscape was previously submerged under saline or fresh water. Examples of low, saline areas in Nebraska are the saline/sodic wetlands like Facus Springs just east of Chimney Rock, Kiowa Basin in western Scotts Bluff County and saline wetlands like those near Lincoln.

On irrigated lands, irrigation water is the primary source of salts. When new lands are brought under irrigation or if salinity management is inadequate, soils prone to salt accumulation may be saline, sodic or both. Under these conditions, economical crop production is not feasible without reclamation. The reclamation process, whether it be for saline, sodic or toxic soils, requires large amounts of non-saline water to leach the salts from the intended crop root zone. Frequently, man-made drainage systems must be installed to aid natural drainage in removing the extra water required to leach salts from the soil.

Quantifying Salinity Hazards

Salinity, sodicity and toxicity must be quantified for proper diagnosis and management. Because saline hazards are normally caused by saline irrigation water or shallow saline groundwater, sampling these waters is particularly important. When saline conditions are present or suspected, soil samples from throughout the root zone are critical to determine what management practices are required to minimize or eliminate the salinity hazard.

When sampling water, 10 to 20 ounces (300 to 600 ml) are usually sufficient for a number of laboratory analyses. Samples should be labeled to provide sampling date and location, refrigerated at about 40°F (4°C) and analyzed as soon as possible. Well samples should be collected after pumping for several hours.

Selecting a soil sampling strategy to determine water quality depends on both your objectives and the potential variance among samples. If salinity is already a major problem, sample locations can be selected by the visual appearance of soils or plants. Soil samples should be taken as 1 foot increments through the crop root zone. Soil samples from 0 to 1, 1 to 2, 2 to 3 and 3 to 4 foot depths are typical. Take samples from several locations where salinity is suspected or plants are growing poorly. To reduce the cost of analysis it is possible to mix samples from different locations. For comparison, take a similar set of samples from areas where plant growth is excellent. If salinity is not yet a serious problem, symptoms are probably not visible. In this case, a systemic sampling of the field should be completed and compositing of samples should be minimized. A soil sample of about 1 pound (0.5 kg) is needed for each soil depth of interest. Samples should be air-dried, passed through a 2-mm sieve, thoroughly mixed and placed in durable, labeled containers. In addition to sampling date and location, indicate the soil depth on the label.

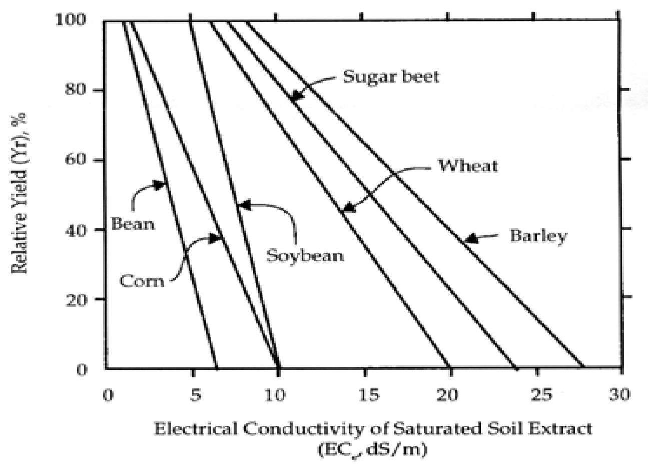
Salinity is quantified using various units of measure. Salt concentration (C) from laboratory analyses is frequently labeled as total dissolved solids (TDS) and reported as milligrams of salt per liter of water (mg/L) or as grams of salt per cubic meter of water (g/m3). The units of mg/L or g/m^3 are equivalent numerically and equal to parts per million (ppm). Salinity, the total salt concentration, in units of mg/L, g/m^3, or ppm is the sum of the concentrations of each salt constituent. An easier and quicker method of quantifying salinity is to measure the electrical conductivity of irrigation water (EC_i) or water extracted from a saturated soil sample (EC_e). Electrical conductivity is normally reported in units of millimhos per centimeter (mmhos/cm) or deciSiemens per meter (dS/m), which are numerically the same. The relationship between salt concentration (C) and electrical conductivity (EC) is approximately C = 640 EC. The approximate relationship between the electrical conductivity of irrigation water (EC_i) and soil salinity is $EC_e = 1.5\ EC_i$, if about 15 percent of the applied water is draining from the crop root zone.

