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A Review of Salinity and Sodlicity in Irrigation

Younes D. Ezlit, Rod J. Smith and Steven R. Raine

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University of Southern Queensland

CRC for Irrigation Futures

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Executive Summary

Scarcity of fresh water has led to use of low quality waters (high sodicity and salinity) that were considered unsuitable for irrigation in the past. Mismanagement of irrigation using this water can increase the potential for soil degradation and limit crop production in the long-term. Irrigation using highly saline-sodic water requires appropriate management to avoid long-term development of sodicity and salinity problems. The main factors that control the sodicity and salinity problems are maintenance of sufficient leaching and avoidance of soil structure degradation due to sodicity. However, the management options are determined by complex factors such as soil type and condition, water quality, irrigation practice and crop type. The fundamental processes occurring within soil profile under irrigation with highly saline sodic waters, and the problems related to salinity and sodicity in the soil-water-plant system are complex. Modelling is an efficient tool to quantify and manage these problems. However, there has been limited research in modelling of irrigation under highly sodic and saline conditions.

This paper is part of the doctoral research project titled 'Modelling the Change in Conductivity of Soil Associated with the Application of Saline –Sodic Water'. A complete copy of the thesis can be obtained from www.irrigationfutures.org.au.

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1. Introduction

World growth in population demands more food and fibre. The need for food and fibre production necessitates water to be used more efficiently in irrigated agriculture. However, the scarcity of fresh water is limiting irrigation development. One of the more feasible solutions is to use marginal water for irrigation purposes. Marginal water is generally saline and/or sodic water that has been considered unsuitable for agriculture in the past. Using marginal waters for irrigation requires further consideration of the possible negative effects of salinity and sodicity.

World-wide, most irrigation systems have inherently low efficiencies. In arid and semi-arid areas, significant amounts of water are allocated for irrigation. In these areas, water use efficiency can be improved by increasing the spatial and temporal precision of irrigation applications. However, as irrigation efficiency is increased, salts from the irrigation water are not leached out of the root zone. Consequently, increasing salinity and sodicity in the root zone may become a major concern (Raine et al., 2005). Under these conditions, using marginal water for irrigation without appropriate management can compound salinity and sodicity problems. Many researchers attempted to provide guidelines to use this sodic/saline water for irrigation. However, these guidelines may not be appropriate for different soils and conditions. In addition, the process of quantifying the effect of sodicity may be inherent with errors. Therefore, the aim of this paper is to review the problems related to salinity and sodicity in the soil-water-plant system, and the methods used to quantify these problems.

2. Salts in the Root Zone

2.1. Salinity

Salinity is the concentration of dissolved mineral salts in water and soil-water as a unit of volume or weight basis (Ghassemi et al., 1995). Different qualities of water usually contain nearly the same ions of the elements. The major ions present in water are the anions of chloride (Cl^-), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}) and nitrate (NO_3^-), and the cations of sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+). In hyper saline water, other constituents can be present, such as barium (Ba), strontium (Sr), lithium (Li), silicon dioxide (SiO_2), rubidium (Rb), iron (Fe), molybdenum (Mo), manganese (Mn), and aluminium (Al^{3+}) (Tanji, 1990). Soil solutions have the same components of elements that are in water. The ratios of the constituents in soil-water depend on the chemical reactions that take place in soil-water-plant systems under different conditions.

Chemical analyses provide full details of water salinity (i.e. pure water or soil-water extract) and specific ion concentration. However, as a general predictor, salinity usually is described in irrigation as total salts irrespective of its constituents.

The total dissolved solids (TDS) can be determined simply by evaporating a known amount of water to dryness, and weighing the quantity of dissolved materials contained in that amount. The TDS has historically been expressed in parts per million (ppm), which is a unit of measurement of the weight of salt per unit weight of solution. This unit can be used more readily for more diluted solution, such as water encountered in irrigation. However, ppm might not be accurate in high salinity. A more appropriate unit is mg/L (Bresler et al., 1982). It should be noted that the TDS method might contain some errors because various salts exist in water in different hydration states, which depend on the drying condition (Bresler et al., 1982). In addition, measuring TDS is tedious and time consuming.

Electrical conductivity (EC) is used as a fast method to evaluate water salinity. EC measurements are based on the fact that the electrical current transmitted between two electrodes (i.e. with standardised solution, temperature and electrodes areas that usually equal to unity) increases with an increase of soluble ionic salts and vice versa. The basic SI unit of EC is Siemens per metre (S/m). In agriculture, EC is often low; thus deciSiemens per metre (dS/m) is widely used. The unit (mmhos/cm) used in the past is numerically equal to dS/m.

EC can be related to electrolyte concentration as in Equation 1 for different solution conditions:

$$\log C_o = \alpha + \varpi \log EC \quad \text{Equation 1}$$

where C_o is the salt concentration expressed in mmol_e/L, ϖ and α are empirical parameters which vary with different mixed solutions, and have values of about one.

Bresler et al. (1982) and Smith and Hancock (1986) reported that such a relationship might not always hold, especially at higher solute concentrations. A simplified version of Equation 1, which can be used to calculate salt concentration presented in mmol_e/L for a range of EC between 0.1 and 10 dS/m can be written as (Bresler et al., 1982; Dudley, 1994; USSL Staff, 1954):

$$C_o \approx 10 \times EC \quad \text{Equation 2}$$

Bresler et al. (1982) have indicated that the EC in Equation 2 increases less rapidly with increase of salt concentration. At higher salt concentrations, equivalent to that in sea water (about 33 g/L), Equation 2 underestimates the actual salinity by nearly 20 per cent.

Soil-water salinity depends on the water content at which the salinity needs to be determined. Separating the soil solution from the soil sample is difficult and the quantity of extracted water is usually insufficient to conduct chemical analyses. Therefore, an extra known volume of water can be added to the soil sample before extracting the soil solution. The extraction process can be performed after mixing a given weight of soil with a certain volume of water. Different soil-water extract ratios have been used to predict soil salinity such as 1_{soil}:5_{water}, 1_{soil}: 2.5_{water} and 1_{soil}:1_{water} extract. A good approximation of soil-water salinity is that measured in a saturated soil paste extract. Saturated soil paste extract can be prepared in which a given weight of soil sample is saturated and then the soil solution extracted. Since the water content at saturation is nearly twice that of field capacity, the salinity measurement of the saturated extract is approximately half of the salinity at field capacity (Rhoades, 1982). The salinity predicted in soil solution at field capacity is usually used as a standard value for comparison of salinity data.

Soil salinity in the field can be monitored using various instruments. Examples of these instruments are a salinity sensor based on electronic conductivity, time domain reflectometry (TDR), and inductive electromagnetic meter (Dudley, 1994). More details

about the instruments used to predict field soil salinity were reported by Rhoades et al. (1999).

Soluble salt is usually added to the root zone with irrigation water. The suitability of water for irrigation is evaluated by the amount of soluble salt included, its constituents and the crop response. Ayers and Westcot (1976) concluded that water quality problems occur in four general categories, which are salinity, soil permeability, toxicity, and miscellaneous. Assessment of water salinity is highly dependent on crop salt thresholds. Soil permeability has a strong impact on water and solute movement. Degradation of soil permeability can produce complex problems related to water logging and aeration. In addition, declining soil permeability might compound the salinity problems. Toxicity occurs when certain ions exceed the crop tolerance level. Salinity problems might also result in other problems such as delaying of crop maturity and excessive vegetative growth because of excessive nitrogen in irrigated water (Ayers & Westcot, 1976).

Hoffman (1986) determined three main factors to evaluate water for irrigation which are salinity, sodicity and specific ion toxicities. Pratt and Suarez (1990) pointed out that water suitability for irrigation might be influenced by chemical reactions of dissolved salts in water, chemical and physical properties of soils, climatic conditions, and irrigation management practices. Bar-Yosef (1999) added two further factors in the case where municipal or recycled water is used for irrigation. These factors are biochemical oxygen demand, which is the quantity of oxygen required for microbial degradation of organic compounds in water at 20° C, and total suspended solids in water. Many guidelines have been provided for irrigation water quality, which depend on these factors (e.g. ANZECC & ARMCANZ, 2000; Ayers & Westcot, 1985; USSL Staff, 1954). These factors should be evaluated concurrently before using water for irrigation.

2.2. Sodicity

The level of sodium present in a water or soil is important as it influences the structural stability of clay minerals and the potential for dispersion, erosion and drainage problems. The sodicity of water or soil is usually described in terms of the relative proportion of sodium cations, compared to the divalent cations (i.e. calcium and magnesium) in solution. The sodium adsorption ratio (SAR) of water (including soil solutions) is calculated as:

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}} \quad \text{Equation 3}$$

where the cation concentrations are expressed in mmol/L. However, sodicity in soils is expressed by the exchangeable sodium percentage (ESP) and calculated as:

$$\text{ESP} = \frac{\text{Exchangeable Na}}{\text{CEC}} \times 100 \quad \text{Equation 4}$$

where CEC is the cation exchange capacity. The CEC is the sum of exchangeable cations such as Na^+ , Ca^{2+} , Mg^{2+} and K^+ (as well as Al^{3+} in low pH soils) expressed in mmol/100 g.

2.3. Salinity and Sodicty Problems in Irrigation

The term salinity refers to the concentration of ions in water (Burger & Celkova, 2003). The salinity level for water to be considered as saline depends on the purpose of the water use. Guidelines have been provided for different water uses, including drinking, agriculture and industry. Agriculturally, salinity is the concentration of dissolved mineral salts in water and soil-water as a unit of volume or weight basis (Ghassemi et al., 1995).

Salinity problems become visible when salt concentrations in the soil solution exceed crop threshold levels. Crops can tolerate low concentrations of salt throughout the root zone. Productivity declines above the threshold concentration. The salt tolerance thresholds for crops vary between species. Maas and Hoffman (1977) summarised previous published work and carried out a comprehensive review of crop salt tolerance data, which was subsequently updated by Maas (1990). However, the data indicates that some crops can tolerate a high level of salinity (e.g. 7 dS /m for barley). In addition, the decline of crop yield occurs gradually above the salinity threshold level. Such crop behaviour allows for crop selection and management for irrigation with different water qualities. However, salt tolerance data has inherent uncertainties concerning plant responses to spatial and temporal variations in root zone salinity (Hopmans & Bristow, 2002; Meiri & Plaut, 1985).

Sodicty describes the relative concentration of sodium (Na^+) compared with the divalent cations, mainly calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the soil solution. Sodicty problems manifest at higher relative Na^+ concentration and lead to degradation of soil structure. Sodicty problems are usually inherent with salinity in irrigated clayey soils having

significant sodium content. Sodicity is common also in soils irrigated with water containing considerable bicarbonate concentrations. This is because bicarbonate anions raise soil pH and can result in precipitation of divalent cations and an increase in the relative sodium concentration. High levels of sodium in irrigation water typically result in an increase of soil sodium levels, which affect soil structural stability, infiltration rates, drainage rates, and crop growth potential.

The interrelation between sodicity and salinity levels in irrigation water introduces a dual problem in terms of crop response, soil structure degradation, and irrigation management. An increase of water salinity is shown to have a positive consequence on the sodicity effect. Sodicity has less impact at higher electrolyte concentrations at any particular level. Nevertheless, continuous use of saline irrigation water might lead to an accumulation of salt above the threshold level of crops. On the other hand, low water salinity and high levels of sodicity can cause soil degradation and a reduction in soil permeability. Such degradation results in aeration and waterlogging problems, which negatively affect the crop yield. Consequently, waterlogging and low permeability might also induce salt accumulation within the root zone. Rising salinity associated with an increase of relative Na^+ concentration presents two threshold values to be considered: the lower level is the salinity threshold above which the soil structure remains stable, and the higher salinity threshold level is the salt tolerance threshold of the grown crop.

