Basics of Salinity and Sodicity Effects on Soil Physical Properties

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Salinity

Introduction

It has been known since at least the beginning of recorded history of crop cultivation that salts have an affect on agriculture. Over five thousand years ago, the people of Mesopotamia farmed The Fertile Crescent of the Tigris and Euphrates Rivers (in modern day Turkey and Iraq), some of the richest farmland in the world at the time. As salt began accumulating in the soil, due to inadequate leaching and drainage of irrigation waters, the farming culture changed from growing wheat and barley to growing only salt-tolerant barley. Eventually, as salt took over, nothing grew in these once fertile valleys, and the land was abandoned (Hadas, 1965). Just before the time of Christ, Romans plowed the fields of conquered Carthage and applied salt to the fields, in an attempt to prevent the Carthaginians from reestablishing themselves. Efforts to recolonize the area 24 years later failed because the salted fields remained unproductive (Hadas, 1965). Salts have been a known problem for thousands of years, particularly in arid and semiarid areas where there is insufficient rainfall to leach salts from the root zone (Miller and Donahue, 1995). During the last decade, in the Colorado River Basin alone, (eastern Utah, western Colorado, and Arizona) salts have cost agriculture more than $100 million a year (Anonymous, Agrichemical Age, 1989).

Irrigation water always includes some amount of dissolved substances, collectively called salts. These salts include dissolved solids derived from the weathering of rocks and soil by water and salts dissolved from soil the water previously passed through. Lime, gypsum and other salt sources are dissolved over time, leading to varying degrees of salinity in irrigation water (Miller and Donahue, 1995; Ayers and Westcot,1976; Buckman and Brady, 1967). **Whether or not water is suitable for irrigation, in terms of salinity, depends primarily on the kind and amounts of salts present, the soil type in question, specific plant species and growth stage, and the amount of water leached beneath the root zone, or the leaching fraction (LF)** (Ayers and Westcot, 1976; Bauder, 2001; Hanson et al., 1999; Rhoades, 1977; USDA, Natural Resources Conservation Service, 2002; Western Fertilizer Handbook, 1995).

Soil solution salinity and plant available water

Salinity in soil becomes a problem when the total amount of salts which accumulate in the root zone is high enough to negatively affect plant growth. Excess soluble salts in the root zone restrict plant roots from withdrawing water from the surrounding soil, effectively reducing the plant available water (Western Fertilizer Handbook, 1995; Bauder, 2001; Bauder and Brock, 2001; Hanson et al., 1999; USDA, Natural Resources Conservation Service, 2002). Basically, water is both held tighter to the soil in saline environments and is also less available for plant uptake due to osmotic forces. This leads to reduced water uptake and increased plant stress. This principle is best illustrated in Figure 1, which presents the water content at any specific water potential when the soil solution salinity ranges from $EC_{sw} < 2$mmhos/cm to $EC_{sw} = 30$. For instance, in this example 30% soil water equates to a soil water potential of approximately -1 bar at an ECsw < 2 mmhos/cm whereas the same water content equates to a soil water potential of approximately -12 bars at an $EC_{sw} = 30$ mmhos/cm. This will likely cause a decrease in growth and many of the same symptoms associated with drought, such as wilting or leaf loss. Excessive salinity may eventually result in the plant dying (Ayers and Westcot, 1976; Barbour et al., 1998; USDA, Natural Resources Conservation Service, 2002; Western Fertilizer Handbook, 1995).

When plant growth is compared in two identical soils with the same moisture levels, but one soil has salty water and the other soil has salt-free water, plants will be able to extract and use more water from the soil with salt-free water (Figure 1). Another way to look at this is the effect salts will have on the boiling and freezing point of water. Salty solutions will have a higher boiling and lower freezing temperature than pure water, meaning that increased energy is needed to make steam or ice when salts are present. Similarly, **a plant must expend increased energy to get water from the soil if sufficient salts are present to affect the osmotic potential** (Western Fertilizer Handbook, 1995; Barbour et al., 1998; Bauder and Brock, 2001; USDA, Natural Resources Conservation Service, 2002).

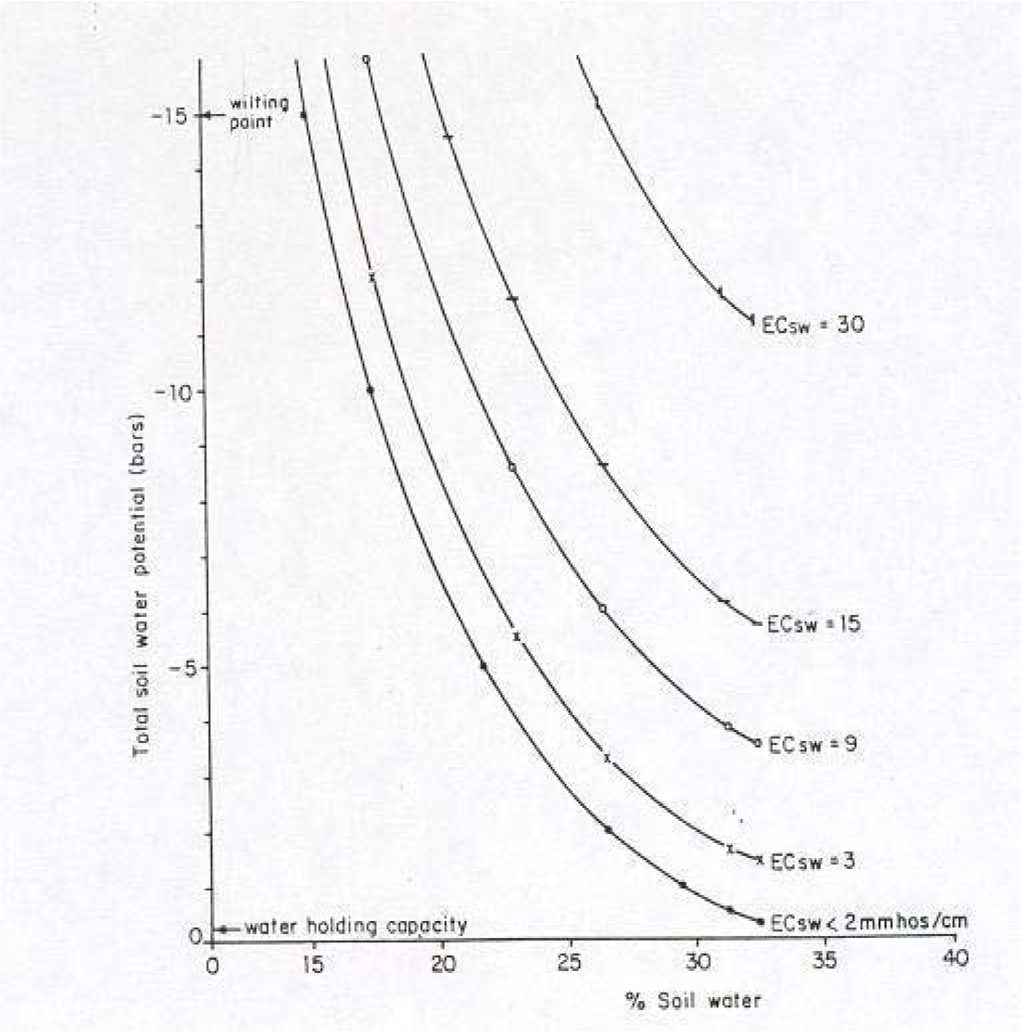


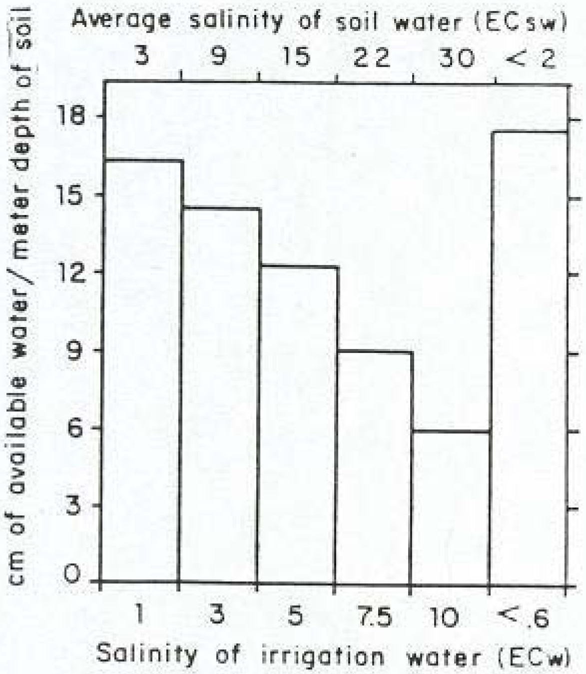
Figure 1. Total available soil water potential as influenced by average soil water salinity (ECsw) for a clay loam soil, i.e., effect of soil water content (%) and EC of soil water on total soil water potential. (Source: Ayers and Westcot, 1976)

Plant available water is at its maximum and soil salinity is at its lowest concentration immediately after irrigation. However, as plants use soil water, the force with which the remaining water is held in the soil increases, making it progressively more difficult to withdraw water. Also, as water is taken up by plants through transpiration or is lost to the atmosphere by evaporation, the salinity of the remaining water increases. This is due to the fact that the majority of the salts are left behind in both processes while the amount of water the salt is dissolved in is progressively reduced. This effect becomes most pronounced during periods of high evapotranspiration (ET) demand, such as hot sunny summer days and during the peak of the growing season (Hanson et al., 1999; Barbour et al., 1998; USDA, Natural Resources Conservation Service, 2002; Western Fertilizer Handbook, 1995).

Again referring to Figure 1, when the EC of the soil water = 30 dS/m (=30 mmhos/cm), and the soil water content is at 27%, plants will be at their wilting point, i.e. -15 bars osmotic potential. In contrast, at an ECsw < 2 dS/m, plants will not reach their wilting point until the soil is at approximately 15% soil water. Another way of looking at this is that if a crop has a constant ET demand of 6 mm/day (0.25 inches/day), the soil will have a 27½ day supply of available water (water the crop can utilize) at a soil water ECsw = 3 dS/m, a 20 day supply of available water at EC_{sw} = 15 dS/m, and a 10 day supply of available water at EC_{sw} = 30 dS/m (Ayers and Westcot, 1976).

Figure 1 demonstrates another important point regarding the relationship between irrigation water and soil salinity. **It is widely accepted that the salinity of soil water is equal to approximately three times the salinity of irrigation water, assuming relatively little leaching is occurring** (Ayers and Westcot, 1976). In conditions of relatively high leaching fractions, the soil water solution and drainage water will have a salinity level slightly greater than the irrigation water. **When considering salinity effects of the irrigation water, the plants and soil actually are subject to the salinity of the resultant soil solution, which is a function of the salinity of the applied water.** Soil solution salinity is dependent on soil type, climate, water use, and irrigation factors. Also, soil salinity generally increases between irrigation periods due to evapotranspiration, a fact which salinity charts do not take into account (Western Fertilizer Handbook, 1995; Barbour et al., 1998; USDA, Natural Resources Conservation Service, 2002).

Figure 2 presents information similar to that in Figure 1, but in a slightly different way, illustrating that the amount of available water decreases as the salinity of irrigation water increases. In this particular example, at an EC of the irrigation water = 10 dS/m, about 6 cm of water is available per meter of depth (0.72 inches/foot), while at an ECw = 1 dS/m, nearly 17 cm of water is available per meter of soil. Figure 2 provides a direct way of seeing how salinity levels affect how much water will be available for plant uptake (Ayers and Westcot, 1976).



Note: EC_w = mmhos/cm or dS/m; EC_{sw} = mmhos/cm or dS/m.)