Measuring the salinity level of water in soil is rather difficult. First of all, in the field, the water content of the soil fluctuates from extremely dry to saturated. To overcome this problem, soil samples are saturated in the laboratory by adding distilled water as the soil paste is stirred. A suction filter then obtains a sufficient amount of water to measure electrical conductivity. The advantage of the saturation extract method of measuring salinity is that the saturation percentage of soil is directly related to the range of water contents found in the field and can be used to appraise the effect of soil salinity on crop yield.

Salinity

Salt mixtures normally found in agriculture include chloride, sulfate and bicarbonate compounds of sodium, calcium and magnesium. As shown above, salts in the soil water become more concentrated as evaporation and transpiration occur leaving all the salts behind.

Figure 1. Impact of soil salinity on the yield of some Nebraska crops.



Crop Salt Tolerance. Crops differ greatly in their response to salinity. The most distinct signs of injury from salinity is reduced crop growth and loss of yield. Crops can tolerate salinity up to certain levels without a measurable loss in yield (this is called the salinity threshold). The more salt tolerant the crop, the higher the threshold level. At salinity levels greater than the threshold, crop yield reduces linearly as salinity increases. This relationship between soil salinity and crop yield for several crops important in Nebraska is illustrated in *Figure 1*. In equation form, this relationship is:

Equation 1: $Y_r = 100 - s(EC_e - t)$

where Y_r is crop yield relative to the same conditions without salinity, *t* is the threshold salinity, *s* is the linear rate of yield loss with increasing salinity beyond the threshold (slope of the line) and EC_e represents the average root zone salinity measured as the electrical conductivity of a saturated soil extract.

Crops differ greatly in their values of both threshold (t) and slope (s). Values of threshold and slope for many Nebraska crops are presented in *Table I*. To calculate the yield of a crop, insert the appropriate values for t and s from *Table I* and the EC_e of the crop root zone into equation 1. For example, if the soil has an average EC_e of 3.7 dS/m and corn was grown for grain, the crop yield relative to nonsaline conditions would be Y_r = 100 - 12 (3.7 - 1.7). From this, we can calculate the expected crop yield would be 76 percent.

Table I. Threshold (t) and slope (s) values to calculate crop yield as a function of soil salinity for various crops.

Crop	*Threshold (t) dS/m*	*Slope (s) % / dS/m*
Alfalfa	2.0	7.3
Barley for grain	8.0	5.0
Bean, dry edible	1.0	19.0
Clover	1.5	12.0
Corn for grain	1.7	12.0
Corn for silage	1.8	7.4
Fescue, tall	3.9	5.3
Potato	1.7	12.0
Sorghum for grain	6.8	16.0
Soybean	5.0	20.0
Sugar beet	7.0	5.9
Tomato	2.5	9.9
Wheat for grain	6.0	7.1

The impact of salinity on corn yield is shown in *Figure 2*. The upper row of corn ears were produced with nonsaline irrigation waters. Irrigation waters of 8 dS/m (about 5,100 ppm) were applied to grow ears in the lower row. Salinity not only reduced the size of the ears but also reduced the number of ears. The total yield with irrigation water having an EC_i of 8 dS/m was less than half of that without salt.

Figure 2. Typical ears of corn from a salt tolerance experiment. Ears in the top row are from nonsaline points; those in the lower row recieved irrigation water having an electrical conductivity of 8 dS/m.

Factors Modifying Crop Salt Tolerance. Sometimes crops are exposed to conditions differing significantly from those for which the salt tolerant data were obtained. Several factors, including soil, crop and environmental conditions interact with salinity to cause a different yield response.

Variety or hybrid and stage of growth are crop factors which may modify the salinity response. Typically, crop breeding attempts to emphasize high productivity rather than salinity tolerance. Consequently, differences in salt tolerance between varieties or hybrids are not common among field and garden crops, with the exception of soybeans, where varieties can show large differences in salt tolerance.