Sodicity-salinity effects on the physical and hydraulic properties of the soil are very complicated processes that can be influenced by many factors. The main factors that control sodicity problems are soil type (Felhendler et al., 1974; Quirk & Schofield, 1955), clay type and content (Goldberg et al., 1991), pH of the soil solution (Suarez et al., 1984; Sumner, 1993), the manner of application of irrigation water, the initial water content in the soil (Dehayr & Gordon, 2005), and organic matter. Therefore, the soil structure degradation due to rising sodicity is unique for a given soil and its condition (Evangelou & McDonald Jr, 1999). The mechanisms of developing sodicity and related salinity problems under irrigation is conceptualised in Figure 1. Determining the sodicity effect within a given soil requires a comprehensive knowledge of the mineralogy, structure and chemistry of that soil.

In Figure 1, it is assumed the source of total salt and sodium concentration is the irrigation water. The time required to develop sodicity and salinity problems can be determined by the sodicity and salinity levels in irrigation water, along with management practices under this condition. The management options include leaching

for salinity control, amelioration to manage the increase of sodicity level, along with crop selection.

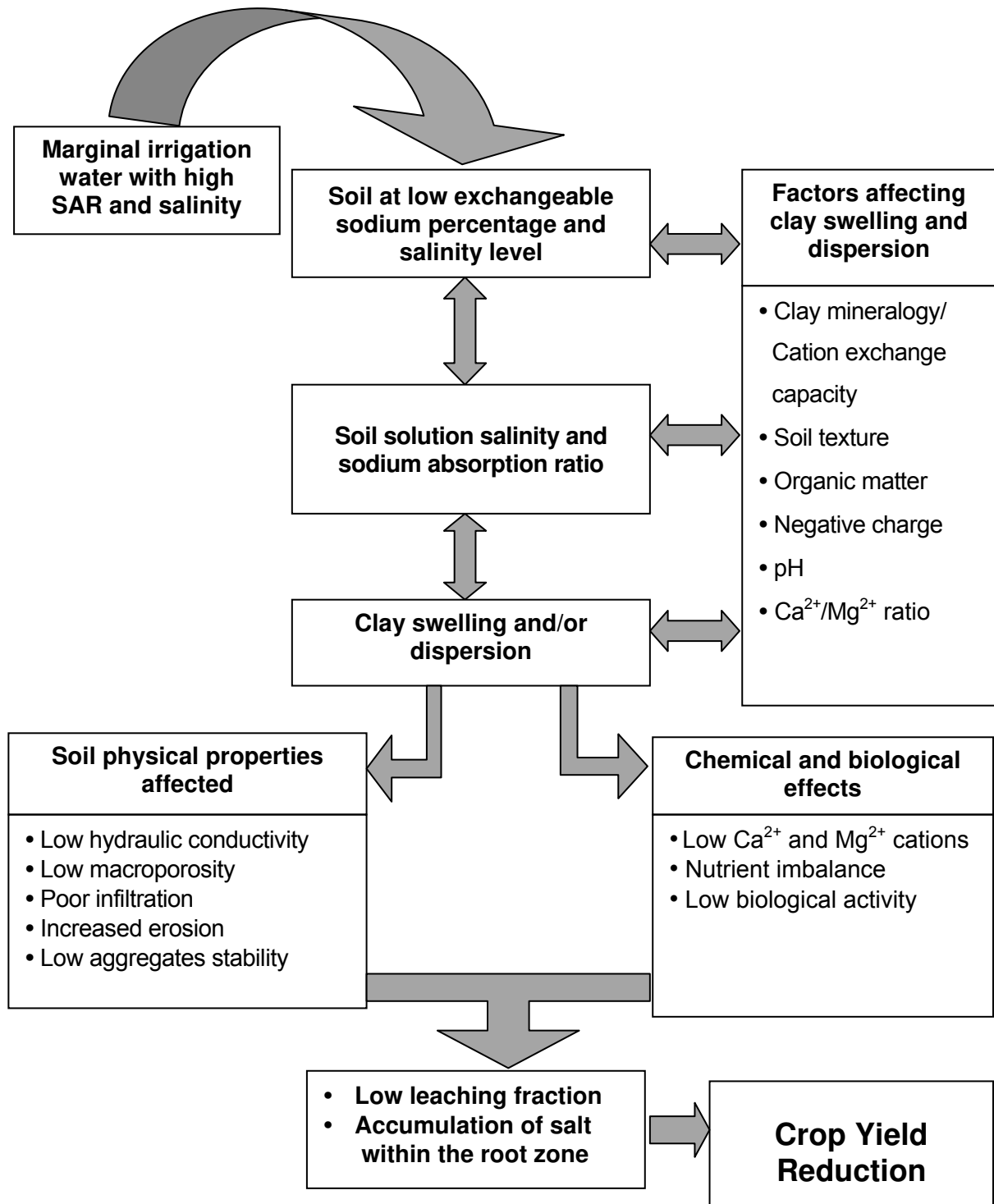


Figure 1. Development of soil problems under saline-sodic conditions (Modified from Surapaneni and Olsson, 2002).

2.4. Relationships between SAR and ESP

Using the measured ESP as an indicator of the level of sodium on soil exchange surfaces may have errors due to the difficulties in determining the CEC. Qadir and Schubert (2002) concluded the reasons for deficiency of ESP in three points: (a) the extraction of exchangeable Ca^{2+} and Mg^{2+} during the chemical analysis process might cause some CaCO_3 and MgCO_3 to dissolve, erroneously leading to an increase of CEC, especially in calcareous soils; (b) the CEC in variable charge soils depends on pH, solute concentration and buffering capacity of soil-water extract; (c) the removal of Na^+ by extraction from a source that does not contain a true form of exchangeable Na^+ , such as sodium zeolites. Furthermore, determining the CEC is time consuming.

So and Aylmore (1993) showed that the exchangeable sodium content (ESC) (in which levels of sodium are expressed on an oven-dried soil basis, rather than relative to the cation exchange capacity (Cook & Muller, 1997)), which is closely related to SAR, is a better indicator to evaluate sodicity. Likewise, Cook and Muller (1997) compared using ESP and ESC to evaluate sodicity, and concluded that ESC or SAR were more the appropriate indices to evaluate the negative Na^+ effect. However, using the ESC as an indicator of the level of sodicity instead of ESP is still limited in the literature.

SAR is thermodynamically more appropriate because it approximates the activities of various cations in solution (Chartres, 1993). In addition, SAR requires fewer parameters (the concentration of Na^+ , Ca^{2+} and Mg^{2+}), and can be determined from the same soil-water extract used to evaluate the EC in soil solution (Qadir & Schubert, 2002).

SAR, however, does not take into account the change of calcium concentration in soil solution as a result of change of solubility of the Ca^{2+} (Ayers & Westcot, 1985; Qadir & Schubert, 2002). Sodium remains soluble and in equilibrium with exchangeable soil sodium all the time. Conversely, Ca^{2+} does not remain completely soluble. Ca^{2+} might be raised in soil solution because of dissolution of soil minerals. Ca^{2+} usually precipitates in the presence of carbonates, bicarbonates and/or sulphates in solution. This process follows the irrigation, which might lead to error in the calculation of SAR of soil-water. In brief, the presence of carbonates and bicarbonates in the water contributes to soil structural degradation in the long-term because the precipitation of calcium carbonate will further increase the relative concentration of sodium ions or the values of SAR in soil-water. Adjusting the SAR to account for the increase of carbonate and bicarbonate concentrations in irrigation water has been reported by Ayers and Westcot (1985), Rhoades (1982) and Suarez (1981).

Furthermore, averaging the concentrations of Ca^{2+} and Mg^{2+} in Equation 3 assumes that both cations contribute equally to overcome the adverse effect of Na^+ cations. However, many researchers (e.g. Brady, 1990; Emerson & Chi, 1977; Keren, 1991; Rengasamy, 1983) pointed out that Mg^{2+} has a low tendency to flocculate the soil colloid compared with Ca^{2+} , especially where Mg^{2+} is present in significant proportion. Conversely, a high concentration of Mg^{2+} might induce clay dispersion. Therefore, equal weight should not be given to Mg^{2+} and Ca^{2+} while calculating SAR (Qadir & Schubert, 2002). In general, SAR evaluation procedures are widely used for most waters encountered in irrigation (Ayers & Westcot, 1985).

The ESP is closely related to the SAR of the applied water. USSL Staff (1954) indicated that if the exchange reactions between soil solution and the soil colloid reach an equilibrium state, the ESP is closely equal to SAR in the range of 0 - 40. The SAR-ESP relationship provides an easy way to estimate the ESP (Qadir & Schubert, 2002). Empirical relationships between SAR and ESP have been established for different soil types. For example, Rengasamy et al. (1984) established a linear relationship between SAR in soil-water extract (1:5) and ESP with R^2 about 0.82 for 138 samples of Australian soils. The linear relationship can be written as:

$$\text{ESP} = 1.95 \text{ SAR}_{1:5} + 1.8 \quad \text{Equation 5}$$

However, Equation 5 was obtained for relatively low values of $\text{SAR}_{1:5}$ (0.38-12.4) and ESP (0.42-22.2).

The SAR-ESP relationship developed by SSSL Staff (1954) was based on a linear correlation between experimental measurements of soil exchangeable sodium ratios (i.e. $\text{ESR} = \text{EXNa}/(\text{CEC}-\text{EXNa})$) and ESP for 51 American soils. The linear relationships produced ($R^2=0.923$) was:

$$\text{ESR} = -0.0126 + 0.01475\text{SAR} \quad \text{Equation 6}$$

where EXNa is the exchangeable sodium concentration.

Since the ESP can be calculated from ESR as:

$$\text{ESP} = 100 \times \left(\frac{\text{ESR}}{1 + \text{ESR}} \right) \quad \text{Equation 7}$$

The relationship can also be written as:

$$ESP = \frac{100(-0.0126 + 0.01475SAR)}{1 + (-0.0126 + 0.01475SAR)} \quad \text{Equation 8}$$

It is noteworthy that the SAR-ESP relationship varies from one soil type to another due to differences in clay minerals content and texture in soils. Figure 2 shows the comparison of different empirical parameters for Equation 8 over a wide range of SAR. It can be observed from Figure 2 that at low SAR values some equations produce negative values of ESP and that SAR= 0 at ESP higher than zero. The equation developed by USSL Staff (1954) gives negative values of ESP below SAR (0.5). The equations of Ghafoor et al. (1988) also produced negative values of ESP for SAR values less than three. These results indicate that the minimum value of ESP of zero (Dudley, 1994) was ignored during the regression analyses between SAR and ESR. The negative predictions for ESP values produced from these equations indicate that these models should be corrected at the lower range of SAR-ESP (i.e. as SAR approaches zero). However, Equation 8 has been approved for values of SAR and ESP up to 65 and 50, respectively, for a wide range of soils, including Australian soils (Department of Natural Resources, 1997; Skene, 1965).