Figure 2. Available water per meter depth of soil as influenced by salinity of irrigation water (ECw) and resultant salinity of soil water solution (ECsw). (Source: Ayers and Westcot, 1976.)

Soil solution salinity and plant growth

Increasing soil solution salinity will decrease available water. This will have a negative effect on crop yield and may affect survival, if salinity levels are high enough (Western Fertilizer Handbook, 1995; Ayers and Westcot; 1976; Barbour et al., 1998; Bauder, 2001; Bauder and Brock, 2001; Hoffman, 2002; Miller and Donahue, 1995; Saskatchewan, 1987; USDA, Natural Resources Conservation Service, 2002).

Figure 3 illustrates how yield decreases as the soluble salt content of the saturated paste extract of the soil (soil solution) increases from 0 to 30 dS/m. Using the guidelines of a three-fold increase between irrigation water and soil solution salinity, the data in Figure 3 would correspond to irrigation water salinity of 0-10 dS/m. Corn forage, for instance, decreases from 100% of yield potential at a soil EC_{sw} (soil water EC) = 3 dS/m to 50% of potential yield at an EC_{sw} = 10 dS/m. A soil solution of 16 dS/m will result in 100% yield loss for corn forage. **In general irrigation water with an EC of < 0.75 dS/m is considered non-problematic, while irrigation water with an EC 0.75-3.0 dS/m may pose an increasing problem, and irrigation water with an EC greater than 3.0 dS/m will pose a severe problem** (Ayers and Westcot, 1976).

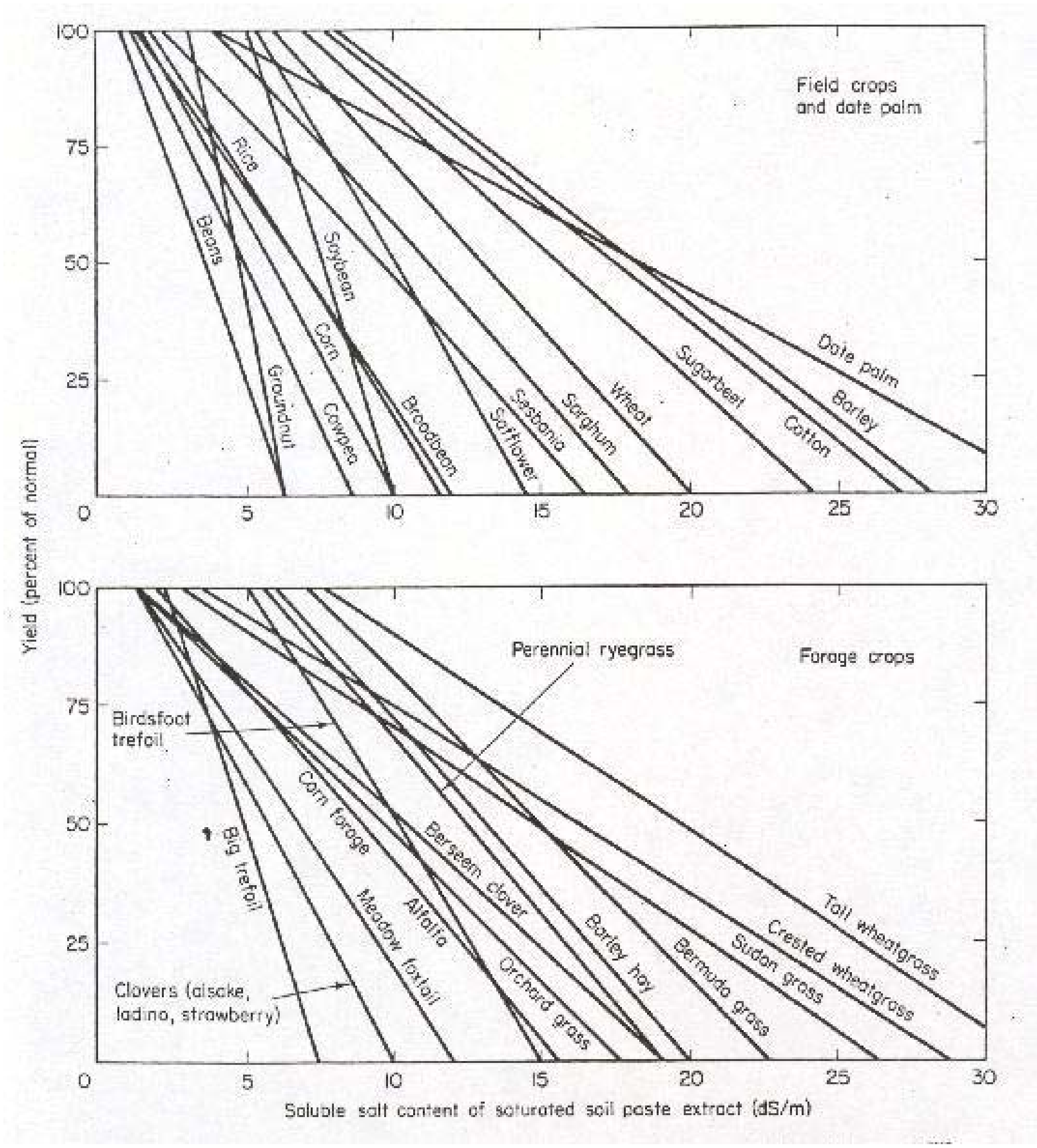


Figure 3. Decrease in crop yield as affected by increasing soil salinity.
(Source: Miller and Donahue, 1995.)

Figure 4 illustrates the EC of the saturation paste extract (EC_e), the associated irrigation water EC (EC_w) and the corresponding leaching fraction at which 0, 10%, 25%, and 50% reduction in yield can be expected to occur for various crops. **While the salinity tolerance of crops varies among species, all crops are negatively affected at some point by increasing salinity levels of the soil solution** (Western Fertilizer Handbook, 1995; Ayers and Westcot, 1976; Buckman and Brady, 1967; Miller and Donahue, 1995).

Crop	EC_e[2]	EC_w[3]	LR	EC_e	EC^w	LR	EC_e	EC^w	LR	EC_e	EC^w	LR	EC_e[4]
		(0%)			(10%)			(25%)			(50%)		Maximum
Barley[5]	8.0	5.3	9%	10.0	6.7	12%	13.0	8.7	16%	18.0	12	21%	28.0
Cotton	7.7	5.1	9%	9.6	6.4	12%	13.0	8.4	16%	17.0	12.0	22%	27.0
Sugar	7.0	4.7	10%	8.7	5.8	12%	11.0	7.5	16%	15.0	10.0	21%	24.0

beets[6]													
Wheat[5,7]	6.0	4.0	10%	7.4	4.9	12%	9.5	6.4	16%	13.0	8.7	22%	20.0
Safflower	5.3	3.5	12%	6.2	4.1	14%	7.6	5.0	17%	9.9	6.6	23%	14.5
Soybeans	5.0	3.3	16%	5.5	3.7	18%	6.2	4.2	21%	7.5	5.0	25%	10.0
Sorghum	4.0	2.7	8%	5.1	3.4	9%	7.2	4.8	13%	11.0	7.2	20%	18.0
Rice (paddy)	3.0	2.0	9%	3.8	2.6	11%	5.1	3.4	15%	7.2	4.8	21%	11.5
Sesbania	2.3	1.5	5%	3.7	2.5	8%	5.9	3.9	12%	9.4	6.3	19%	16.5
Corn	1.7	1.1	6%	2.5	1.7	8%	3.8	2.5	12%	5.9	3.9	20%	10.0
Flax	1.7	1.1	6%	2.5	1.7	8%	3.8	2.5	12%	5.9	3.9	20%	10.0
Cowpeas	1.3	0.9	5%	2.0	1.3	8%	3.1	2.1	12%	4.9	3.2	19%	8.5
Beans (field)	1.0	0.7	5%	1.5	1.0	8%	2.3	1.5	12%	3.6	2.4	18%	6.5

[1] Adapted from "Quality of Water for Irrigation." R.S. Ayers, Jour. of the Irrig. and Drain. Div., ASCE. Vol. 103, No. IR2, June 1977, p. 140.
[2] EC_e means electrical conductivity of the saturation extract of the soil reported in dS/m at 25 degrees C.
3ECw means electrical conductivity of the irrigation water in dS/m at 25 degrees C.
[4] Maximum ECe is the electrical conductivity of the soil saturation extract at which crop growth ceases.
[5] Barley and wheat are less tolerant during germination and seedling stage. EC_e should not exceed 4 or 5 dS/m.
[6] Sensitive during germination. EC_e should not exceed 3 dS/m for garden beets and sugar beets.
[7] Tolerance data may not apply to semi-dwarf varieties of wheat.

Figure 4. Expected reduction in yield for various crops at different soil solution extract and irrigation water salinities. (Source: Western Fertilizer Handbook, 1995, adapted from E.V. Maas, USDA Salinity Laboratory, Riverside, California.)

In addition to the effect of salinity on reducing plant available water, salinity can have a direct toxic effect on plants. Specific ions, such as chlorine, sodium, or boron, may have a toxic effect on plant roots and may stunt or stop their growth (Saskatchewan, 1987; Barbour et al., 1998). Chlorine accumulation in leaf tissues can lead to dessication. Sodium accumulation can lead to dehydration, reduced turgor, and cell death. Cell membrane integrity can be reduced as sodium displaces calcium, and water and nutrient uptake can subsequently be negatively impacted. Sodium can also reduce protein synthesis and alter hormonal activity.

Constituents of salinity-sodium as a component of salinity

In much of the arid and semi-arid United States, most of the salts present in irrigation water and groundwater are either chlorides, sulfates, carbonates or bicarbonates of calcium, magnesium, sodium, and potassium. Each of these salts has a unique solubility, which along with the composition of the mineral material through which water passes, dictates the salts present in the water. When these salts are dissolved in solution, they often ionize, breaking down (disassociating) into cations (positively-charged molecules) and anions (negatively-charged molecules) (Buckman and Brady, 1967). The most common cations in arid and semi-arid areas are calcium, magnesium, and sodium. Each of these cations is base-forming, meaning that they contribute to an increased OH^- concentration in the soil solution and a decrease in H^+ concentration. They typically dominate the exchange complex of soils, having replaced aluminum and hydrogen. Soils with exchange complexes saturated with calcium, magnesium, and sodium have a high base saturation and typically high pH values (Buckman and Brady, 1967; Miller and Donahue, 1995).

Anions affect soil properties directly by increasing salinity, and indirectly by affecting the exchangeable sodium, calcium, and magnesium ratios. Bicarbonates and carbonates are the most common anions in arid and semi-arid areas of the western United States. While sodium and potassium bicarbonates can exist as solid salts, calcium and magnesium bicarbonates are only found in solution. When soil moisture becomes reduced, either by evaporation, plant uptake, or drainage, calcium bicarbonate, $Ca(HCO_3)_2$ (more common than magnesium bicarbonate) decomposes into calcium carbonate (lime), a solid precipitate, CO_2 and water. Through this process, calcium is removed from clay particles while sodium is left behind, creating a sodium-dominated (sodic) soil from a calcium-dominated soil. Carbonates ($C0_3^-$), when present, are usually found at pH > 8. They will also cause calcium and magnesium to precipitate out of solution when the soil dries (Western Fertilizer Handbook, 1995).