Stage of plant growth is another factor in crop salt tolerance. While salinity may delay seed germination and seedling emergence, most crops are capable of germinating at higher salinity levels than they can tolerate during later stages of growth. Corn, for example, will germinate at a salinity level twice as high as the threshold for grain yield. Typically, crops are most sensitive as seedlings and tolerance increases as plants mature.

In Nebraska, rainfall is the most critical environmental factor. Rainfall before and during the irrigation season makes it possible to use more saline irrigation water because salts will dilute in the root zone and leaching is increased. To calculate the average water salinity, consider both rainfall and irrigation water. The average salinity of the applied water (Ca) can be calculated from:

Equation 2: $[C_a = C_r\ D_r + C_i\ D_i] \div [D_r + D_i]$

The variable C can be expressed as concentration (mg/L or ppm) or electrical conductivity (dS/m or mmhos/cm). D is depth (inches). The subscripts a, r and i indicate average applied, rain and irrigation water, respectively. For example, in western Nebraska, if 12 inches of rainfall and 20 inches of irrigation water with a salt content of 2,000 mg/L were applied during the growing season, the resulting average salt concentration of the applied water would be:

$$C_a = [(0 \text{ x } 12 \text{ in.}) + (2{,}000 \text{ mg/L x } 20 \text{ in.})] \div [12 \text{ in.} + 20 \text{ in.}]$$

$$C_a = 1{,}250 \text{ mg/L}$$

In eastern Nebraska, if rainfall totaled 24 inches and 8 inches of the same irrigation water was used, the resulting average salt concentration of the applied water would be:

$$C_a = [(0 \text{ x } 24 \text{ in.}) + (2{,}000 \text{ mg/L x } 8 \text{ in.})] \div [24 \text{ in.} + 8 \text{ in.}]$$

$$C_a = 500 \text{ mg/L}$$

If corn was grown under these two conditions would soil salinity cause a loss of yield? To convert these salt concentrations to electrical conductivity, divide C_a by 640. This results in an EC_a of 2.0 dS/m in west Nebraska and 0.8 dS/m for the east example. These values can be converted to soil salinity, assuming a leaching fraction of 0.15, by multiplying EC_a by 1.5. Soil salinity, expressed as EC_e, is 3.0 dS/m in the first (west) example and 1.2 dS/m for the second. From Table I, the threshold value (upper limit with no yield loss) for corn grain is 1.7 dS/m. From this information, it can be determined the irrigation water for the east example will not cause a loss of yield, For the west example, if leaching was 0.15, the corn yield would be 84 percent (Y_r = 100 - 12 (3.0 - 1.7)), using equation 1.

Sodicity

When the concentration of sodium becomes excessive in proportion to calcium plus magnesium, the soil is said to be sodic. Excessive sodium causes soil mineral particles to disperse and water penetration to decrease. High sodium concentrations become a problem when infiltration rate is reduced to the extent the crop is not adequately supplied with water or when the hydraulic conductivity of the soil profile is too low to provide adequate drainage. Excess sodium may also add to cropping difficulties through crusting seed beds, temporary saturation of the surface soil, high pH and the increased potential for disease, weeds, soil erosion, lack of oxygen and inadequate nutrient availability. If calcium and magnesium are the predominant cations adsorbed on the soil exchange complex, the soil tends to be easily tilled and have a readily permeable granular structure.

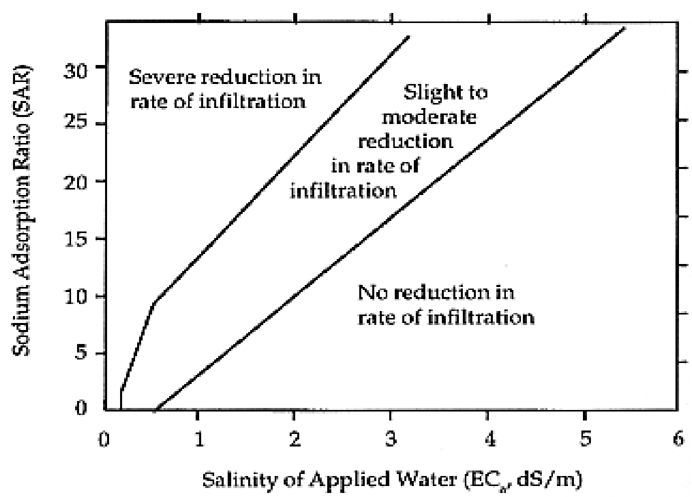
The sodium-adsorption-ratio (SAR) of irrigation water is generally a good indicator of the sodium status that will occur in the soil. SAR is defined as:

Equation 3: $SAR = [C_{Na}] \div [(C_{Ca} + C_{Mg})1/2]$

where all ion concentrations (C) are in mol/m^3. Na, Ca and Mg refer to sodium, calcium and magnesium. If the units are meq/L, the sum of $C_{Ca} + C_{Mg}$ must be divided in half before taking the square root. For most surface-source irrigation waters, equation 3 is a suitable indicator of sodicity.

The permissible value of the SAR is a function of salinity. High salinity levels reduce swelling and aggregate breakdown (dispersion), promoting water penetration. High proportions of sodium, however, produce the opposite effect. *Figure 3* represents the approximate boundaries where chemical conditions severely reduce infiltration of water into soil, where slight to moderate reductions occur and where no reduction is expected in most soils. Regardless of the sodium content, water with an electrical conductivity less than about 0.2 dS/m causes degradation of the soil structure, promotes soil crusting and reduces water penetration. Rainfall and snow melt are prime examples of low-salinity waters which reduce water penetration into soils. As *Figure 3* illustrates, both the salinity and the sodium-adsorption-ratio of the applied water must be considered when assessing the potential effects of water quality on soil water penetration.

Figure 3. Relative rate of water infiltration as affected by salinity and sodium adsorption ratio.



Toxicity

Specific constituents of irrigation water, such as boron, chloride and sodium, are potentially toxic to crops. Many trace elements are toxic to plants at very low concentrations. Both soil and water testing can provide analyses to discover any constituents that might be toxic.

In Nebraska's water, the amount of potentially toxic elements is normally low so toxicity problems are rare. Irrigation waters containing more than 1.0 mg/L boron may cause toxicity in boron-sensitive crops. In general, Nebraska groundwater contains less than 1.0 mg/L of boron. The only occurrences of boron levels of about 0.5 mg/L are water samples from sandstones of the Dakota group near Lincoln and northeast Nebraska and undifferentiated aquifers in southeast Nebraska. Boron concentrations may also approach 0.5 mg/L in both the North Platte and South Platte Rivers. Irrigation return flows to these rivers are the probable cause of these higher levels.

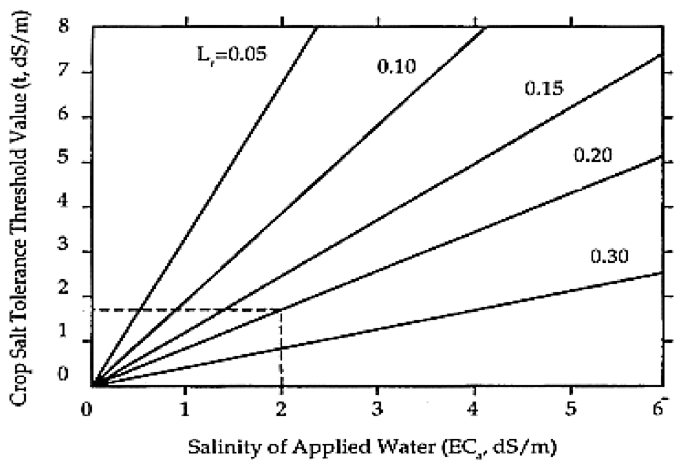
Most of Nebraska's common crops, with the exception of soybeans, are not particularly sensitive to either chloride or sodium. This exception, however, can be avoided by selecting cultivars bred to restrict chloride transport to the shoots. Woody plant species like grape, citrus and stone-fruit trees are susceptible to chloride and sodium toxicity.

Leaching

To prevent salts from increasing to levels detrimental to crop production, water must drain through the crop root zone. In most instances, natural drainage is sufficient to leach salts from the crop root zone. If natural drainage is not adequate, however, a drainage system must be installed. Where salinity is a hazard, the length of time before productivity is reduced depends on water management, drainage and the area's hydrogeology.