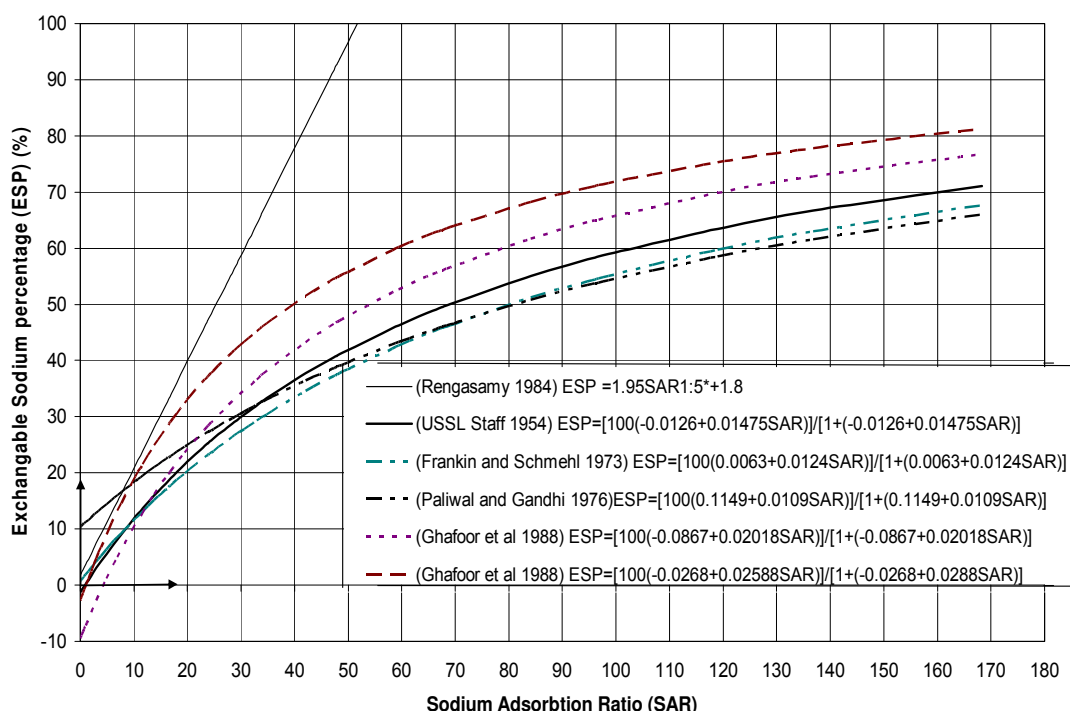


Figure 2. Comparison of different SAR-ESP relationships published in literature at wide range of SAR (0-169) (Source: Qadir and Schubert, 2002).

Note: SAR1:5 is the Sodium Adsorption Ratio of soil to water extract 1:5, and SAR is Sodium Adsorption Ratio of saturated soil paste extract.

2.5. The Distribution of Salts within the Root Zone

The salt movement and accumulation within the root zone varies with different irrigation systems. Salt distribution profiles depend on the irrigation system and its management, climate, and the soil condition. Sprinkler, border check, and level basin irrigation systems produce one dimensional vertical flow. Thus, for these systems, most of the salts are expected to accumulate in the lower parts of the root zone (Burt, 1995). The upper parts are leached by the applied irrigation water. Root water extraction results in salts increasing in concentration as water flows downward through the soil profile (Tanji & Kielen, 2002). Reduced water flow at depth also leads to a reduced capacity to flush salts from deeper parts of the root zone (Burt, 1995; Tanji & Kielen, 2002). Furrow and trickle (i.e. line source) irrigation systems produce two dimensional water flow. The salt may accumulate in the upper part of the root zone between the adjacent rows (Figure 3). A semi-spherical water flow is inherent with drip (i.e. point source) irrigation, allowing the salt to accumulate away from the water source.

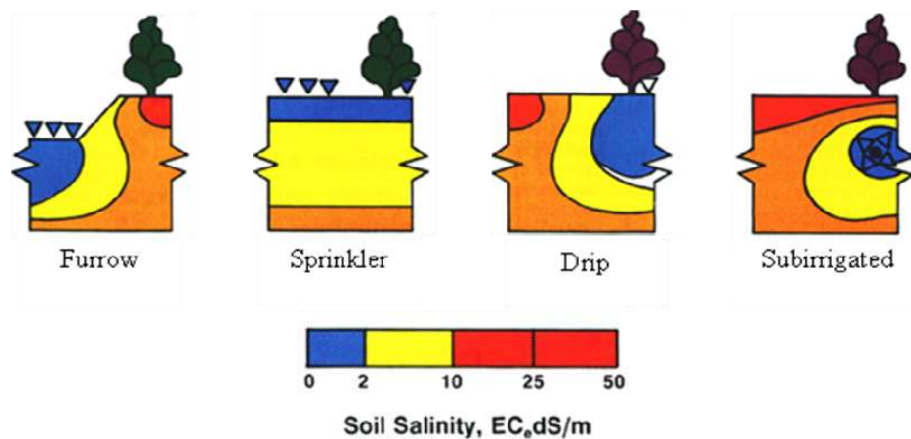


Figure 3. Root zone salt distribution under different irrigation systems (Source: Oster et al., 1984).

A more complicated situation can be found under sub-irrigation systems. In these systems, water and solute flow in spherical dimensions. The main complexity in this system is water moves upward to soil surface. Such water movement allows salt to accumulate in the surface soil. However, rainfall can flush downward the salt accumulated near the soil surface, which makes controlling salinity under this system difficult.

Furthermore, root zone salt distribution is different in the presence of a shallow water table as capillary rise plays a major role in redistributing the accumulated salt within the root zone (Burt, 1995; Scherer et al., 1996).

Smith and Raine (2000) divided the historical hierarchy of irrigation practices into three stages: traditional irrigation, precise irrigation and prescription irrigation. The past practise of irrigation was simply applying water to crops. Current practise is more precise irrigation which ensures the efficient and uniform application of water to meet the spatial average requirements of crops. Future prospects include prescription irrigation, which is the accurate, precise and possibly spatially variable application of water to meet the specific requirements of individual plants. Clearly, new developments in both design and management can provide differential delivery of optimal irrigation water quantities over an entire field (Perry, 2006), which is not uniform and has a variation in soil type, soil-water capacity, yield potential and topography (Dennis, 2006). Precision irrigation as a current practise can be defined as the accurate and precise application of water to meet the specific requirement of individual plants or management units and minimise adverse environmental impact (Raine et al., 2005). Under these systems more attention should be paid to salinity and sodicity effects.

2.6. Crop Responses to Saline Conditions

The responses to saline conditions vary among crops, but the reaction can be similar. Two kinds of salinity effects can be distinguished. The first is the osmotic effect, which can induce losses of the plant energies that are needed for other physiological processes. If the osmotic potential of the soil becomes low, the root tissues suffer osmotic desiccation (Katerji et al., 2003; Tanji, 1990). The second is the toxicity effect, as a result of a certain ion level rising above its threshold (Katerji et al., 2003; Tanji, 1990), which makes determining the general thresholds for crops more complicated (Patel et al., 2002). The situation can be more severe at the lower water contents, where the plant is expected to reach wilting point at higher levels of moisture than when less saline water is used (Burt, 1995). In addition, the salinity has a strong impact on the chemical properties of the soil in a way that can hamper the absorption processes of the vital nutrient elements (Lauchli & Epstein, 1990). Figure 4 shows the main effects of salinity on crop growth.

During last century, many researchers conducted experiments to determine the salt tolerance of crops. Maas and Hoffman (1977) have summarised these findings and carried out a comprehensive analysis of salt tolerance data, which was updated by Maas (1990). The assumption is made that the plant responds to uniform root zone salinity. Crop tolerance is described as functions of yield reduction across a range of soil salinity (Maas & Hoffman, 1977; van Genuchten & Hoffman, 1984).

There are substantial difficulties in determining a soil solution parameter that can be readily measured in the field and is related to plant response (Smith & Hancock, 1986). Many empirical methods have been proposed to determine root zone salinity that can be used as an indicator of plant response. Bernstein (1961; 1964) assumes salinity in the drained water can be equal to the plant salinity thresholds at which the yield in the salt tolerance experiments decrease to 50 per cent for forage, field, and vegetable crops, and 10 per cent for fruit crops. Bernstein and Francois (1973) suggest the leaching requirement of Bernstein (1961; 1964) can be reduced to one-fourth as crop growth is comparatively insensitive to salt concentration in the lower part of the root zone. Van Schilfgaarde et al. (1974) recommend the thresholds should equal the salinity at which the roots cannot extract the water from the root zone. However, based on experimental evidence, Hoffman and van Genuchten (1983), and Rhoades (1974) state that the Bernstein (1961; 1964) method overestimates the plant salt threshold, and the van Schilfgaarde et al. (1974) method underestimates the plant salt threshold.

A logical assumption for the root zone salinity is that the salinity in the soil-water will be between the irrigation salinity and salt concentration in the drainage water C_d (Bernstein & Francois, 1973; Cavazza, 1989; Rhoades, 1974). Rhoades (1974) believes the crops respond to an average salt concentration in the soil solution C_{ws} , which lies between the salt concentration in the irrigation water C_{ir} and C_d , which can be shown as:

$$C_{ws} = \frac{\kappa_s}{2}(C_d + C_{ir}) \quad \text{Equation 9}$$

where κ_s is an empirical constant.

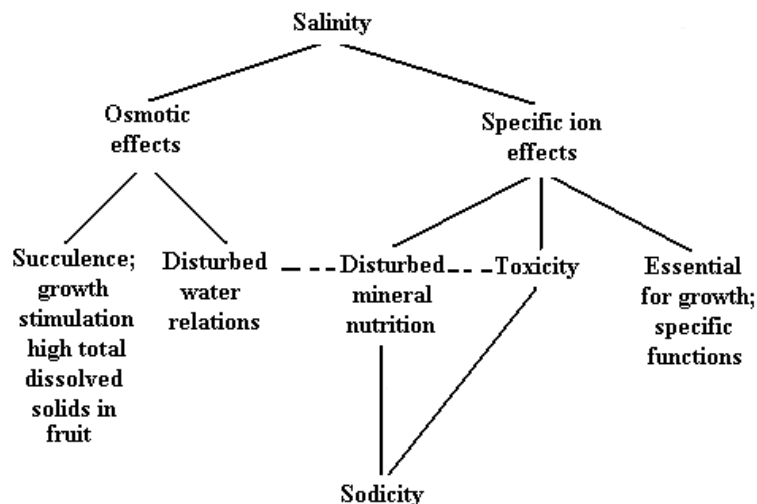


Figure 4. The effects of salinity and sodicity on plants (Source: Tanji, 1990).

Hoffman and van Genuchten (1983) related crop response to the linearly averaged salt concentration of the root zone. The relationship was expressed as a ratio of the salt concentration of the irrigation water. An exponential root water uptake pattern function was assumed giving:

$$\frac{\bar{C}}{C_{ir}} = \frac{1}{L_f} + \frac{\delta}{z_r L_f} + \ln \left[L_f + (1 - L_f) e^{-z_r / \delta} \right] \quad \text{Equation 10}$$

where \bar{C} is the linearly averaged salt concentration of the root zone, δ is an empirical constant set to $0.2z_r$, z_r is the depth of the root zone, and L_f is the leaching fraction.

The effect of the variation of salinity on the plant response is involved through the weighted average root zone salinity.

The spatial variation of the salt concentrations might have a significant effect on the crop response. Bernstein and Francois (1973) recommended using the weighted average root zone salinity. Minhas et al. (1990) related crop performance to the weighted average root zone salinity. Maas (1990) reported that crop growth is closely related to the soil-water salinity in that part of the root zone where most water uptake takes place. Therefore, plant tolerance to salt could be related to the time-integrated salinity of the part of the root zone contributing the most root uptake. Furthermore, Rhoades (1982) mentioned that crop yields are better correlated with the water-uptake weighted root zone salinity for crops irrigated on a daily or near daily basis (localised or drip irrigation). Moreover, Ayers and Westcot (1985) commented that the differences are not great but may become important with higher salinity.

Many researchers, however, indicated that the plant responds to average root zone salinity irrespective of root water extraction. For example, Meiri (1984) concluded there is a stronger relationship between crop yield and average root zone salinity, compared with weighted average root zone salinity. Hoffman (2006) stated “the plant response is better correlated with average root zone salinity, but the problem is determining that average”. Evidently, clarifying the effect of the variation of salinity within the root zone requires a better prediction of spatial distribution of soil profile salinity.