Role of salinity in flocculation

In addition to decreasing plant available water and being potentially toxic to plants, soil solution salinity can also affect soil physical properties. Salinity can have a flocculating affect on soils, causing fine particles to bind together into aggregates. Elevated salt concentration in the soil solution will promote clay particle aggregation. The net result of this aggregation is that voids between the soil aggregates will be relatively larger than in non-flocculated soil, the soil will remain more permeable, and the soil will be less likely to become or remain waterlogged upon wetting. This enhanced aggregation is beneficial in terms of soil aeration, root penetration and root growth (Buckman and Brady, 1967; Hanson et al., 1999; McNeal, 1968; Oster and Schroer, 1979). Flocculation is generally enhanced when the soil solution salinity exceeds a value of approximately 960 mg/L (1.5 dS/m) or the salinity of the irrigation water exceeds a value of 0.5 dS/m (Hanson et al., 1999). Relatively high salt concentration in the soil solution essentially pushes adsorbed cations closer to the soil particles surface, keeping soil aggregates together (Miller and Donahue, 1995; Barbour et al., 1998; Buckman and Brady, 1967; Shainberg and Letey, 1984; Western Fertilizer Handbook, 1995). **The relationship between soil salinity and its flocculating effects, and soil ESP (exchangeable sodium percentage) and its dispersive effects, dictate whether or not a soil will stay aggregated or become dispersed under various salinity and sodicity combinations.** Soil type (clay mineralogy), texture, irrigation practices, and rainfall all have an effect on flocculation and dispersion (Miller and Donahue, 1995; Ayers and Westcot, 1976; Barbour et al., 1998; Bauder, 2001; Bauder and Brock, 2001; Buckman and Brady, 1967; Hanson et al., 1999; Hardy et al., 1983; Levy et al., 1999; McNeal, 1968; Oster and Schroer, 1979; Saskatchewan, 1987; Shainberg et al., 1981; Shainberg and Letey, 1984; van de Graaff and Patterson, 2001). While increasing salinity of the soil solution has a positive effect on enhancing or stabilizing soil aggregation, at high levels salinity has a negative and potentially lethal effect on plants (Western Fertilizer Handbook, 1995; Barbour et al., 1998; Miller and Donahue, 1995; USDA, Natural Resources Conservation Service, 2002). Thus, one cannot merely increase salinity in order to maintain soil structure without considering the impact the increased salinity will have on plants.

Because of the difference in osmotic potential between the bulk soil solution and the interior of soil aggregates, purer water (eg. less saline) is more likely to flow into the spaces (micropores) between clay platelets. If the bulk solution salinity becomes low relative to the salinity of the aggregates, this water migration may cause swelling and dispersion of clay particles. In contrast, high EC water has the opposite effect. In this latter case, water between the clay platelets, in the micropores, is more likely to flow into the larger macropores in the soil. Thus, the space between the clay particles is reduced, and hence the particles are more likely to stay together and soil structure is maintained. Consequently, water entering the macropores does not have the same dispersive effect as water in the micropores. Additionally, higher salinity water will have an increased charge because of a larger number of dissolved ions. This increased charge means that less total solution is necessary to balance the charge on clay platelets. Hence, less water is present between clay platelets, in the micropores, when saline water is present than when non-saline water is present (Hanson et al., 1999; Agassi et al., 1981; Buckman and Brady, 1967; Miller and Donahue, 1995).

Sodium and Sodicity

Assessment of the relationship between soil solution salinity and soil physical properties requires knowledge of the constituents of the dissolved salts, and especially the sodium concentration. Sodium has the opposite effect on soils that salinity does. While elevated electrolyte concentration may enhance flocculation, sodium saturation may cause dispersion. Because of its relatively large size, single electrical charge and hydration status, adsorbed sodium tends to cause physical separation of soil particles. The physical separation of soil particles results in sufficient distance between individual soil particles such that repulsive forces between like molecules exceed bonding forces and dispersion occurs. **Thus, soil dispersion is the primary physical process associated with high sodium concentrations** (Miller and Donahue, 1999; Ayers and Westcot, 1976; Bauder, 2001; Bauder and Brock, 2001; Buckman and Brady, 1967; Chen and Banin, 1975; Falstad, 2000; Frenkel et al., 1978; Hanson et al., 1999; Hardy et al., 1983; van de Graaff and Paterson, 2001). A second, somewhat reversible process associated with sodium saturation is platelet and aggregate swelling. The reason other ions such as calcium and magnesium do not have this same effect is because smaller, non-hydrated divalent cations tend to cluster closer to the clay particle (their +2 charge causes a stronger attraction to clay surfaces than sodium, which has a +1 charge). This combination of conditions does not cause the disruption to soil structure that sodium does (Chen and Banin, 1975; Hanson et al., 1999; Shainberg and Letey, 1984). Figure 5 helps illustrate this difference in physical arrangement of sodium and calcium molecules on the clay surface. Basically, attractive forces which bind clay particles together are disrupted when too many sodium ions get between the clay particles. When such separation occurs, repulsive forces begin to dominate, and the soil disperses (Hanson et al., 1999; Buckman and Brady, 1967; Chen and Banin, 1975; Falstad, 2000; Frenkel et al., 1978; Saskatchewan, 1987; Western Fertilizer Handbook, 1995).

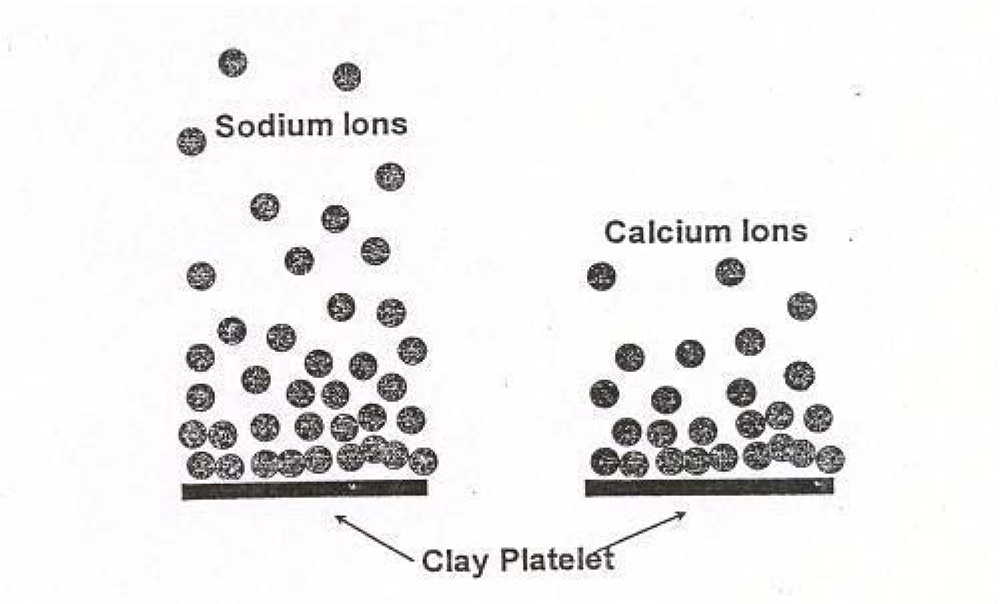


Figure 5. Behavior of sodium and calcium ions attached to a clay platelet. (Source: Hanson et al., 1999.)

Dispersion of clay particles causes plugging of soil pores. Upon repeated wetting and drying and associated dispersion, soils reform and solidify into an almost cement-like soil with little or no structure, depending on the sodium concentration and clay type (Frenkel et al., 1978; Buckman and Brady, 1967; Chen and Banin, 1975; Hanson et al., 1999; Henderson, 1981; Miller and Donahue, 1995; Saskatchewan, 1987). **The effect this sodium-induced dispersion will have on the soil can be assigned to three main categories: reduction in infiltration, reduced hydraulic conductivity, and surface crusting.** Each of these conditions makes it difficult for plants to become established, for roots to penetrate the soil, and for plants to obtain adequate water and nutrients. Overall, these effects negatively impact plant yield and survival (Hanson et al., 1999; Ayers and Westcot, 1976; Falstad, 2000; Saskatchewan, 1987; Western Fertilizer Handbook, 1995).

Calcium and magnesium ions generally have the opposite effect on soil structure that sodium does, i.e. they will keep soil flocculated (Agassi et al., 1981; Ayers and Westcot, 1976; Bauder, 2001; Hanson et al., 1999; Miller and Donahue, 1995). Calcium and magnesium compete for the exchange sites occupied by sodium so that increased calcium and magnesium concentrations reduce the amount of sodium that will be bound to soil particles (Hanson et al., 1999).

Extensive research has been conducted regarding the chemistry of SAR and adjustments to the calculation of SAR to account for various aspects of solution chemistry. One such calculation is the adjusted SAR. Adjusted SAR takes into consideration calcium and magnesium loss through precipitation caused by the presence of carbonates and bicarbonates in solution. Therefore, although various methods to calculate adjusted ESP and SAR exist, they all result in adjusted values greater than the original ones, as the proportion of sodium increases as calcium and magnesium decrease. **Adjusted SAR and ESP values are widely accepted as more representative than other measures of what actually occurs in the field** (Hanson et al., 1999).

Infiltration

Dispersed clay particles within the soil solution can clog soil pores when the particles settle out of solution (Shainberg and Letey, 1984; Ayers and Westcot, 1976; Buckman and Brady, 1967; Miller and Donahue, 1995; Shainberg and Letey, 1984). Additionally, when dispersed particles settle, they may form a nearly structureless cement-like soil (Ayers and Westcot, 1976; Buckman and Brady, 1967; Miller and Donahue, 1995; Shainberg and Letey, 1984). This pore plugging and cement-like structure make it difficult for plants to get established and grow. It also impedes water flow and water infiltration into the soil.

The disruption of soil hydraulic properties has two main consequences. First, there is less water infiltrating into the soil, and therefore less plant available water, particularly at deeper depths (Barbour et al., 1998; Bauder and Brock, 2001; Buckman and Brady, 1967; Miller and Donahue, 1995; Western Fertilizer Handbook, 1995). And **secondly, runoff, and therefore water loss and soil erosion, may be enhanced** (Hardy et al., 1983; Buckman and Brady, 1967; Miller and Donahue, 1995).

Figure 6 illustrates how infiltration rate will vary with the addition of applied water, depending on the EC of the applied water and ESP of the soil. In this experiment distilled water (DW) is representative of rainwater, as both are essentially free of salts (Buckman and Brady, 1967; Agassi et al., 1981; 1967; Hardy et al., 1983; Miller and Donahue, 1995). Agassi et al. (1981) assessed the effect of water with varying levels of EC (applied through misting) on infiltration rates, in soils with different ESP's. Figure 6 shows four graphs, each one representing a different initial ESP. The graphs illustrate how the infiltration rate of soils with ESP's of 26, 6.4, 13.6 and 1.0 decreased as the EC of the applied water decreased. The infiltration rate decreased 60 - 80% at all ESP values when less than ¼ inch of simulated rainfall (DW) was applied. For soils with an ESP of 13.6, the infiltration rate remained consistently higher with increased EC of the applied water. Following 50 mm cumulative application of water with EC of 5.6 mmhos/cm to a soil with ESP = 13.6, the resulting infiltration rate was 10 mm/hour, while water with an EC of 0.5 mmhos/cm led to an infiltration rate of only 4 mm/hour. The greater salinity level in the applied water caused or enhanced flocculation, which helped maintain soil structure and increase the infiltration rate. The top two graphs, which represent soils with initial ESP's of 13.6 and 1.0, illustrate the dispersive effects of increased sodicity. The soil with an initial ESP of 1.0 and applied water with EC = 5.6 dS/m had an infiltration rate of 16 mm/hour while the soil with an initial ESP of 13.6 and applied water EC = 5.6 dS/m had an iniltration rate of 10 mm/hour. Under some circumstances, infiltration rate is progressively reduced as ESP increases.