The ratio of the amount of drainage (D_d) divided by the amount of water applied (D_a) is called the leaching fraction ($L = D_d/D_a$). The minimum leaching fraction required to prevent a crop yield reduction is termed the leaching requirement (L_r). The leaching requirement is a function of the applied water's salinity and the salt tolerance of the crop. This relationship is shown graphically in *Figure 4*.

Figure 4. Leaching requirement (L_r) as a function of the salinity of the applied water and the crop's salt-tolerance threshold value.



To estimate the L_r, consider the earlier situation where 12 inches of rainfall (D_r) and 20 in. (D_i) of irrigation water with a salt content of 2,000 mg/L (C_i) were applied to grow corn. Assume the evapotranspiration (ET) of corn for the season totaled 24 in. (D_{ET}) and soil water content in the fall was the same as in the spring. Thus, 8 in. should have drained below the root zone ($D_d = D_r + D_i - D_{ET} = 12 + 20 - 24$). The resulting E_{Ca} was 2.0 dS/m (see above).

The salt tolerance threshold for corn grown for grain is 1.7 dS/m (*Table I*). Entering *Figure 4* for an ECa value of 2.0 dS/m and a threshold value of 1.7 dS/m, the intersection of lines drawn from these values gives a L_r of 0.20. The leaching fraction achieved for this example is:

$$L = D_d = [8/(20 + 12) = 0.25] \div [D_i + D_r]$$

In this example, sufficient water leached through the root zone to prevent a yield loss of corn grain.

Salinity Hazards in Nebraska

With Nebraska's subhumid to semi-arid climate and its predominately well-drained agricultural soils, salinity is usually not a problem. The following are representative values of water quality in Nebraska. Because there can be major differences among wells used for irrigation within relatively short distances, the values given here should be taken only as indicative of what might be expected in a given area. Surface waters, on the other hand, do not typically change in salt concentration over short distances. Because of this, the values given for streams should be good indicators of the potential salinity hazard.

Table II. Examples of the salinity of surface waters in Nebraska.

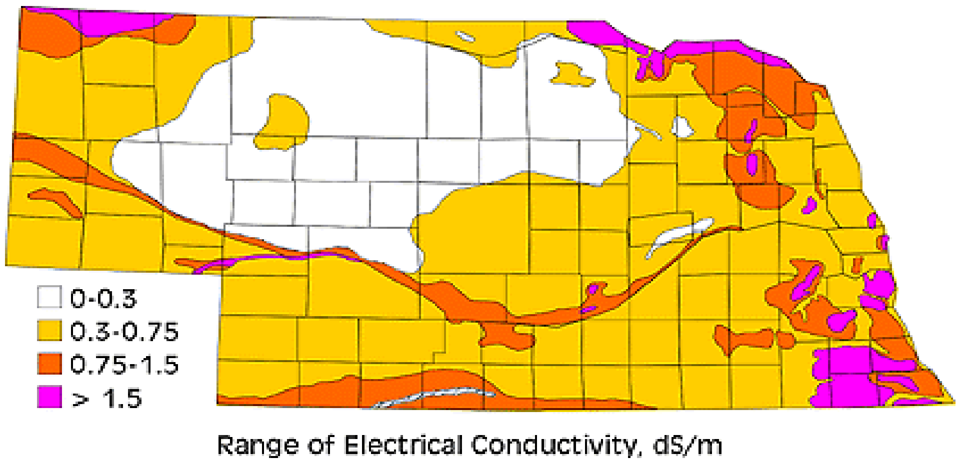
Stream	*Location*	*Electrical Conductivity dS/m*
Niobrara R.	near Verdel	0.3
Platte R.	near Grand Island	0.9
Platte R.	at Louisville	0.6
Dismal R.	near Thedford	0.2
Elkhorn R.	at Waterloo	0.5
Salt Creek	near Waverly	4.1
Big Nemaha R.	at Falls City	0.7
Republican R.	near Orleans	0.7
Big Blue R.	at Seward	0.7
Little Blue R.	at Hollenberg, KS	0.5

Surface Waters. *Table II* lists mean values for salinity, reported as electrical conductivity, in streams throughout the state. These values are from U.S. Geological Survey monitoring stations for the years 1987-89. Of the nine streams presented in *Table II*, only Salt Creek had an electrical conductivity above 1.0 dS/m.