2.7. Leaching of Salts from the Root Zone

Leaching is associated with water flow in soil. Most solute transport is by the convection (Raine et al., 2005). The main leaching occurs during irrigation when the irrigated water

infiltrates and redistributes in the soil. This infiltrated water does not mix readily with the soil-water. Miyazaki et al. (1993) concluded infiltrated water pushes the soil solution away from the infiltrating source during the infiltration. However, the displacement of the soil solution might not happen in blocked pores or in the inner pores of clayey aggregates. Furthermore, an early study by van Genuchten (1976) indicated a part of the solute might remain in these spaces.

During the irrigation, two paths of infiltrated water into the soil can be distinguished; bypass water flow, and soil matrix water flow. Bypass flow is the part of the infiltrated water that passes quickly into the cracks or larger pores and out of the root zone (Tanji & Kielen, 2002). This part of the infiltrated water does not significantly participate in the leaching process. The second passes through the pores, which are filled by soil solution, and convey a high part of the soluble salt (Miyazaki et al., 1993).

The main strategy that should be used for efficient leaching is to reduce bypass flow and the proportion of soil pores that do not contribute to matrix flow (Miyazaki et al., 1993). The bypass flow can be controlled by the infiltration rate or application rate during the irrigation to ensure that unsaturated flow processes dominate (Khosla, 1979; Rycroft & Amer, 1995). Reducing the application rate might also allow the solute in the remaining soil solution to diffuse to the drained water (Rhoades, 1982). Furthermore, rising sodicity levels might lead to an increase of micro-pores that retain soil solution. This might affect the leaching processes negatively. Under such conditions, using the pulse irrigation technique could improve the leaching process (Hamdy, 2002).

2.7.1. Leaching under Steady State Conditions

Traditional methods for determining the leaching requirement of an irrigated soil assume steady state conditions. There are four fundamental assumptions associated with this approach. Firstly, irrigation water mixes completely with the soil solution. Secondly, the exchange processes and chemical reactions which take place in soil are not taken into consideration, which means there are no salts precipitated or dissolved. Thirdly, the amount of salt supplied by fertilisers and exported by crops is negligible. Finally, the drained water carries the same mass of salt as applied in the irrigation water. Soil salinity is assumed constant from one season to the next (Rhoades, 1974; Tanji & Kielen, 2002; USSL Staff, 1954). The simple formula to calculate the leaching requirements (LR) based on steady state conditions can be expressed as (USSL Staff, 1954):

$$LR = \frac{D_d}{D_{ir}} \cong \frac{EC_{ir}}{EC_d} \quad \text{Equation 11}$$

where D_d is the depth of drained water, D_{ir} is the depth of irrigated water, EC_{ir} is the electrical conductivity of the irrigation water (dS/m), and EC_d is the electrical conductivity of the drainage water (dS/m).

The steady state assumptions have been made to simplify the leaching calculation. However, weathering of the soil matrix and dissolution of fertilisers may be a significant source of salts in the long-term (Rhoades, 1982). Similarly, salts may precipitate out of solution or be taken up by the crop. In addition, mixing of the irrigation water with soil solution is not always complete and is influenced by the presence of the preferential flow paths (Miyazaki et al., 1993). The term leaching efficiency has been used to indicate there is a fraction of irrigated water which passes through the large pores within the root zone (i.e. with little increase in the salt content) (Stevens, 2002), while the remaining water mixes with soil solution in the smaller pores to convey the salt out of the root zone. However, fine-textured soils (where cracks and large pores may abound, and significant micro-pores retain water) have lower leaching efficiency (Bouwer, 1969).

The steady state leaching might be achieved under a few cases, particularly in the long term. However, steady state conditions are difficult to achieve due to variations in the applied water quality, solute movement within the soil, root water uptake dynamics and the physical and chemical changes within the soil profile. Therefore, salt concentration and distribution is expected to vary during the cropping season (Mmolawa & Or, 2000). Van Hoorn et al. (1997) conducted experiments in lysimeters using different crops and concluded that complete mixing and homogeneous salt distributions do not exist in reality. However, the steady state model might be useful for estimating the long-term average salinity of the soil profile.

2.7.2. Leaching under Unsteady State Conditions

The main criterion for unsteady state conditions is that some of the salt added by the irrigation water remains in the root zone or vice versa. The unsteady state conditions are dominant, especially in the field where the leaching fractions are low (Hamdy, 2002). The salt stored in the root zone can be predicted as (Tanji & Kielen, 2002; van Hoorn & van Alphen, 1994):

$$\Delta Sa = \frac{I_{ir} EC_{ir} - \frac{D_d Sa_{start}}{\theta_{fc}}}{1 + \frac{D_d}{2\theta_{fc}}} \quad \text{Equation 12}$$

where I_{ir} is the depth of irrigation water, ΔSa is the change of salt storage within the root zone, Sa_{start} is the initial amount of the salt in the root zone, and θ_{fc} is the moisture content at field capacity.

An alternative model which has been used in heavy soils is the chloride mass balance model (Rose et al., 1979). Chloride is a toxic element that moves readily with water within the soil and into the plants (Ayers & Westcot, 1985). In this model, the deep percolation is predicted by assuming the irrigation water is the sole source of input of chloride within the root zone. Taking into consideration the preferential flow, the equation can be written (Slavich & Yang, 1990):

$$z_r \bar{\theta}_s (1 - \bar{\alpha}) \frac{d\bar{C}_{Cl}}{dt} = i_{ir} C_{ir} - dL [f_z C_z + (1 - f_z) C_{IW}] - b_z i_{ir} C_{SW} \quad \text{Equation 13}$$

where z_r is the root zone depth, $\bar{\theta}_s$ is the depth weighted mean volumetric soil-water content at field above z_r , $\bar{\alpha}$ is the depth weighted mean anion exclusion volume as a proportion of the volumetric soil-water content above z_r , \bar{C}_{Cl} is the depth weighted mean soil-water chloride concentration at saturation above z_r , f_z is the proportion of the matrix flow that has the concentration of the soil matrix, \bar{C}_z is the chloride concentration of soil-water at z_r at field saturation water content, C_{SW} is the chloride concentration of soil-water at z_r , b_z is the proportion of applied water moving as bypass flow past z_r , t is the time, i_{ir} is the rate of irrigation water application, and dL is the leaching rate.

3. The Effect of Salinity and Sodicy on Soil and Water Movement

3.1. Clay Minerals and Dispersion

Brady (1990) categorised clay types in four major groups of colloids present in soils: layer silicate clays, iron and aluminium oxide clays, allophone and associated amorphous clays, and humus. All the groups have general colloidal characteristics, however each group has some specific characteristics. Silicate clay minerals are the most prominent clay minerals in soils of temperate areas and tropical soils (Brady, 1990). The most important property of this group is the clarity of their crystallines, which are layer-like structured. The silicate clay fraction in general consists of many plate-like minerals. Crystalline particles are made up of two basic units which are tetrahedral silica and octahedral aluminium hydroxide in alternating layers, as shown in Figure 5. Due to imperfections in the crystals the Si^{4+} is substituted with aluminium (Al^{3+}) ions, and some Al^{3+} ions are replaced by magnesium (Mg^{2+}) ions. Silicate clays commonly have permanent negative charges which enable clay fractions to attract cations.

The silicate clays fall into three subcategories, which are 1:1, 2:1, and 2:1:1 type minerals. The layers of 1:1 types are made up of one sheet tetrahedral silica and an octahedral aluminium hydroxide sheet. The 2:1 types are comprised by an octahedral sheet between two tetrahedral layers to form a sandwich like shape. The crystals of 2:1:1 type minerals consist of two slides of silica tetrahedral and two octahedral. In general, only the 2:1 clay minerals exhibit swelling during the wetting process. Most swelling clay minerals for this group are smectite minerals, such as montmorillonite (Churchman et al., 1993).

The increase of relative concentration of a specific cation in the soil solution can increase the adsorption ratio of that cation on the colloid surface. The order of strength of adsorption on the clay surface, when the cations are present in equivalent quantities in the soil solution is Aluminium (Al^{3+}) > Calcium (Ca^{2+}) > Magnesium (Mg^{2+}) > Potassium (K^{2+}) = Ammonium (NH_4^+) > Sodium (Na^+) (Brady, 1990). Clay particles do not have a very strong preference for which cations are adsorbed to compensate for their built-in negative charges (van de Graaff & Patterson, 2001). The relative concentration of the cations in the soil solution might determine which is the dominant cation being adsorbed. For example, increasing the Na^+ cations in the soil solution will replace gradually the Ca^{2+} and Mg^{2+} cations. However, it is easy to replace Na^+ on the exchange complex by increasing the divalent cations such as Ca^{2+} , because Na^+ is less effective in neutralising the negative charges, and clay fractions have preference for cations with more than one positive charge (van de Graaff & Patterson, 2001).

Therefore, when excessive irrigation water is applied, it is most likely that the cations adsorbed on the negative charges are closely related to the relative concentrations of cations in the added water.

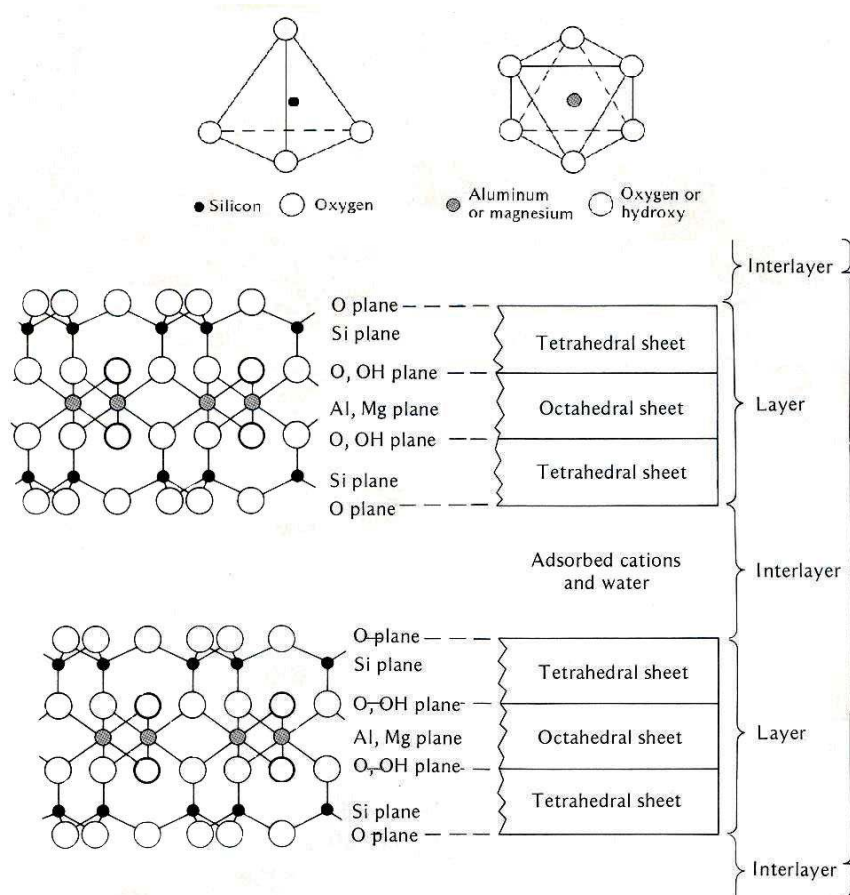


Figure 5. Basic molecular and structural components of silicate clays (Source: Brady, 1990).

Sodicity is manifested when the sodium concentration in the soil solution increases and the structural stability of soil aggregates degrades significantly. Quirk and Schofield (1955) explain that soil structural degradation caused by sodicity in soils is due to swelling and dispersion processes. Swelling is the increase of aggregate size as a result of water and sodium cations entered between the platelike structure, while dispersion describes the process of separating and moving the clay layers with percolated water. According to the diffuse double layer theory (DDL), both swelling and dispersion processes stem from the balance between repulsive forces (as a result of osmotic pressure) in diffuse double layer and Van Der Waals forces of attraction on clay fraction surfaces (Sumner, 1993). Swelling is a reversible and continuing process and depends on the threshold concentration of ambient solution and the degree of sodicity. Dispersion is not a continuing process and may occur even at low SAR, as long as soil salinity cannot prevent dispersion. Dispersion is an irreversible process because flocculation by

increasing concentration above the threshold level does not restore the original particle associations and orientations (Levy, 2000).