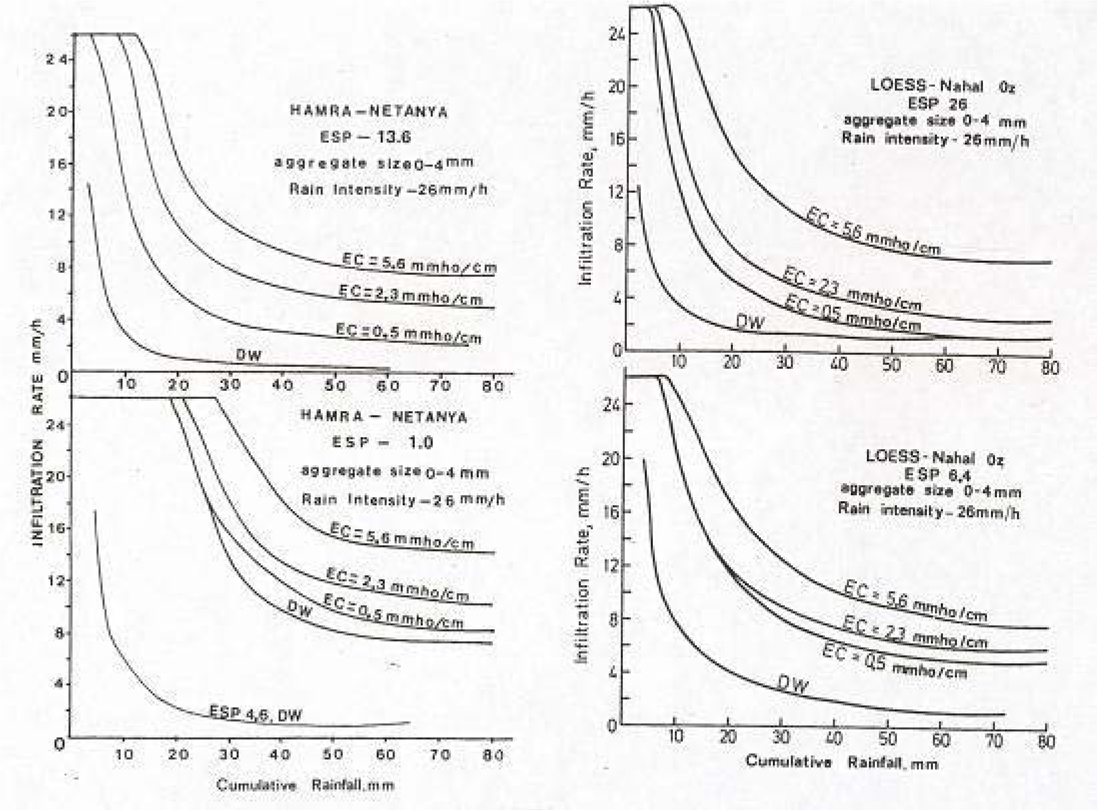


Figure 6. Infiltration rate as a function of cumulative rainfall and initial ESP of soil and EC of applied water. (Source: Agassi et al., 1981.)

In this particular example, infiltration rate of soil with ESP = 1.0 and 50 mm cumulative water applied is 16 mm/hour while the infiltration rate of soil with ESP = 13.6 is 10 mm/hr and the infiltration rate of soil with ESP = 26 is only 8 mm/hr. For a given ESP, the EC of applied water has the reverse effect, i.e. as the salinity of the applied water increases, the infiltration rate for a specific amount of applied water is greatest at the greater EC.

Figure 7 illustrates the flocculating effects of salinity and the potential effect of sodium dispersion on erosion. This example presents the percentage of water not infiltrated (% runoff) for two different soil types with increasing EC and different ESP's. As can be seen, the greatest % runoff occurred at very low EC's, with increasing EC steadily, but more gradually, decreasing percent runoff. Higher EC resulted in more soil flocculation; hence soil structure, pores and fissures are all maintained or enhanced and infiltration increases. This results in less water running off. The reverse occurs with respect to increasing ESP. The lowest % runoff (and greatest infiltration) for all ECs occurred at ESP =1.0, and higher ESPs yielded greater % runoffs. Different soil types between the two graphs explains why the ESPs of 13.6 and 26.0 are roughly comparable. **The degree of dispersion differs among clay mineralogy and soil type** (Agassi et al., 1981).

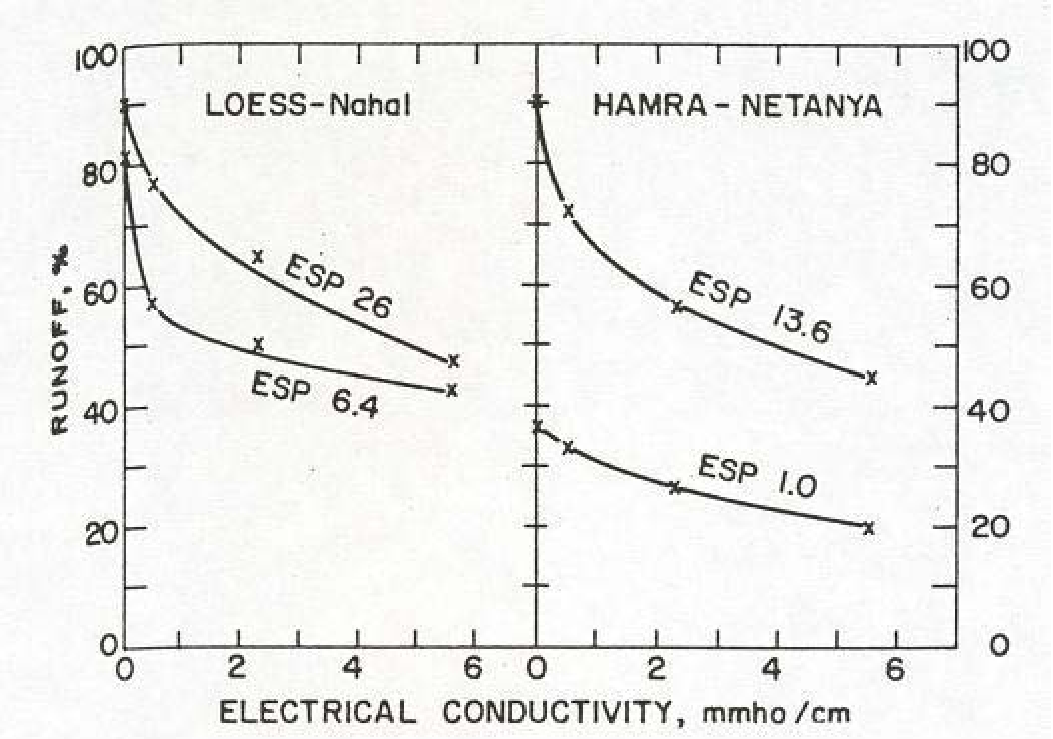


Figure 7. % Runoff as a function of intitial ESP of soil and EC of applied water. (Source: Agassi et al., 1981)

Hydraulic conductivity

Not only does **dispersion and subsequent resolidifying of soil material cause reduction in the amount of water entering the soil, it also affects the rate at which water flows through the soil** (McNeal, 1968; Ayers and Westcot, 1976; Frenkel et al., 1978; Hardy et al., 1983; Henderson, 1981; Saskatchewan, 1987; Western Fertilizer Handbook, 1995). Soil with well-defined structure, particularly in arid and semi-arid areas, will contain a large number of macropores as well as many cracks and fissures. These macropores, cracks, and fissures allow for relatively rapid flow of water through the soil profile (Miller and Donahue, 1995; Buckman and Brady, 1967). **When high concentrations of sodium affect a soil, the subsequent loss of structure reduces the hydraulic conductivity, or rate at which water moves through a soil** (Shainberg and Letey, 1984; Hanson et al., 1999; Hardy et al., 1983; Levy et al., 1999). The subsequent soil swelling and waterlogging often leads to anaerobic conditions. Anaerobic soil conditions reduce or prevent plant growth. They also decrease organic matter decomposition rates, which rely on oxygen-dependent microorganisms to break down plant matter. This decrease in decomposition results in organic matter-rich soil, which is dark-brown or black in color. These soils are referred to as black alkali soils (Western Fertilizer Handbook, 1995).

Surface crusting

Surface crusting is a readily recognized diagnostic of sodium-affected soils. The primary causes of surface crusting are: 1) physical dispersion caused by impact of raindrops and irrigation water, and 2) chemical dispersion which is dependent on the soil ESP and the EC of the applied water (Agassi et al., 1981, Hardy et al., 1983).

As early as the 1950s, researchers were examining the specifics of crust formation. McIntyre (1958) found soil crusts to consist of two distinct parts: an upper skin (0.1mm thick) caused by the impact of raindrops and a washed in layer caused by the accumulation of clay particles. The washed in layer was only present in soils which dispersed easily.

In arid and semi-arid regions presence of crusted salt and sodium-affected soil is a recognized occurrence (Bauder and Brock, 1992). The structure of the soil's crust, usually the top six inches, differs significantly from the structure of the subsoil. Though the volume of crust-affected soil is relatively small, proportionate to the total soil plants will be growing in, it has a disproportionate effect on seedling emergence and water penetration, making crop establishment very difficult (Cary and Evans, 1974; Barbour et al. 1998; Western Fertilizer Handbook, 1995).

Hardy and associates (1983) have found that in soils which were easily dispersed, permeability of the bulk of the soil was approximately three orders of magnitude, or one thousand times, greater than the permeability of the crust. Thus, the subsoil is effectively hydraulically sealed off by the upper crust.

Morin et al. (1981) hypothesized that the dramatic, often threefold, difference in hydraulic conductivity between the surface crust and bulk of the soil created a suction mechanism, effectively sealing off most of the soil. This process was subsequently advanced to explain the stability of the crust's hydraulic conductivity, which stays extremely low, and the similarity in hydraulic conductivity of soils with very different textures and mineralogies (Agassi et al., 1981).

Although some degree of crusting may be caused naturally by the physical impact of incoming water, especially rainfall, the dispersive effects of sodium may be greater than the effects of rainfall or irrigation (Hardy et al., 1983). Agassi and associates (1981) found that crust formation due to rainfall is greatly enhanced by clay dispersion and movement in the soil. They also found that the relative freedom of particle movement at the soil surface enhances crusting. When clay particles disperse within the soil water, the dispersed particles effectively cement the soil surface by two mechanisms. First, dispersed clay particles plug macropores in the soil surface, effectively sealing off avenues for water and roots to move through the soil. Secondly, during dispersion aggregate structure is lost, and a structureless brick-like arrangement is formed when the soil dries. This makes it very difficult for water movement and for plants to break through this surface crust (Hanson et. al., 1999; Barbour et al., 1998; Buckman and Brady, 1967; Miller and Donahue, 1995; Rhoades, 1977; Saskatchewan, 1987; Western Fertilizer Handbook, 1995).

EC/SAR Relationship

The ratio of salinity (EC) to sodicity (SAR) is the dictating factor determining the effects of salts and sodium on soils. More than fifty years of research have been conducted to determine this relationship as precisely as possible, and the subject is now well enough understood to make accurate predictions of how specific soils will behave when exposed to different levels of salts and sodium. **The bulk solution salinity will have specific effects on soil physical and chemical properties. Simultaneously, the soil solution sodium concentration and the sodium adsorbed on the soil exchange complex may have a different effect on soil physical and chemical properties.**

Salts (including sodium) are present in the soil water solution, and therefore move with soil water, generally in a downward direction, as water drains through the soil profile. Sodium, however, attached to the soil particles, will not move downward with soil water (Hanson et al., 1999; Ayers and Westcot, 1976; Buckman and Brady, 1967; Miller and Donahue, 1995; Oster and Schroer, 1979; Shainberg and Letey, 1984; van de Graaff and Patterson, 2001). It should also be noted that the relationships presented herein generally do not take into account the downward migration of salts due to leaching by rainfall, and hence lowering of soil water EC.