With the typical rainfall amounts in Nebraska, even the most salt sensitive crops, such as beans and strawberries, should not suffer yield losses when provided with irrigation waters with electrical conductivity below 1.0 dS/m. Waters like those reported for Salt Creek, however, are not suitable for irrigation except for the most salt tolerant crops: wheat, barley and sugarbeet.

Groundwaters. In Nebraska, the High Plains aquifer system is the most important for irrigation. This aquifer system underlies about 85 percent of the state. About 96 percent of the state's irrigation wells are drilled into this system. Other aquifers are the Niobrara, the Dakota, unconsolidated sand and gravel in present and ancient stream valleys, and several undifferentiated aquifers. Except for relatively small regions along the Platte River and the undifferentiated aquifers in extreme northwest and eastern Nebraska, groundwaters have an electrical conductivity below 1.5 dS/m (see *Figure 5*).

Figure 5. Typical values of electrical conductivity in the principle groundwater reservior accross Nebraska.



Groundwater located beneath the Nebraska Sand Hills, an area of about 20,000 mi² in north central Nebraska, has an electrical conductivity less than 0.3 dS/m (see figure 5). As of 1984, all but about 400 of the more than 70,000 registered irrigation wells in Nebraska are located in the High Plains aquifer system, unconsolidated aquifers and the Niobrara aquifer. With such low salinity values, these groundwaters are suitable for crops grown in the state.

More saline groundwater is generally found in the Dakota aquifer system and in the undifferentiated aquifers. The electrical conductivity from these aquifers frequently exceeds 1 dS/m with about 25 percent of the water samples analyzed exceeding 2 dS/m. Depending upon the crop, rainfall and management, the yield of salt-sensitive crops may be reduced by these waters.

Examples of groundwater analyses from wells across Nebraska are given in *Table III*. These examples were selected to present a range in water quality, but are not meant to be indicative of all groundwater in the county mentioned. For example, analyses from several Saunders County wells are given in Table III to show the large range in water quality possible over short distances. Caution is warranted if groundwater is to be withdrawn in areas indicated in Figure 5 where saline waters are possible.

Summary

Table III. Quality measures of groundwater from selected wells in Nebraska.

County	*Electrical Conductivity dS/m*	*SAR*	*Sodium mg/L*	*Calcium mg/L*	*Magnesium mg/L*	*Chloride mg/L*	*Boron mg/L*
Box Butte	0.5	1.5	44	52	10	5	0.12
Cheyenne	0.4	1.4	33	26	10	7	0.13
Gosper	0.8	1.0	38	87	17	20	0.14
Hall	1.2	1.4	73	150	38	48	0.12
Jefferson	1.6	5.9	234	96	14	-	-

Otoe	0.1	1.4	13	4	2	10	0.39
Saline	1.9	13.6	408	50	11	502	0.21
Wayne	0.6	0.5	19	75	18	3	0.09
Webster	0.5	0.5	16	64	8	18	0.08
Different Well Waters from Saunders County							
Saunders	0.6	0.5	17	57	20	16	0.12
Saunders	1.1	7.9	216	42	9	168	0.43
Saunders	2.0	12.2	388	54	14	291	0.64

In areas where rainfall does not adequately leach salts from the soil, the design and management of irrigation systems must prevent damaging accumulations of salt in the crop root zone. In most cases, salinity or sodicity effects are slow in developing, frequently taking years to be obvious. Thus, periodic testing of soils and waters are required to monitor the change in salt content. If salinity is a hazard, timely irrigations must be of sufficient quantity and uniformity to both meet the crop's needs and leach salts adequately, without creating excessive surface runoff or deep percolation.

The response of crops to salinity, sodicity and toxicity varies widely among plant species. The relationship between crop yield and soil salinity has been quantified for many crops under typical growing conditions. The precise relationship, however, depends on a number of soil, crop and environmental factors. Sodicity typically reduces infiltration which leads to reduced crop yields. Crops can also be sensitive to specific solutes, like chloride and boron. With proper crop selection and appropriate irrigation management, economic yields can be sustained under low to moderate saline conditions.

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