The clay mineral crystal layers in soils are closely associated with each other to form structures known as “domains” or “tactoids” (Quirk, 2001). In such systems, dispersion can only occur if the individual mineral layers separate. Quirk (2001) describes this system using a simple “three plate model”, in which individual clay crystals overlap as shown in Figure 6.

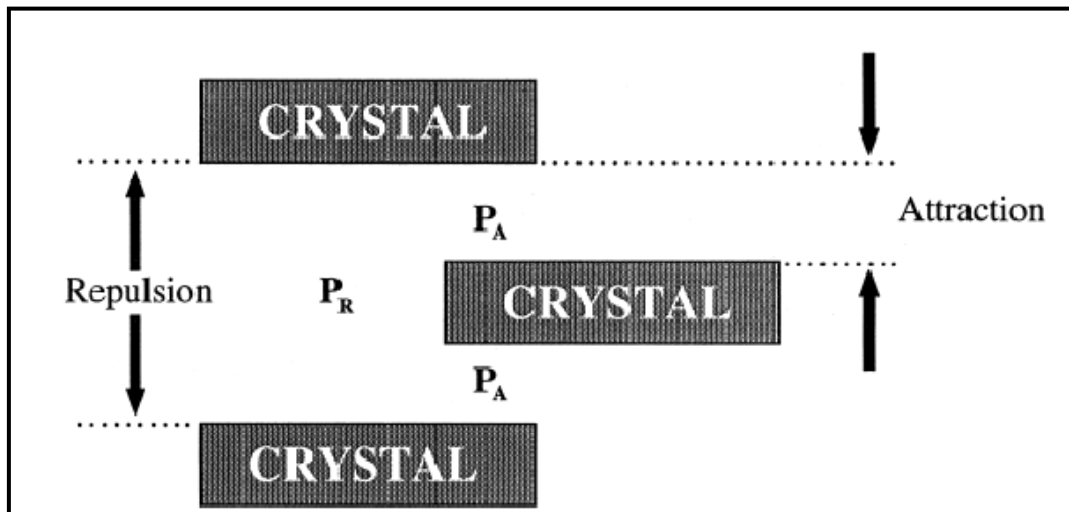


Figure 6. A simple 3-plane model to describe the arrangement of clay crystals in a clay domain (Source: Quirk, 2001).

This model is useful for illustrating the swelling and dispersion processes, and the effect of exchangeable sodium on dispersion. When water or an electrolyte solution is added to soil, repulsive pressure (P_R) develops over the surface area of the larger slit-shaped pores. These forces arise from associated osmotic effects and the change in the diffuse double layer. At the same time, an attractive pressure (P_A), associated with Van Der Waals forces, operates over the surface area of the closely aligned crystals (Kjellander et al., 1988; Raine & Loch, 2003). Dispersive cations, mainly sodium, tend to concentrate in the slit-shaped pores (Sumner, 1993) and form extensive double layers (compared to smaller double layers for cations of higher valence), particularly if the salt concentration of the soil solution is low. Thus, the repulsive force can more readily exceed the attractive force in soil systems containing sodium, resulting in “spontaneous dispersion” when the soil is exposed to excess water at low electrolyte concentration (Raine & Loch, 2003). When the repulsive force is nearly equal to the attractive force, dispersion will require the input of a threshold to shear stress from flowing water or raindrops (Sherard et al., 1976).

Cook et al. (2006) demonstrated that the structural stability of soils, which have reactive clay content, is dependent on the interaction between soil sodicity and salt concentration in the soil solution. Clays will swell and disperse spontaneously at a certain relative sodium concentration value when the salt concentration in soil-water is below a critical electrolyte concentration, defined as the threshold concentration (Quirk & Schofield, 1955). This will be discussed later in the chapter.

3.2. Clay Dispersion and Hydraulic Conductivity

The impact of sodicity is usually evaluated in terms of the reduction in saturated hydraulic conductivity (K_{Sat}), or occasionally infiltration rate. It is worth noting that comparing the absolute K_{Sat} measurements for a given soil is difficult and may lead to erroneous results. The K_{Sat} values for a given soil can vary substantially and depend on soil conditions. The measurement of K_{Sat} in the laboratory depends on the length of the soil columns and the way they are packed. Therefore, the use of relative K_{Sat} could eliminate these variations (Ayers & Westcot, 1985; McNeal, 1968; Quirk, 2001; Quirk & Schofield, 1955; Simunek & Suarez, 1997; Simunek et al., 2005). The relative K_{Sat} requires having a measurement of K_{Sat} under conditions at which there is no reduction of K_{Sat} due to sodicity.

The potential for reduction of infiltration or K_{Sat} is evaluated on the basis of the salinity and relative Na^+ content of the applied water. It has been shown by many researchers (e.g. Quirk & Schofield, 1955, Levy et al., 2005) that aggregate slaking, clay swelling and dispersion are the main processes resulting in K_{Sat} decrease. Slaking is a physical process in which soil aggregates disintegrate. Aggregates break down either by explosion of entrapped air or by differential swelling into smaller size aggregates or micro aggregates during wetting of a dried soil (Ruiz-Vera & Wu, 2006). Slaking causes a reduction in K_{Sat} as a result of disintegration of the soil aggregates when water is added to dried clayey soils. Auerswald (1995) found that the air entrapped within the soil pores was the main reason of aggregate disintegration of pre-wetted aggregates of 113 arable top soils during percolation tests, while shear force of the percolating water, swelling, and clay dispersion had an insignificant effect on aggregate disintegration. Furthermore, Abu-Sharar et al. (1987) states the extent of slaking depends on relative concentration of Na^+ , and for soils with lower salinity levels, dispersion can be noted at the final stages of the slaking process. However, the K_{Sat} reduction is mainly attributed to the interrelated phenomena of swelling and dispersion (Levy et al., 2005). Swelling reduces soil pore sizes, and dispersion clogs soil pores (Frenkel et al., 1978). Drastic changes in

K_{Sat} due to dispersion and particle movement are irreversible, while K_{Sat} change because of swelling is reversible. Therefore, determining which process is predominant is important (Frenkel et al., 1978).

The K_{Sat} reduction at high salt concentration and SAR of water added seems to be attributed mainly to the swelling. McNeal and Coleman (1966), Quirk and Schofield (1955), and Russo and Bresler (1977a) suggest that swelling of clay particles associated with an increase in SAR could result in total or partial blockage of the conducting pores. McNeal et al. (1966) found a linear relationship between reduction of K_{Sat} and macroscopic swelling of the extracted soil clay. In swelling clay, during soil wetting, the swelling process under sodic condition can be highly dispersive because ion hydration and osmotic swelling forces pull water into interlayer spaces between the clay platelets. The swelling forces push clay particles apart and cause the breakdown of the aggregates of swelling soils (Quirk, 2001). Furthermore, many of the bonds between particles can be broken at the shear plane of the wetting front during the initial stage of water infiltration into dried soil (Quirk, 2001).

Clay swelling due to sodicity has not been noted at ESP less than 15 per cent (Oster et al., 1980). However, Smith and McShane (1981) and Ayers and Westcot (1985) reported low salinity irrigation water, especially below 0.2 dS/m, can cause severe infiltration problems regardless of the level of sodicity, as a result of an excessive leaching of Ca^{2+} cations from the soil. Frenkel et al. (1978) investigated the change of the water suction along soil columns dominated by montmorillonite, vermiculite and kaolinite at low SAR and electrolyte concentrations of the water applied. The results show that the hydraulic gradient increased with depth before decreasing again (Figure 7). The increase in suction was higher when diluted water was applied. The results indicate the upper parts of the soil columns were clogged as a result of clay fraction movement or dispersion.

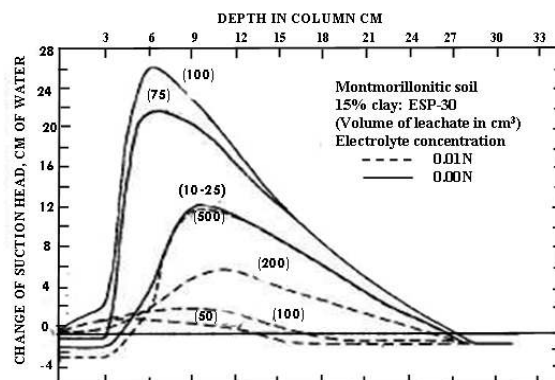


Figure 7. Change of suction head produced by leaching a column of soil dominated by Montmorillonite (Source: Frenkel et al., 1978).

Note: 15 per cent clay, ESP =30, with 0.01N, SAR 30 solution and pure water added.

Emerson and Bakker (1973) explain that when water with a low electrolyte concentration and SAR is added to the soil, the solute concentration in the macro-pores drops to levels below the critical concentration. As a result, a sharp osmotic gradient will be created between the water solution in the micro-pores (i.e. inner pores in clay aggregate between clay layers) and the water in the macro-pores. This osmotic gradient at critical concentration of added water (at which the shear stress on the clay particles exceeds a critical value) will pull the water into the inner pores between the platelets. This in turn leads to clay dispersion of the outer layers of the aggregates and is followed by a decreasing osmotic gradient. A lower osmotic gradient below the critical concentration may cause swelling in the remaining clay aggregates. Although the aggregates do not break down, swelling of the soil aggregates into the inner-aggregate pores occurred (Jayawardane & Beattie, 1978). This explanation was experimentally emphasised by Pupisky and Shainberg (1979), in which water of a wide range of SAR and electrolyte concentration were added to red brown soil columns. In addition, Pupisky and Shainberg (1979) concluded that at low ESP and electrolyte concentration, the main process causing degradation of K_{Sat} is clay dispersion. Swelling is the main reason at higher ESP and soil-water salinity.

The dispersion process might be highly dependent on the osmotic gradient, initiated between the added water solution percolating in macro-pores and water solution in the micro-pores. Keren and Singer (1988) show that adding deionised water to soil columns after a leaching by 10 mmol_c/L solutions with SAR 5, 10 and 20 results in a sharp decrease in K_{Sat} and the appearance of clay fraction in the outflow. Nevertheless, no clay fraction was noted in the outflow and the reduction of K_{Sat} was less and gradual when applying 10 mmol_c/L solution, and was followed by incrementally lower concentrations before applying deionised water.

The reduction in K_{Sat} under sodic conditions can be interpreted basically as a result of the relative effect between both swelling and dispersion processes. The K_{Sat} reduction is a result of many factors inherent with soil itself and soil condition. Dominant clay types may be a major factor determining which process prevails. The threshold concentrations concept, discussed later in section 3.4, is useful to distinguish between the processes of clay swelling and dispersion within the soil. The K_{Sat} reduction within soil might be the result of total effect of clay types within the soil, which may disperse or swell by different manners as affected by many factors associated with soil conditions.

3.3. Factors Affecting Dispersion and Hydraulic Conductivity

3.3.1. Temporal Changes in Soil-Water Content

The effect of temporal changes in soil-water, such as the initial water content, rate and ageing of wetting under sodic conditions, might have a significant effect on K_{Sat} reduction. Panabokke and Quirk (1957) EXPLAIN that the rate of wetting is the main factor causing the breakdown of aggregates or slaking. This result from Panabokke and Quirk (1957) suggests slaking will result in a further decrease in K_{Sat} . Key and Angers (2000) state that slaking at different initial water content (i.e. result in different initial wetting rates) might shift the pore size distribution towards smaller pores.