One of the first studies to investigate the interactive effect of the EC x SAR relationship was conducted by McNeal (1968). He assessed the swelling factor, or the amount a soil is likely to swell, as a consequence of a combination of sodium, adjusted ESP, and salts in solution (EC). The degree to which sodium-induced dispersion interacted with salt-induced flocculation was defined as a swelling factor. **Increasing the adjusted ESP or decreasing the salt concentration caused an increase in the swelling factor**. This is best illustrated in Figure 8. Similar to adjusted SAR, adjusted ESP takes into account the precipitation of calcium and magnesium out of solution. The swelling factor is a measure of the degree to which soil will expand as water is held within the soil matrix. The amount of water retained is directly affected by both ESP and EC (McNeal, 1968).

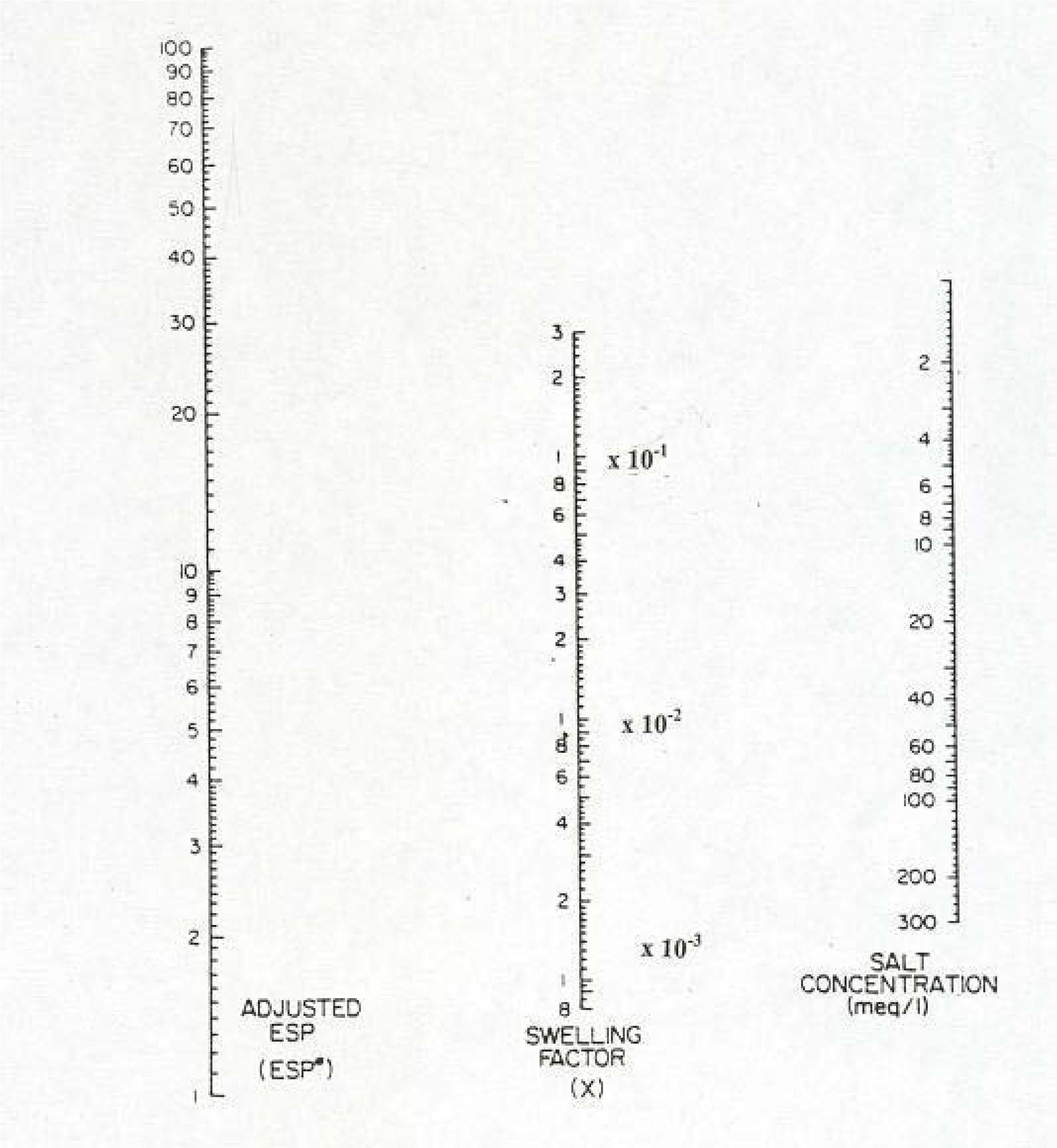


Figure 8. Swelling factor as a function of adjusted ESP of soil and salt concentration of soil solution. (Source: McNeal, 1968.)

Using Figure 8, it is possible to draw a line from the adjusted ESP in the left column to the appropriate salt concentration in the right column. The line intersects the middle column, the Swelling Factor, indicating the degree to which the soil will swell. For instance, drawing a line between adjusted ESP = 2 and an EC = 40 meq/L yields a swelling factor of 3 x 10^{-3}, or 0.003. In this example swelling, and subsequently dispersion, is not a problem. However, a combination of adjusted ESP = 30 and EC = 2 yields a swelling factor of 2.8 x 10^{-1}, or 0.28. In this example, swelling and dispersion are very likely. Figure 8 makes it possible to appreciate how **the dispersive effects of high ESP can be mitigated with the flocculating effects of high EC.** For instance, an adjusted ESP = 30 yields a swelling factor of 0.05 when combined with an EC = 60. Conversely, a low adjusted ESP can still cause swelling if EC is correspondingly low. For instance, an adjusted ESP = 7, less than half of the accepted threshhold, and EC of 1 yield a swelling factor of 0.1, likely a problem (McNeal, 1968).

Another approach to assessing the interactive effect of solution salinity and sodicity on soil physical properties is shown in Figure 9, reported by Blaine Hanson and associates (1999). This figure was derived from Ayers and Westcot (1976), and subsequently modified by Oster and Schroer (1979). Figure 9 presents the potential impact of various combinations of SAR solution and EC of irrigation water on infiltration rates.

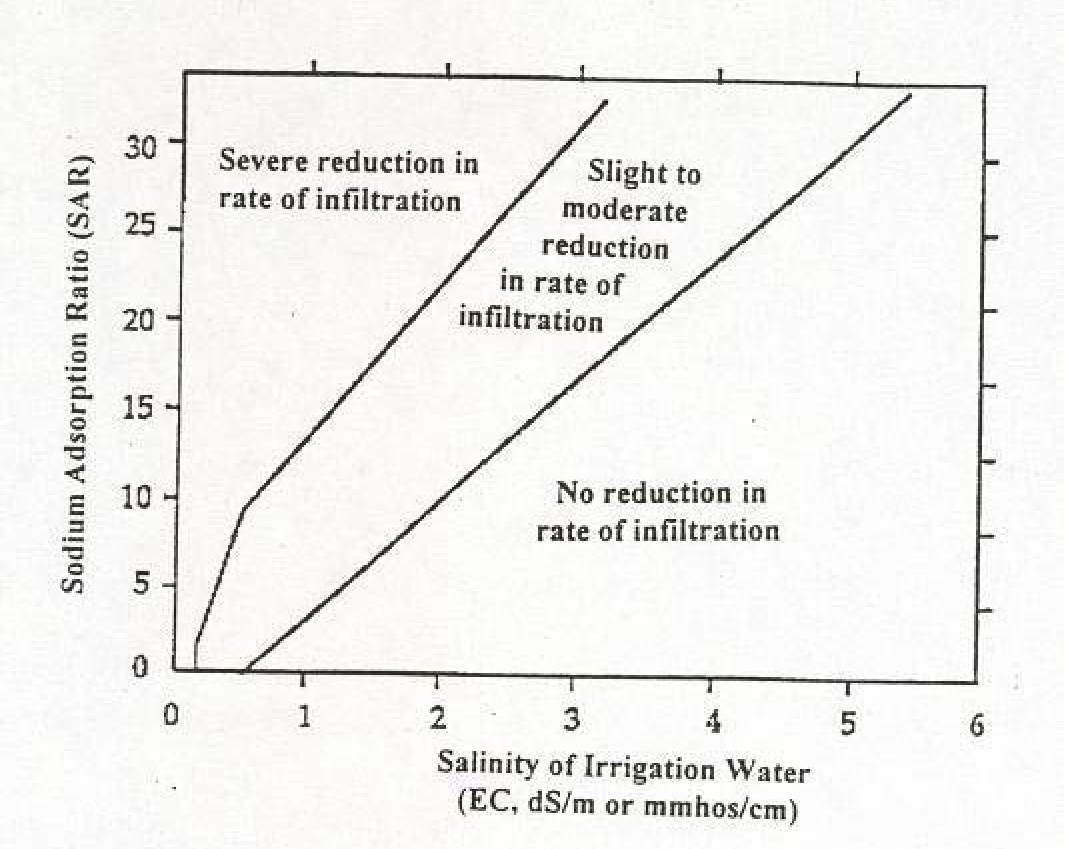
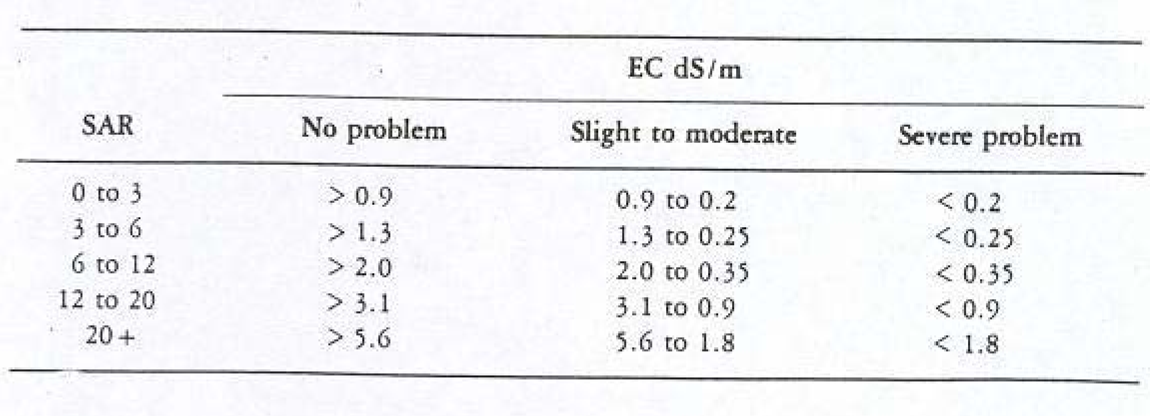


Figure 9. Potential for reduction in rate of infiltration resulting from various combinations of EC and SAR of applied water. (Source: Hanson et al., 1999.)

A severe reduction in infiltration is likely to occur with the condition of relatively low EC and high SAR. For example, at a SAR = 15, a severe reduction in infiltration will occur at an EC = 1 dS/m. An EC of 2.5 or less results in a slight to moderate reduction in infiltration. With an EC greater than 2.5, there will likely not be a reduction in infiltration. Figure 9 illustrates the same relationship previously reported: **increasing sodium concentration disperses soil and increasing salinity flocculates soil** (Hanson et al., 1999).

Figure 10 presents a tabular refinement of the data presented in Figure 9. Developed by Ayers and Tanji (1981), incorporating work done by Ayers and Westcot from guidelines developed for the United Nations on irrigation water quality, the table defines this relationship between EC, SAR and infiltration reduction. Ayers and Westcot initially identified five categories or ranges of SAR, the lowest range being SAR = 0 to 3. EC levels which pose no problem, a slight to moderate problem, and a severe problem for each SAR range are presented. For instance, **for an SAR of 12 to 15 an EC greater than 3.1 dS/m does not represent a problem, while in the same SAR range an EC of 3.1 to 0.9 poses a slight to moderate problem, and an EC < 0.9 poses a severe problem.**



SAR	EC dS/m		
	No problem	Slight to moderate	Severe problem
0 to 3	> 0.9	0.9 to 0.2	< 0.2
3 to 6	> 1.3	1.3 to 0.25	< 0.25
6 to 12	> 2.0	2.0 to 0.35	< 0.35
12 to 20	> 3.1	3.1 to 0.9	< 0.9
20+	> 5.6	5.6 to 1.8	< 1.8

Figure 10. Guidelines for interpretation of water quality suitability for irrigation (in terms of reduced infiltration) (Source: Ayers and Tanji, 1981.)

Climate, soil types, crop and plant species, and management all collectively dictate acceptable levels of salinity and sodicity of irrigation water. Figure 11 (Saskatchewan, 1987) presents a more specific relationship between salinity, sodicity and permeability hazard, accounting for leaching fractions, soil texture, and rainfall effects. The diagonal EC/SAR line in Figure 11 presents the maximum concentration of salinity and sodicity of applied water for various soil types. EC x SAR combinations of values greater than this line present a potential or absolute hazard for the given soil textures. The single-dashed area immediately above the line represents a potential permeability hazard, accounting for the effect of rainfall. **The flushing or leaching of salts beneath the root zone reduces the potential for flocculating effects of salts but does not affect the sodium bound to the soil itself** (Bauder and Brock, 2001; Buckman and Brady, 1967; Hanson et al., 1999; Miller and Donahue, 1995; Shainberg and Letey, 1984). Rain events, particularly intense storm events, flush salts beneath the root zone and increase the likelihood that dispersion will occur. In Figure 11, any EC x SAR combination in the hatched area poses a permeability problem regardless of rainfall effects.

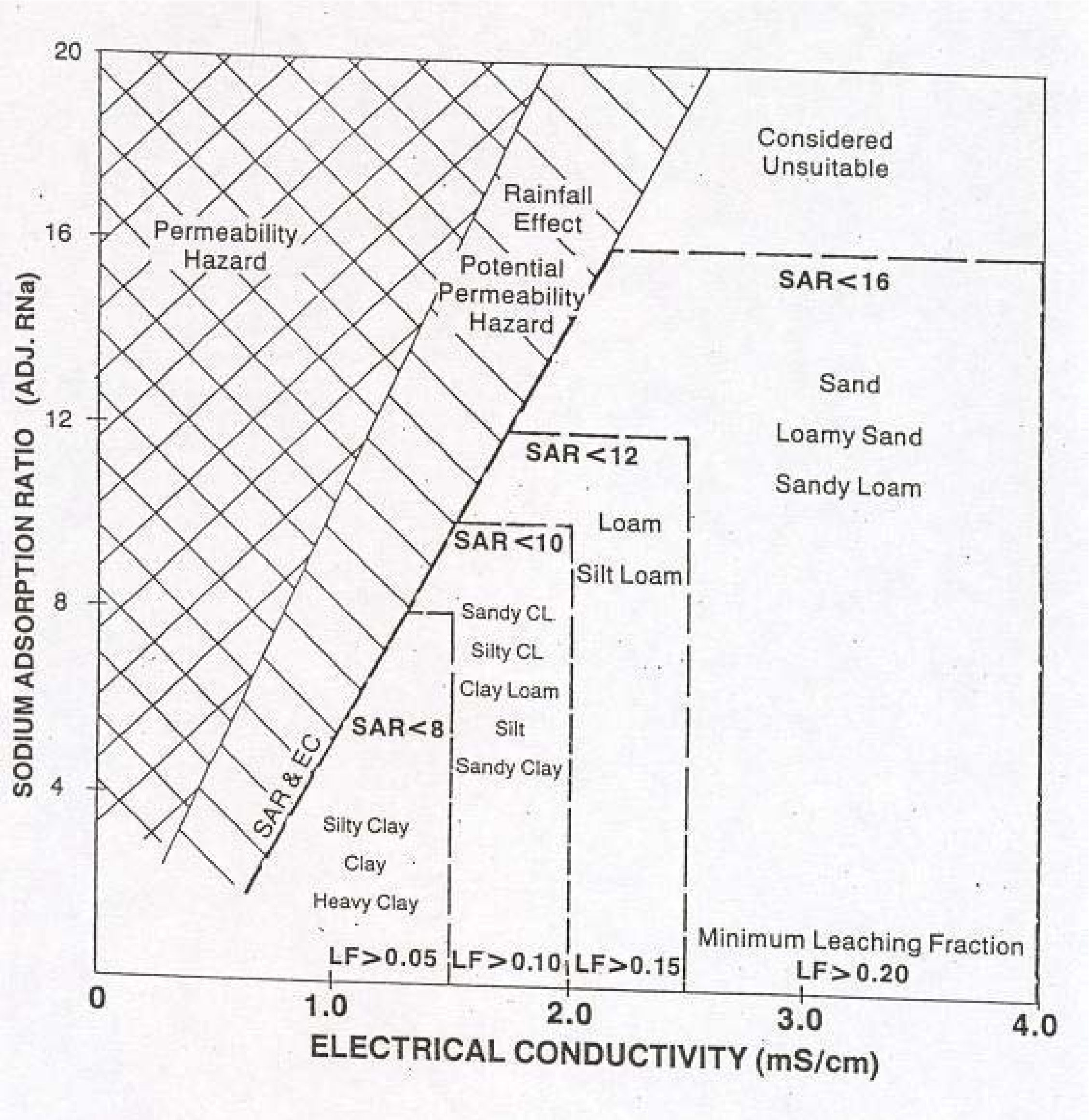


Figure 11. Guidelines for salinity (EC) and SAR of irrigation water suitable for various textural categories. (Source: Saskatchewan Water Corporation, 1987.)

The results reported by Ayers and Westcot (1976), Ayers and Tanjii (1981), and Oster and Schroer (1979) are substantiated by other research. Abu-Sharar and associates (1987) studied the percentage of clay material within a soil dispersed (grams dispersed/ 100 g of soil) when subject to different EC and SAR combinations. The effect of different SAR levels, (0, 10, 20), in combination with several levels of salinity were compared (Figure 12). **For a given EC, increasing SAR resulted in a greater dispersed to aggregated clay ratio. For each SAR level, increasing salinity caused the dispersed to aggregated clay ratio to decrease,** with the greatest decline occuring when EC was increased from 4 to 9 mol/m^3 (Abu- Sharar et al., 1987).

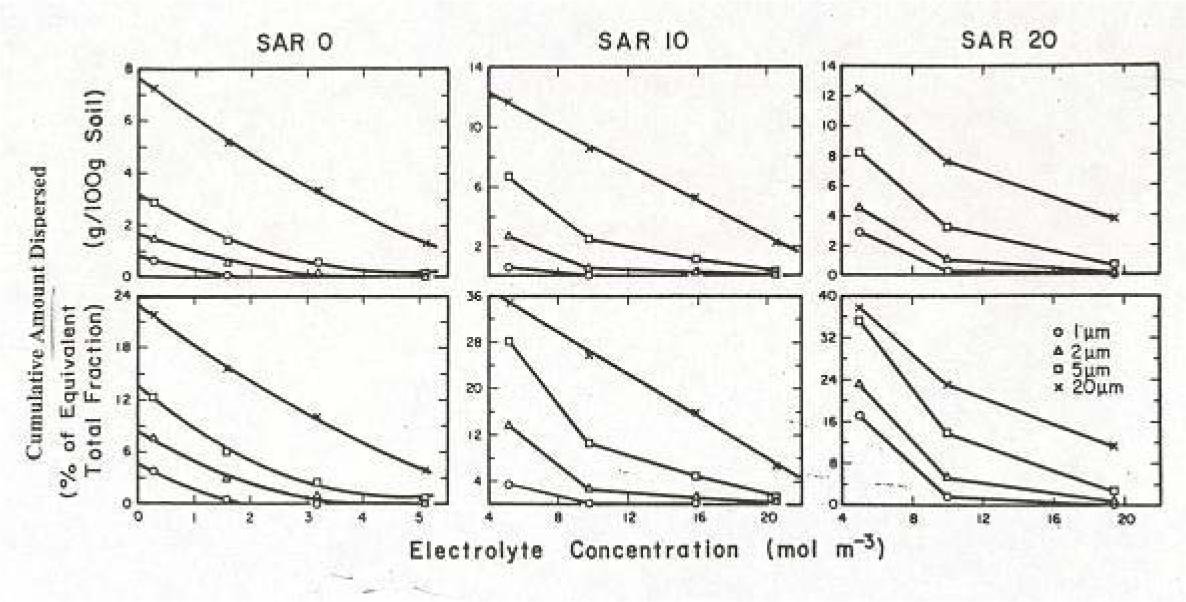


Figure 12. Effect of EC x SAR combinations of applied water on the ratio of dispersed to aggregated clay. (Source: Abu-Sharar et al., 1987.)

Oster and Schroer (1979) conducted a similar study examining infiltration rates with water with varying levels of salinity and sodicity. Their results were similar. For instance, for SAR values between 2 and 4.6, the final infiltration rate increased from 2 to 28 mm/hour as the EC of the applied water increased from 5 to 28 molc/m^3. **Oster and Schroer concluded that as SAR increases, higher salt concentrations are required to maintain a relatively constant degree of swelling and dispersion.** The reverse was reported to be the case with lower SAR (Oster and Schroer, 1979).

Figure 13 illustrates the effect of SAR and varying salt concentration on hydraulic conductivity. In this example, the salinity of the irrigation water varied from distilled water (DW) to water with an EC of 3.0 dS/m. The data demonstrate that **for any specific irrigation water salinity, hydraulic conductivity decreases quite rapidly as SAR increases. The SAR at which the conductivity diminishes depends on the EC of the applied water, although the rate of decrease is approximately the same as sodium levels in the irrigation water increase** (Shainberg and Letey, 1984).