Moutier et al. (1998) examine the addition of water at two sodicity levels (i.e. ESP = 0 and 10) to columns of two clayey soils. The K_{Sat} was measured in the soil columns under two different hydraulic gradients (2.9 and 12 cm) and different ageing durations, which produced different leaching times. For both sodicity levels, the results showed the lower hydraulic gradient (20 h leaching) maintained significantly higher K_{Sat} compared with leaching under a higher hydraulic gradient (a short period leaching of 3h). In addition, Moutier et al. (2000) evaluate the effect of the rate of leaching with Ca-solutions below a threshold concentration and with distilled water. The results show that when the soil samples were leached with Ca-solutions, K_{Sat} depends highly on the rate of wetting (i.e. the higher wetting rate the lower K_{Sat} produced). However, leaching with distilled water led to a notable decrease in K_{Sat} irrespective of the wetting rate.

Shainberg et al. (2001) studied the K_{Sat} of five soils, varying in texture with a range of ESP (i.e. 2, 6, 10 per cent) leached with distilled water, as a function of wetting rate. The results indicated that K_{Sat} values at the beginning of the leaching were larger for slow wetting compared with fast wetting. Furthermore, Shainberg et al. (2001) observed that the K_{Sat} of sodic soils decreased more steeply and to lower values with the increase in the rate of wetting. Levy et al. (2005) studied the combined effect of water quality, ESP, and the rate of wetting on the initial, steady state, and relative K_{Sat} of four semiarid soil types varying in texture. They concluded the wetting rate effect increased with increasing clay content in the soils, especially when distilled water was applied. Levy et al. (2005) suggest the wetting rate, sodicity and salinity should not be

considered independently but simultaneously to better simulate possible conditions that may prevail in the field.

3.3.2. Clay Mineralogy and Content

The imperative factor that has been related to soil deflocculation or the reduction of the hydraulic conductivity is the type and the amount of clay mineral content in soil (Goldberg et al., 1991). For example, McNeal and Coleman (1966) found that soils containing high proportions of kaolinite were more stable compared with soils containing montmorillonite. In addition, they noted that dispersion increases with increase of montmorillonite in soils. Alperovitch et al. (1985) and Oster et al. (1980) found illite clay was more sensitive to sodicity than montmorillonite. Oster et al. (1980) explain that the selectivity for exchangeable Na^+ is greater for illite compared with montmorillonite. McNeal et al. (1968) show the K_{Sat} further decreases under sodic conditions when clay content increases in the soil. McIntyre (1979) found that for soils containing illite clay K_{Sat} decreased linearly with increasing clay content. However, the decrease of K_{Sat} with increasing clay content was not significant for soils containing montmorillonite.

Reduction in K_{Sat} seems to be more complicated in soils of different texture and mixed clay mineralogy. Surprisingly, a change of K_{Sat} can occur in coarser texture soils. For example, Felhendler et al. (1974) found clay dispersion increased and K_{Sat} decreased in soils with higher silt content, compared with other soils that had the same SAR, clay mineralogy, and electrolyte concentration. Pupisky and Shainberg (1979) found the K_{Sat} in sandy soil with low clay (mixed montmorillonite and kaolinite) content increased because of deflocculation and clay movement out of the soil column. The clay type mixture and soil texture is one of the main factors for determining the soil flocculation condition.

3.3.3. Soil pH

Sumner (1993) explains that soils are composed of a wide range of clay minerals that exhibit both permanent and variable charges of both polarities. “The change of pH in soil solution has no effect on the flocculation of permanent charge minerals. Conversely, in case of variable charge minerals, the increase of pH above pH_0 (i.e. the pH value at which there is equal numbers of positive and negative charges on the particle surface) increases negative charges. Whereas below it, positive charges increase and soil water solution oppositely charged surfaces would interact owing to the soil system to be flocculated”, argues Sumner (1993). Figure 8 illustrates the effect of pH in three soil

systems that have permanent charge minerals, variable charge minerals and a mixed soil system that have both types of the clay minerals. The point of zero net charge (PZNC) in Figure 8 is defined as the soil pH at which the positive and negative charges in the whole permanent and variable charges surfaces are equal. A detailed description of the effect of pH on clay charges can be also found in Brady (1990), and Brady and Weil (2008).

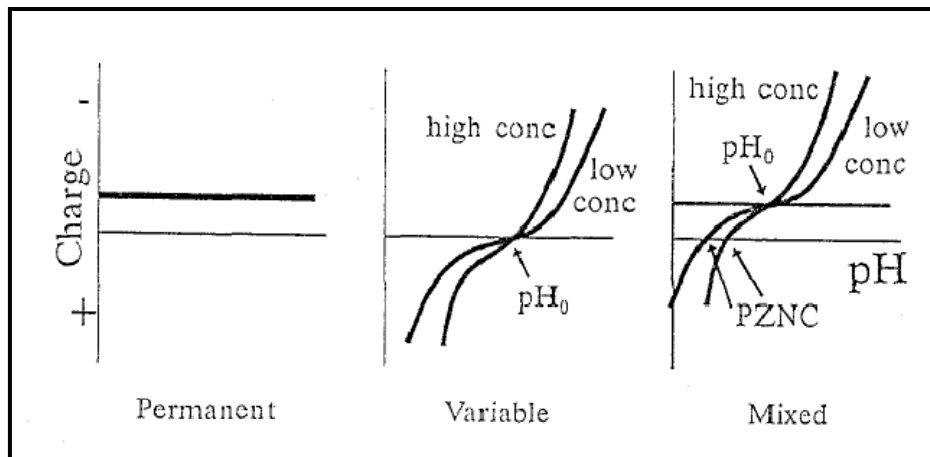


Figure 8. Variation in charge with pH and electrolyte concentration of the ambient solution for permanent, variable and mixed charge systems (Source: Sumner, 1992)

The pH of the soil solution is shown to have a significant effect on clay dispersability at a given salinity and sodicity level for most soils. Suarez et al. (1984) examined the effect of a range of pH values, including six, seven, eight, and nine on K_{Sat} for three different soils at constant SAR and electrolyte concentrations. The results showed the K_{Sat} decreased and clay dispersion increased with increase of pH in two clayey soils dominated by montmorillonite and kaolinite respectively. The reason given for this result is the differences in the quantities of variable-charge minerals and organic matter. Gupta et al. (1984) found increasing pH from six to 10.8 for a Na saturated soil with a high percentage of illite resulted in an increase in clay dispersion.

It is worth noting the increase of pH could cause a significant increase of the ESP. Khajanchi and Meena (2008) mention there is a linear relationship between the ESP and the pH of the soil saturated paste. Figure 9 shows clearly that a small increase in the pH could result in a large increase in ESP values. This suggests the increase in the pH enhances the preference of Na^+ to be adsorbed on clay colloids. It also indicates the increase of ESP with pH is the main factor determining the clay deflocculation at given sodicity and salinity levels. Thus, the negative effect of pH on soil deflocculation may be due to the increase of the ESP.

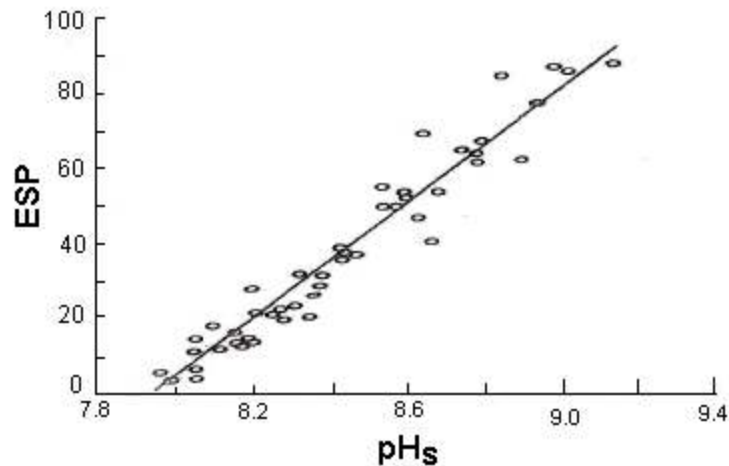


Figure 9. Relationship between soil pH at saturated paste and ESP of Alluvial alkali soil (Source: Khajanchi & Meena, 2008).

3.3.4. Organic Matter

Quirk (1994) mentions that organic matter, which can stabilise soil aggregates against slaking, can also induce clay dispersion. He refers to this behaviour as the organic matter paradox. The negative effect of the organic matter has been reported by many researchers. For example Gupta et al. (1984) demonstrated that increasing soil organic matter under moderate to highly sodic conditions (i.e. ESP between 10 and 30) encouraged clay dispersion in soils. They noted that the dispersion is more pronounced in non-calcareous than calcareous soils. Goldberg et al. (1988) explain that organic matter in arid zone soils, in which the organic carbon content was below one per cent, appeared to promote clay dispersion. Sumner (1993) found that organic matter which has a greater preference for Ca^{2+} over Na^{+} , than the clay minerals (Black, 1968) may be causing the inorganic clay fraction to become relatively enriched in Na^{+} which then would promote dispersion. Nelson et al. (1999) state that organic anions enhance dispersion by increasing the negative charge on clay particles and by complexing Ca^{2+} and other polyvalent cations, such as those of Al^{3+} , thereby reducing their activity in solution.

Organic materials such as fungal hyphae and fine roots, however, can help prevent dispersion by stabilising macro aggregates and thereby reducing the surface area from which clay can disperse (Tisdall, 1996). Barzegar et al. (1997) found that the role of organic matter on clay dispersion is controlled mainly by (a) the degree of sodicity, (b) the nature of the organic matter, (c) the degree of mechanical disturbance and (d) other characteristics of the soils, such as clay content and type. Barzegar et al. (1997) also investigated the effect of organic matter (i.e. 50 g/kg of Pea- *Pisum sativum* L. straw) added to two different soil types at different levels of sodicity (i.e. SAR 0, 5, 15, and 30)

and concluded that organic matter has at least as great a role in aggregation in sodic soils as in non-sodic soils.

3.4. Relationships between Sodicity, Salinity and Saturated Hydraulic Conductivity

Guidelines for evaluating the negative impact of sodicity in terms of K_{Sat} , according to SAR and irrigation water salinity, were developed by Quirk and Schofield (1955). Figure 10 shows an example of the guidelines which indicate the degradation of soil physical properties and permeability rates with salinity and SAR.

The division between the deflocculation and the flocculation conditions in a given soil are somewhat arbitrary because the change occurs gradually and no clear cut break point exists between the two phases. Quirk and Schofield (1955) and Quirk (1994) propose two terms to determine the transition phase between the flocculation and deflocculation, and deflocculation to dispersion. These are the Threshold Electrolyte Concentration (TEC) and Turbidity Concentration (TC).

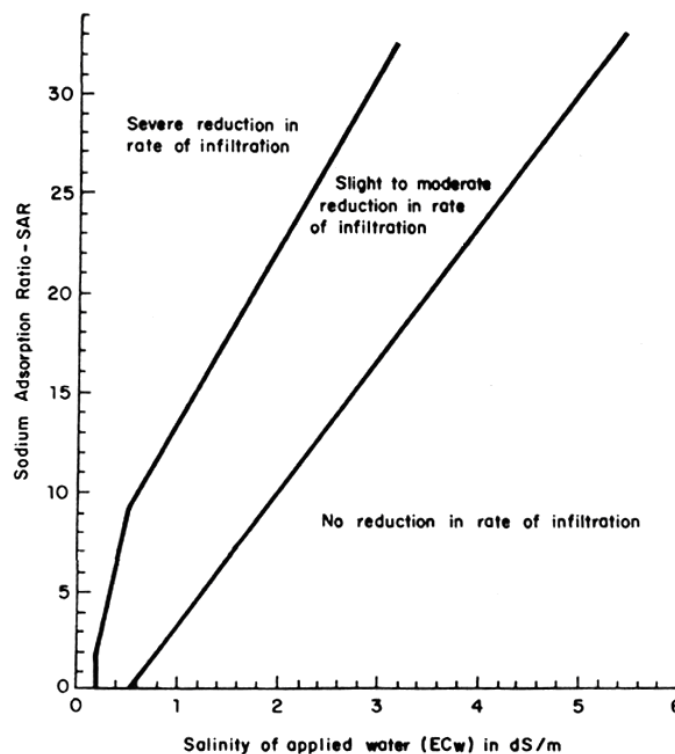


Figure 10. General guidelines adopted for relative infiltration as affected by salinity and sodium adsorption ratio (Source: Ayers & Westcot, 1985).