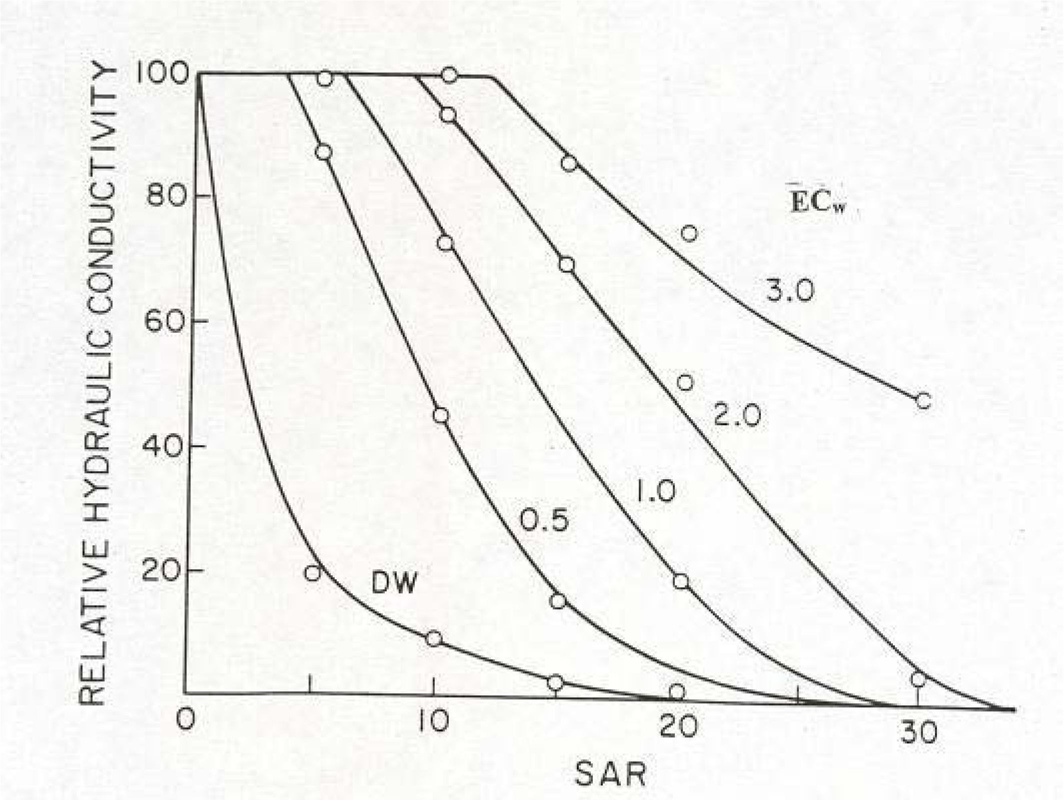


Figure 13. Effect of EC and SAR of applied water on relative hydraulic conductivity. (Source: Shainberg and Letey, 1984.)

Modifications due to texture

Soil texture plays an important role in all aspects of irrigation, and the role of soil texture with respect to the effect of salinity and sodicity is no exception. Texture is strongly correlated with a soils ability to percolate water (permeability and infiltration), how much water the soil can store (available water holding capacity), and the soil's ability to adsorb or desorb chemical ions (exchange capacity) (Miller and Donahue, 1995; Buckman and Brady, 1967; Saskatchewan, 1987).

Clay soils have relatively high water holding capacities and are slow to drain because of their smaller pore diameters. Conversely, sandy soils retain less water and are faster to drain. Under normal irrigation practices, sandy soils will have naturally occurring greater leaching fractions (loss of water from the root zone) than clay soils when both soils are irrigated with equal volumes of water (Saskatchewan, 1987). Correspondingly, sandy soils can withstand higher salinity irrigation water as more of the water, and hence salts, will be leached beneath the root zone.

A second important aspect of soil texture is the fact that clays generally compromise the majority of cation exchange sites in soils. This is because clays, by virtue of their small particle size, have the most surface area, and therefore the most exchange sites. Consequently, clay soils have the greatest risk for excess sodium binding and dispersion (Miller and Donahue, 1995; Buckman and Brady, 1967; Saskatchewan, 1987). Sands, with their substantially larger particle size, have less total surface area, and therefore fewer exchange sites. Silts fall somewhere in between (Miller and Donahue, 1995; Buckman and Brady, 1967; Saskatchewan, 1987).

Adsorption of sodium onto the soil exchange sites is dictated by the chemistry of the soil solution. When irrigation water with high concentrations of sodium relative to the concentration of calcium and magnesium enters the soil solution, cations on the exchange sites of the soil particles begin to reflect the higher sodium concentrations (Shainberg and Letey, 1984; Hanson et al., 1999; van de Graaff and Patterson, 2001). Eventually, a new equilibrium chemistry between the exchange sites and soil solution will be achieved. As clay content increases, so does the time necessary to reach this new equilibrium. Correspondingly, the time to reverse the sodium accumulation increases (Saskatchewan, 1987). Reduced permeability and hydraulic conductivity due to sodicity compound this problem. Thus, it is likely that soils with large clay fractions will not only be more prone to dispersion, but will also be more resistant to attempts to counter this increased soil ESP (Yaron and Thomas, 1968).

In summary clays are inherently more prone to dispersion than are silts and sands. More salts, including sodium, will accumulate in clay soils as opposed to sandy soils because of clay's inherently lower leaching fraction and greater exposed soil surface. Secondly, **the chance for sodium permeability problems is inherently greater in clay soils because of their structure.** Third, **the greater the clay content, the more time required to reverse the sodium accumulation.** And finally, it should be noted that clay soils are inherently more difficult to work with than sandy soils in terms of tillage, mechanical alteration, leaching, and drainage, especially when they become dispersed (Western Fertilizer Handbook, 1995).

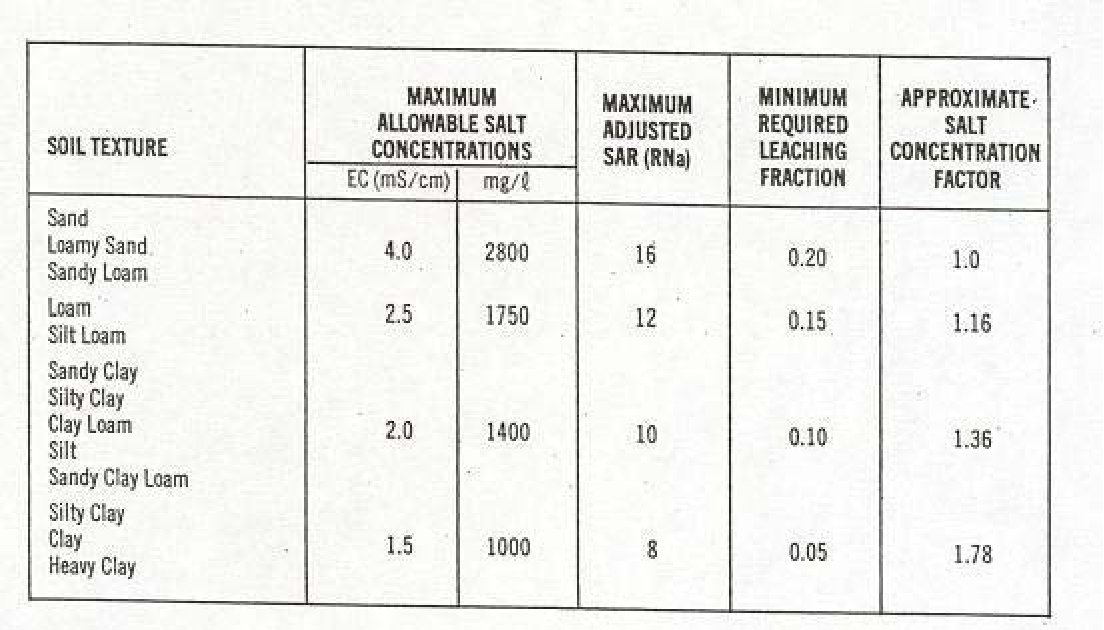
Modifications due to clay type

Ayers and Westcot (1976) reported that **sodium reduces the permeability more in soils predominated with montmorillonite clays than in soils with illite-vermiculite clays, and much more than in soils with kaolinite-sesquioxide clays,** which are the least affected. This is due to the structure of the crystal lattices of the respective clay types (Saskatchewan, 1987). Differences in cation exchange capacities of various clay mineralogies explain much of this difference as well. Montmorillonite clays have the highest cation exchange capacities, followed by illite, and then kaolinite. Thus, **montmorillonite clays have the greatest number of exchange sites per unit of soil where sodium can bind to the soil and cause dispersion of clay particles.** In addition **kaolinite and illite clays have internal chemical bonds which counteract the dispsersive effects of sodium.** Illite clays generally have hydrogen bonds which tend to keep clay aggregates together. Kaolinite clays have potassium bonds which act similarly (Miller and Donahue, 1995). The soil swelling capacity follows the same pattern, with montmorillonite clays having the greatest swelling capacity and kaolinite clays having the least swelling capacity (Buckman and Brady, 1967).

Canadian soil scientists have also defined soil compatibility guidelines pertaining to irrigation water quality. Unlike more general EC x SAR guidelines such as the initial proposals of Ayers and Westcot, after which the figures reported by Hanson et al. (1999) were developed, the guidelines developed for the Saskatchewan Water Corporation account for soil texture as well as salinity and sodicity (Figure 11). They also address the potential for long term salinity and/or sodicity problems. For instance, it may be acceptable to irrigate a sandy soil with higher salinity water, but if groundwater levels are relatively near the surface, groundwater contamination with excess salts may still be a problem (USDA, 2002; Buckman and Brady, 1967; Miller and Donahue, 1995). And similarly, long-term leaching of salts accompanied by retention of sodium in the soil may cause soil dispersion not accounted for in these guidelines (Hoffman, 2002).

Nevertheless, these figures give an immediate comparison of how soils with different textures will react to varying salt and sodium levels.

Figure 14 shows acceptable thresholds of salinity [EC (dS/m) and TDS (mg/L)] and SAR, as well as minimum leaching fractions and approximate salt concentration factors based on the Saskatchewan guidelines. The minimum leaching fraction is the required minimum percentage of applied irrigation water which should leach beyond the root zone. Thus, irrigation practices must account for 20% of the water applied to a soil being lost, i.e. draining beneath the root zone, for sands, loamy sands, and sandy loams. The threshhold EC and SAR values for silty clays, clays, and heavy clays are based on a lower minimum leaching fraction, 0.05 or 5%. These differences in thresholds account for the fact that water will percolate down through a coarse-textured soil faster than one with finer particles (Miller and Donahue, 1995; Buckman and Brady, 1967). The salt concentration factor is an estimate of the average equilibrium salt content in the soil. Equilibrium is the balance achieved between the salinity of the irrigation water and that of the soil.