3.4.1. Definitions of the Threshold Values

Various researchers have identified the boundary between soil flocculation and deflocculation in relation to the total salinity concentration and the SAR of the water

applied. The threshold electrolyte concentration (TEC) and turbidity concentration (TC) are the main parameters used to identify the boundary between the flocculation and the spontaneous clay dispersion of the stable soils. Both terms were introduced by Quirk and Schofield (1955) as indicators to identify the degree of soil degradation under sodic conditions. Quirk and Schofield (1955) measured the K_{Sat} in relation to water sodicity and salinity using soil columns equilibrated with solutions at given SAR values and different electrolyte concentrations. The process of Na-Ca exchange equilibrium between soil solution and soil surfaces can be described theoretically by the Gapon equation, which can be expressed as:

$$\frac{EXNa^+}{EXCa^{2+}} = K_G \frac{[Na^+]}{[Ca^{2+}]^{\frac{1}{2}}} \quad \text{Equation 14}$$

where $EXNa^+$ and $EXCa^{2+}$ are the amounts Na^+ and Ca^{2+} balancing the charge of the soil's exchange complex in units ($mmol_c/100g_{soil}$), K_G is the Gapon exchange constant in units $(mmol_c/L)^{0.5}$. If more dilute solutions than the original one are applied while the ratio of $EXNa / EXCa$ is maintained on the exchange complex, then dilution has to be accompanied by a reduction of the Ca^{2+} by the square of the dilution factor for Na^+ , explains Quirk (2001).

3.4.2. The Threshold Electrolyte Concentration (TEC)

TEC is defined as the salt concentration at which the soil permeability starts decreasing for a certain sodicity level (Quirk and Schofield 1955). Some level of K_{Sat} reduction might happen because of pore clogging as a natural process of water movement. Water flow can convey fine particles which may plug some of the fine effective pores. Thus, Quirk and Schofield (1955) determined the critical reduction of K_{Sat} at 10 to 15 per cent of the optimal K_{Sat} value. On the other hand, McNeal and Colman (1966) proposed using 25 per cent reduction as critical values of TEC for some American soils tested. Similarly, Cook et al. (2006) introduced a 20 per cent reduction of K_{Sat} as the critical value to determine TEC. Irrespective of the reduction percentage selected as the threshold, it is clear that the usefulness of TEC is to determine practical values of K_{Sat} reduction, which may vary with different soil types.

3.4.3. The Turbidity Concentration (TC)

TC was defined as the salt concentration at which clay fractions appear in the percolated water (Quirk & Schofield 1955). Quirk (2001) explained that the turbidity concentration indicates that soil microstructure is becoming unstable and increasingly so as the amount of turbidity increases as ESP increases and as the salinity concentration of the percolated solution decreases. The reduction of K_{Sat} may occur before the fragments of the clays appear in the outflow (Figure 11).

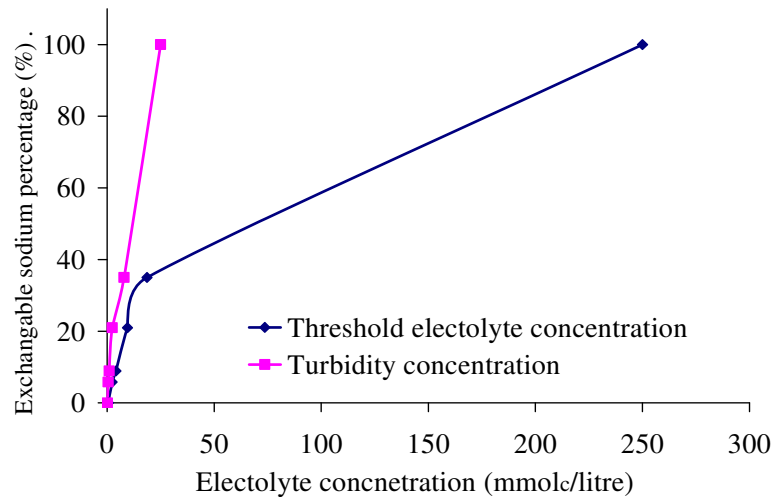


Figure 11. Concentration of electrolyte required maintaining permeability (10-15 per cent reduction) in Sawyers I soil for varying degrees of sodium saturation (Based on data from Quirk & Schofield, 1955).

It should be noted that the misperception of the threshold electrolyte concentration reported in the literature rises essentially from the mystification of a difference between the clay flocculation to dispersion transition, and dispersion to flocculation transition conditions. Quirk (2001) observed the widely held misconception of the definition of the threshold electrolyte concentration (required to maintain a stable permeability) as that electrolyte concentration required to flocculate a dispersed suspension of the soil. He draws attention to the difference between the transition condition from flocculation to deflocculation condition, and the flocculation of dispersed clay suspensions. The flocculation to dispersion transition condition involves face-to-face interaction and requires lower electrolyte concentration at a given level of sodicity to deflocculate. However, the dispersion to flocculation transition involves edge to face interaction for clay suspension and occurs at higher electrolyte concentration. Wearing (2004) indicates that the lower turbidity concentration is because the particles have to be removed from a potential well where the clay crystals overlap.

At a given sodicity level the flocculation concentration (FC) in the dispersion to flocculation transition is much greater than both the TEC and TC. Rowell et al. (1969)

found that at ESP values of 21, the ratio of TC to TEC to FC was 1: 3.5: 7. This result shows soil-water having salinity below FC and above TEC will have no effect on soil structural stability when the flocculation to dispersion is the case. In addition, Wearing (2004) recommends that FC should not be used as an estimate of threshold concentration because of the effect of the peptising agents. In the case of the dispersion to flocculation transition condition, a dispersing of the peptising agents, such as organic matter, could affect clay flocculation and eventually raise the FC values.

The TEC and TC are determined by the soil type and vary with other soil properties (Rengasamy et al., 1984). The variation of TEC is mainly caused by the differences in the clay mineral contents and soil texture (Frenkel et al., 1978; McNeal & Coleman, 1966). Various researchers have developed soil stability indicators for different soils in relation to the total salinity concentration and SAR of the water applied, as shown previously in Figure 10 (Ayers & Westcot, 1985; Quirk & Schofield, 1955; Rengasamy et al., 1984).

It is worth noting that substituting SAR by ESP can improve the visual graphs for a set of soil types. McNeal and Coleman (1966) found that using estimated ESP from SAR of added water to express sodicity further reduces the variation among TEC curves. This improvement can be noted from Figures 12 and 13. This is because ESP is a percentage limited between 0 and 100 per cent which compresses the curves. ESP may be an appropriate way to evaluate the sodicity problem for a set of soil types. Therefore, for a family of soils that has similar general characteristics, expressing the sodicity as ESP values could generalise the soil stability indicators.

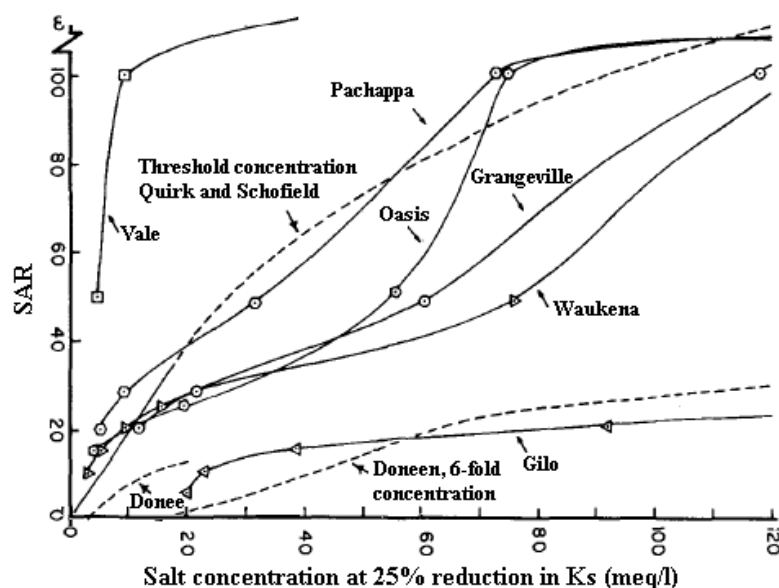


Figure 12. Combinations of salt concentration and SAR at which a 25 per cent reduction in hydraulic conductivity occurred (Source: McNeal and Coleman, 1966).

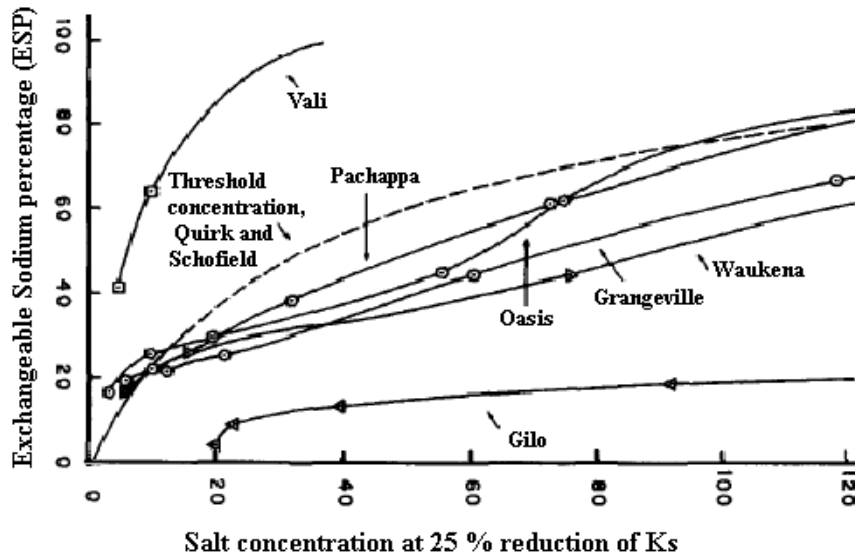


Figure 13. Combinations of salt concentration and ESP at which a 25 per cent reduction in hydraulic conductivity occurred (Source: McNeal and Coleman, 1966).

3.5. Quantifying the Change in Saturated Hydraulic Conductivity due to Sodicy

The preceding discussion regarding the factors that affect K_{Sat} suggests the main processes of the K_{Sat} reduction in soils containing expanding clay are swelling followed by dispersion. McNeal and Coleman (1966), and later on Jayawardane and Beattie (1978), show there is a sigmoidal relationship between the reduction of K_{Sat} and the logarithm of electrolyte concentrations at a given SAR. McNeal (1968) proposed a semi-empirical approach based on a clay-swelling model. In his model, the effect of salinity and sodicity in soils is evaluated using a swelling factor. The swelling factor is used to predict whether the sodium and solute concentration will induce soil physical degradation or flocculation (Warrence et al., 2003). Furthermore, McNeal (1968) used a semi-empirical equation to fit experimental data of the relative K_{Sat} at different combinations of SAR (converted to ESP) and the electrolyte concentration to the calculated swelling factor. The predictive interlayer swelling (i.e. swelling factor) was estimated by an empirical relationship generated from a demixed-ion distribution model for Na-Ca clay systems as:

$$1 - RK_{Sat} = \frac{cx^n}{(1 + cx^n)} \quad \text{Equation 15}$$

where RK_{Sat} is the relative saturated hydraulic conductivity, x is the swelling factor (i.e. the calculated interlayer swelling of soil Montmorillonite), and c and n are constants for a given soil within a specified range of ESP.