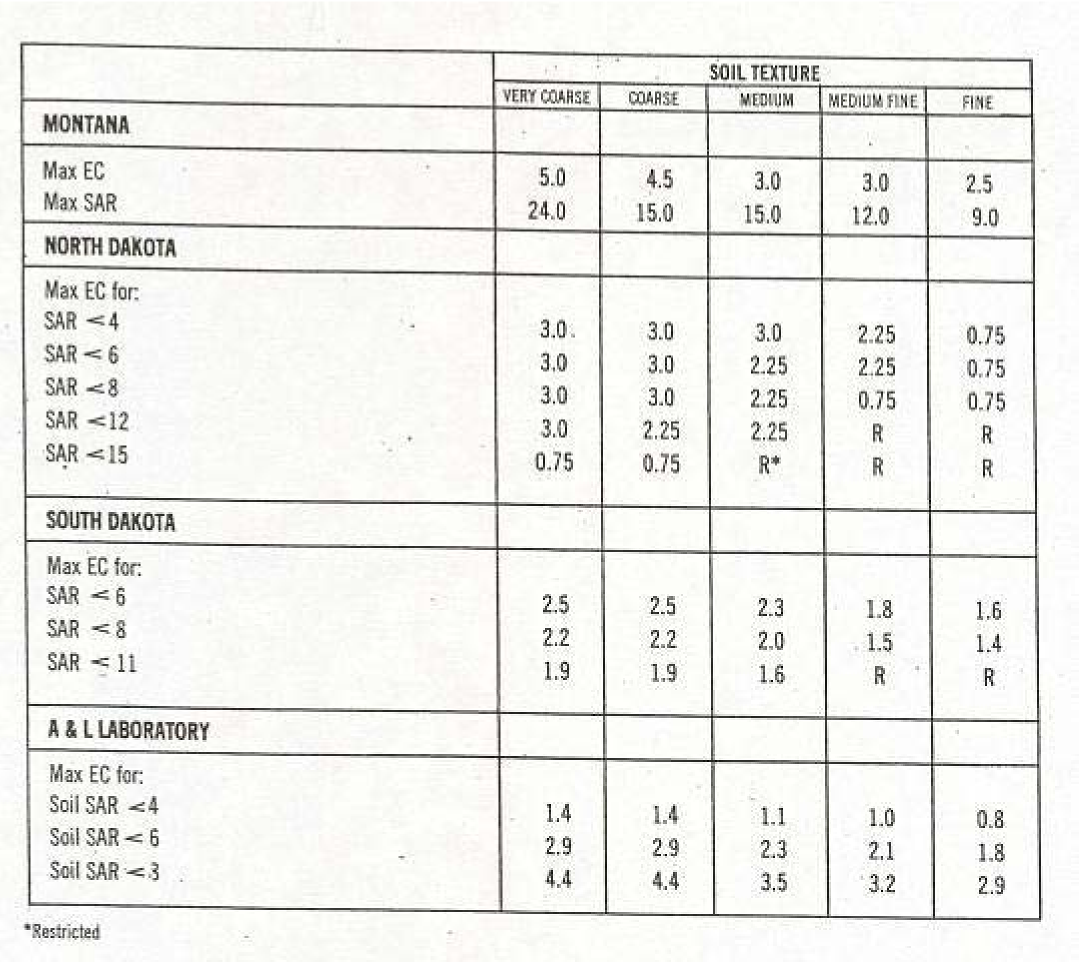


SOIL TEXTURE	MAXIMUM ALLOWABLE SALT CONCENTRATIONS		MAXIMUM ADJUSTED SAR (RNa)	MINIMUM REQUIRED LEACHING FRACTION	APPROXIMATE SALT CONCENTRATION FACTOR
	EC (mS/cm)	mg/ℓ			
Sand Loamy Sand Sandy Loam	4.0	2800	16	0.20	1.0
Loam Silt Loam	2.5	1750	12	0.15	1.16
Sandy Clay Silty Clay Clay Loam Silt Sandy Clay Loam	2.0	1400	10	0.10	1.36
Silty Clay Clay Heavy Clay	1.5	1000	8	0.05	1.78

Figure 14. Salinity and SAR guidelines for irrigation water adopted by Saskatchewan Water Corporation. (Source: Saskatchewan Water Corporation, 1987.)

It should be evident from looking at the chart that coarse-textured soils are less susceptible to the deleterious effects of high EC and SAR levels than are clays. **The threshold SAR and EC values for sands are 16 and 4.0 mS/cm (dS/m), respectively. The threshold values for clays are 8 and 1.5 dS/m. (The adjusted SAR is approximately 25 % greater than unadjusted SAR)** (Hanson et al., 1999). **Therefore, if only an unadjusted SAR value was being used for threshold designation, each value in Figure 14 would need to be reduced by approximately 25 %.)**

Figure 15 presents a summary of the maximum allowable EC and adjusted SARs proposed by the same group in Saskatchewan for Montana, North Dakota, and South Dakota. Included in Figure 15 are proposed maximum allowable values of EC and SAR for five categories of soil texture, ranging from very coarse to fine. Thus, in Montana, for instance, the allowable maximum EC for medium textured soils is 3.0 dS/m and allowable maximum adjusted SAR is 15.0. These adjusted SAR values take into account the precipitation of calcium and magnesium, and hence the rationale for higher sodium proportions and greater SARs.



	SOIL TEXTURE				
	VERY COARSE	COARSE	MEDIUM	MEDIUM FINE	FINE
MONTANA					
Max EC	5.0	4.5	3.0	3.0	2.5
Max SAR	24.0	15.0	15.0	12.0	9.0
NORTH DAKOTA					
Max EC for:					
SAR < 4	3.0	3.0	3.0	2.25	0.75
SAR < 6	3.0	3.0	2.25	2.25	0.75
SAR < 8	3.0	3.0	2.25	0.75	0.75
SAR < 12	3.0	2.25	2.25	R	R
SAR < 15	0.75	0.75	R*	R	R
SOUTH DAKOTA					
Max EC for:					
SAR < 6	2.5	2.5	2.3	1.8	1.6
SAR < 8	2.2	2.2	2.0	1.5	1.4
SAR < 11	1.9	1.9	1.6	R	R
A & L LABORATORY					
Max EC for:					
Soil SAR < 4	1.4	1.4	1.1	1.0	0.8
Soil SAR < 6	2.9	2.9	2.3	2.1	1.8
Soil SAR < 3	4.4	4.4	3.5	3.2	2.9

*Restricted

Figure 15. Summary of proposed EC/SAR guidelines for irrigation water, accounting for texture of soil to which water is applied (Saskatchewan Water Corporation, 1987.)

Referring back to Figure 11 it is evident that as salinity of the irrigation water increases, the tolerable SAR (or in this case adjusted SAR) increases. And the reverse holds true, i.e. lowering the EC necessitates lower SAR limits. The textural categories are accounted for by the vertical dashed line which defines the maximum EC level. The horizontal dashed lines account for the maximum SAR regardless of EC. The combined accounting gives the uppermost EC and SAR thresholds for the soil textural types. Intermediate levels can be readily obtained by matching a given EC with an adjusted SAR. Each textural category assumes, as a precondition, that the given leaching fraction, LF, is occurring. If the leaching fraction is less than the specified value, the EC and SAR threshold values will need to be adjusted downward (Hanson et al., 1999; Buckman and Brady, 1967; Miller and Donahue, 1995; Shainberg and Letey, 1984).

Leaching fraction and rainfall effects

In as much as the leaching fraction is the portion of the applied irrigation water which leaches beneath the root zone, it is assumed that irrigation water with a large leaching fraction (LF) will result in a significant portion of water percolating down through the root zone relative to the amount of water applied (Western Fertilizer Handbook, 1995). During leaching salts move with the water as it leaches past the root zone. Thus, greater LFs allow for greater levels of salts in irrigation water. Correspondingly, greater LFs are also likely to decrease the actual salts that remain in the soil. **The soil solution salinity cannot be less than the salinity of the applied water. The amount of salt remaining in the soil depends on the quality of the irrigation water, how fast it drains through the profile, how much is lost through evapotranspiration, and the amount, rate, and frequency of rainfall.**

The fact that dissolved salts move with soil water while sodium may be adsorbed onto the soil exchange surface has significant bearing on the effect of rainfall on the EC x SAR relationship. This is integral to understanding what actually occurs in the field. The effects that rainwater can have on flushing these salts downward can be quite pronounced (Mamedov et. al., 2000; Hardy et al., 1983). Rainwater of sufficient intensity or duration may flush salts out of the uppermost layer of soil. Soil water and salts contained in it are displaced downward in the soil column by the incoming rainwater (Agassi et al., 1981; Buckman and Brady, 1967; Hardy et al., 1983; Levy et al., 1999; Miller and Donahue, 1995). The result is soil water with appreciably lower EC in the upper portion of the soil. Therefore, the flocculating effect of salinity cannot counter the high soil ESP, and dispersion dominates. The dispersed clay particles clog up macropores and may reform into a cement-like brick pattern, causing a surface crust (Agassi et al., 1981; Ayers and Westcot, 1976; Bauder, 2001; Buckman and Brady, 1967; Hanson et al., 1999; Shainberg and Letey, 1984).

As a general rule, greater LF will reduce salinity levels in the soil but not affect soil ESP nearly as much (Bauder and Brock, 1992; Shainberg and Letey, 1984; Western Fertilizer Handbook, 1995).

Whether or not a greater leaching fraction will cause water to move through the profile faster, and in turn, whether or not this will decrease the ESP is site specific (Miller and Donahue, 1995; Western Fertilizer Handbook, 1995). Quite often in some arid and semiarid areas which have soils with high salts levels, there is insufficient irrigation water or precipitation to achieve high leaching fractions. For instance, in an area (such as eastern Montana) which gets an average of 15 inches of precipitation per year (NOAA, 2002), there is most likely not the necessary amount of excess irrigation water or rainfall to leach salts out of the root zone. Low leaching fractions often lead to salt buildup in the soil over time.

Rainfall can play a similar role in the leaching process. **The way precipitation falls is critical, i.e. whether it occurs as high intensity events or as slow constant precipitation. Agassi et al. (1981) reported that when distilled water simulating rainfall was applied to saline-sodic soil, ESP as low as 6.4 caused dispersion, crust formation, and a sharp decrease in infiltration rate. During extended periods of steady precipitation, infiltrating rainwater replaces water in the soil, reducing the salinity of the soil solution. The net result is a decrease in the flocculating effect of salts and increased potential for dispersion** (Hardy et al., 1983). This effect is most pronounced during sustained flooding events or times such as spring snowmelt, wherein a large amount of water enters the soil relatively quickly, thus significantly diluting the existing soil water (Miller and Donahue, 1995). In semiarid areas of eastern Montana and Wyoming, the majority of precipitation falls in relatively short but intense storm events during the spring and summer and may be subject to by-pass flow (NOAA, 2002). Rapid influx of low EC melted snow in a very short time frame disproportionally lowers the EC compared to ESP, upsetting the balance between flocculation caused by EC and dispersion caused by sodicity (Bauder, 2001). This effect is most pronounced in the uppermost portion of soils.

Conclusion

The relationship between salinity and sodicity is complex but well known. When the basic principles of flocculation, caused by salts, and dispersion, caused by excess sodium, are grasped, the relationship between EC and SAR becomes apparent. As graphs such as Figure 9 illustrate, **reduced infiltration and hydraulic conductivity, and surface crusting caused by sodium, can be mitigated by the flocculating effects of increased salt levels, or an increase in EC. Conversely, even relatively low sodium levels may cause dispersion if EC levels are sufficiently low**. It is necessary to recognize that it is not possible to merely keep increasing EC to counter the dispersive effects of sodium. Generally, at an EC above 2 or 3 dS/m, depending on soil type and crops grown, salt content in the soil will reduce or actually prohibit plant growth (Western Fertilizer Handbook, 1995). While EC is a measure of dissolved salts in irrigation water or the soil solution, ESP is a measure of sodium actually adsorbed onto soil particles. Therefore, while soluble salts can be leached out of the soil, assuming excess water of sufficiently low salt content is present, ESP can only be lowered by chemical modifications which replace sodium adsorbed to the surface of soil particles with calcium and magnesium (Bauder, 2001).

The presence of clays and specific clay types will generally exacerbate dispersion problems. The diluting effect of rainfall and snowmelt will also increase the potential for dispersion (Agassi et al., 1981). It is critical to recognize that soils are actually a complex patchwork of different soil types and textures, all with different chemistries and properties. Particularly relevant to irrigated fields is the different behavior various soils within a single field may have with respect to permeability. The presence of strata with low permeability can make a field unsuitable even if the bulk of the soil has no such problems (Miller and Donahue, 1995; Buckman and Brady, 1967). Textural and structural variability within a soil often leads to marked differences in infiltration as well (Barbour et al., 1998). Thus, it should be noted that the given thresholds assume geologic uniformity as well as consistent infiltration rates throughout the soil profile. Actual field conditions are usually disproportionally affected by low permeability pockets or layers (Saskatchewan, 1987).

Many factors need to be considered when addressing the suitability of irrigation water with respect to salinity and sodicity. The basic relationship between EC and SAR outlined herein will serve as a baseline, with modifications such as soil texture, clay type, leaching fraction, and rainfall serving to provide a more site-specific understanding of how irrigated fields will be affected by salts and sodium. As history has demonstrated, effects salts can have on irrigated land can be devastating, both to agriculture and to societies who depend upon the productivity of the land. While it takes time and energy, understanding how salts and sodium are likely to affect a soil and taking great care to avoid the potential damage they can cause is essential if one hopes to preserve fertile lands.

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