Likewise, Lagerwerff et al. (1969) proposed a physical model in which the reduction of K_{Sat} was predicted by the Kozeny-Carmen equation (Carman, 1937; 1948) after an empirical correction was made to the change of effective porosity based on clay swelling (i.e. the conducting porosity that conveys the water into the soil). Clay swelling was calculated based on diffuse double layer theory.

Mustafa and Hamid (1977) compared both the aforementioned models for two clay soils from Sudan. It was concluded that the McNeal model produced a better prediction of clay swelling. The Lagerwerff model failed to predict the swelling. However, both models were able to demonstrate the decrease of K_{Sat} due to sodicity for both soils especially at higher values of electrolyte concentration and SAR. The failing of the Lagerwerff model might be as a result of limitations inherent with diffuse double layer and Kozeny theories, as described by Lagerwerff et al. (1969). In addition, Russo and Bresler (1977b) state the Lagerwerff model, with its wide range of pore size distribution and the complex geometry of the flow paths, cannot always be applied to the soil material.

Yaron and Thomas (1968) found relative hydraulic conductivity can be related linearly to the average ESP of soil columns at a given C_o as:

$$\frac{K_{Sat}}{K_{Sat}^{Max}} = 1 - \beta(ESP - ESP_T), \text{ when } ESP > ESP_T \quad \text{Equation 16}$$

where β is an empirical parameter which depends on soil type and clay mineralogy, ESP_T is the critical average ESP at which K_{Sat} began to decline for a given salinity, K_{Sat}^{Max} is the maximum saturated hydraulic conductivity under normal conditions, and K_{Sat} is the measured saturated hydraulic conductivity under the given level of average ESP.

Results from Yaron and Thomas (1968) show the parameter β is not consistent over different C_o values, which indicates this empirical equation might not be applicable at a certain level of salinity. In addition, Yaron and Thomas (1968) derived Equation 16 using water with low electrolyte concentration (i.e. 11.3 to 34.5 mmol_e/L) and a range of water

sodicity added to the soil columns having SAR values between 2.8 to 28.5. However, Pupisky and Shainberg (1979) show that the reduction in relative saturated hydraulic conductivity (RK_{Sat}) with increase of SAR at certain C_o is sigmoidal in shape, as in Figure 14. Thus, Equation 16 was derived over a narrow range of SAR, in which the K_{Sat} reduction usually exhibits a linear decrease. Therefore, using such a model for water having higher SAR values is questionable.

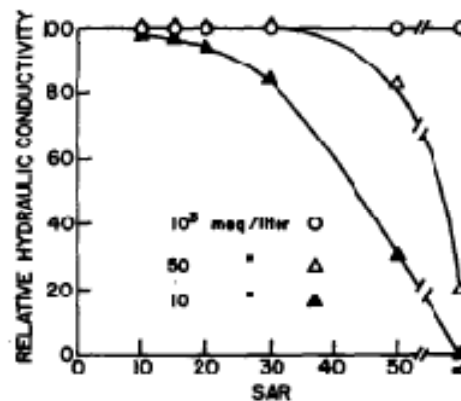


Figure 14. Relative hydraulic conductivity of the soil as a function of solution concentration and composition (solution concentration > 0.01N)
Source: Pupisky & Shainberg, 1979)

Jayawardane (1979) proposes a different approach to predict the reduction in K_{Sat} due to raising sodicity using the equivalent salt solutions method. The equivalent salt solutions are defined as solutions with combinations of SAR and C_o producing the same extent of clay swelling in a given soil (Jayawardane, 1979). Thus, the K_{Sat} reduction for this set of added solutions should be equal. Furthermore, the increase of sodicity level will reduce the pore size for a given soil. Thereby, the assumption was made that the equivalent salt solutions should produce identical soil-water characteristic curves or the same pore size distributions. The equivalent salt solutions, which produce the same reduction of K_{Sat} , were assigned to the value of the pore size index (PSI) produced under this condition. The PSI is similar to that described by (Childs, 1940) and redefined in Jayawardane & Beattie (1978) as the ratio between the equivalent pore neck radius (ζ) produced in the soil when solutions of lower electrolyte concentration are added (i.e. where the K_{Sat} reduction is notable) to β for the soil when solution of the highest electrolyte concentration (i.e. insignificant change in K_{Sat}) at a given level of SAR is added. The PSI has values between 0 and 1. The ζ can be obtained by differentiating soil-water characteristic curves and using the relationship between the radius of a capillary tube and the matric potential. The pore size index was

used as a quantitative evaluation of the effect of C_o and SAR on K_{Sat} . However, Jayawardane (1983) uses the clay swelling factor as described by McNeal (1968) instead of the PSI. Furthermore, Jayawardane (1992) extends the equivalent salt concentrations concept to predict the unsaturated hydraulic conductivity (K_{Unsat}) based on the swelling factor as described by McNeal (1968).

3.6. Relationships between Sodicy, Salinity and Unsaturated Hydraulic Conductivity

Water flow in soil at moisture contents below saturation moves through a part of pores. If a steady state condition exists, the Darcy equation can be applied to unsaturated flow by using matric potential in the hydraulic gradient instead of pressure head. In addition, the unsaturated hydraulic conductivity (K_{Unsat}) (as a function of water content or matric potential) replaces the K_{sat} . This version of the Darcy law is known as the Buckingham-Darcy law (Buckingham, 1907). K_{Unsat} depends on the proportion of pores that are filled by water and can convey it. K_{Unsat} decreases with the decrease of water content and matric potential. K_{Unsat} can be predicted from the soil-water characteristic curve (SWCC) as described by many researchers (e.g. Kosugi, 1996; van Genuchten, 1980; Vogel & Cislserova, 1988). Furthermore, the SWCC is highly dependent on the pore size distribution within the soil. A higher proportion of smaller pores increases the residual water content at a given matric potential, increasing K_{Unsat} at that level. However, the water content at a given matric potential comprises the amount of water retained in soil micro-pores below that matric potential. Thus, water in micro-pores might be below the limitation of laminar flow equation (Darcy law). Therefore, as the proportion of micro-pores water increases, the actual unsaturated water flow within the soil might decrease, which is expected in higher clay content soils.

Sodicy results in a dual change in soil structure (Gonçalves et al., 2007). While the ratio of macroscopic pores is reduced as a result of clay swelling and dispersion, the soil pore sizes are expected to shift to a smaller size with application of sodic water (Levy, 2000). It is generally thought that this process leads to an opposite change in K_{Sat} and K_{Unsat} . K_{Sat} is decreased while K_{Unsat} is significantly increased at a moderate to low range of water contents. Goncalves et al. (2007) measured the K_{Unsat} in a soil profile irrigated with treated sodic sewage effluent, using what they called the instantaneous profile method. The soil generally had a low clay percentage. The result shows the K_{Unsat} increased

under sodic conditions, especially at a low and intermediate water contents, while a lower increase was noted in K_{Unsat} at higher water content.

However, the magnitude of the K_{Unsat} change seems to be highly affected by the increase in the proportion of micro-pores that retain water. Early results from Russo and Bresler (1977a) over the range of suction of 0 to 1 bar show the K_{Unsat} and the diffusivity of columns of loamy soil dramatically decrease with an increase of the SAR in solutions applied. The reduction was higher at low electrolyte concentration. The findings from Russo and Bresler (1977a) show while the water content at a given suction increases with rising sodicity, the actual K_{Unsat} decreases. Figures 15 and 16 show the change in the soil water characteristic curves and corresponding measurements of K_{Unsat} at different SAR and solution concentrations.

The interpretation given is that the swelling or the space between platelets increases. This, in turn, raises the amount of water held in the soil micro-pores in which the water is retained in-between the clay layer. This water does not participate in the water flow. These synthesis results from literature indicate that the clay percentage or soil texture may determine the magnitude of the K_{Unsat} change, especially at moderate to lower water contents. In other words, despite a higher water content, the effective porosity at which water flow occurs might be reduced or increased significantly.

Russo and Bresler (1977b) propose a model to predict the unsaturated hydraulic conductivity under sodic conditions involving the porous nature and electrical properties of the soils (Diffuse Double Layer model (DDL)). However, the model was found to be sensitive to the number of clay platelets in clay particles at a given level of ESP.

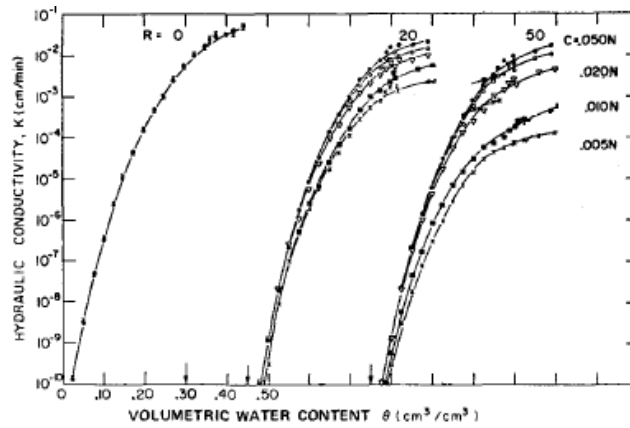


Figure 15. Unsaturated hydraulic conductivities values as a function of volumetric soil-water content and the solution concentrations for three values of SAR (i.e. 0, 20, and 50) .

Note: The curves corresponding to other values of SAR in the original graph have been removed to facilitate the comparison with Figure 16 (Modified from Russo and Bresler 1977a).

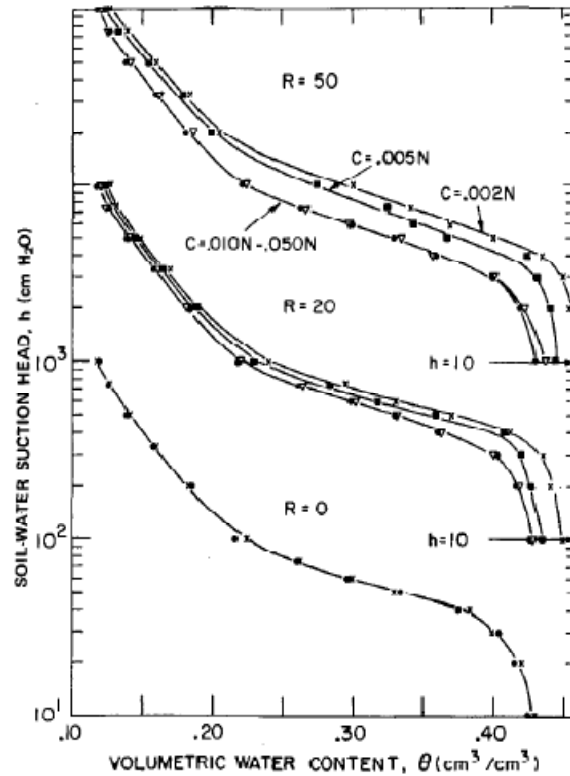


Figure 16. Soil-water suction head (h) as a function of volumetric soil-water content and solution concentration, for three SAR values (i.e. 0, 20, and 50).

Note: $H=10$ (indicated by the arrows) is shifted and the data are translated along the x -axis (Source: Russo and Bresler 1977a).

Simunek et al. (1996) conclude the reduction of K_{Unsat} can be determined from K_{Unsat} function derived from the SWCC. The method assumes the sodicity effect acts in the same manner at low water content. Hence, the K_{Unsat} as a function of (h) can be determined from the SWCC as:

$$K_{Sat} = r K_{Sat}^{Max} \quad \text{Equation 17}$$

where r is a general reduction function account for the sodicity effect. K_{Unsat} , according to van Genuchten (1980) can be calculated as:

$$K_{unsat} = K_{sat} K_{(h)} \quad \text{Equation 18}$$

where $K_{(h)}$ is the relative hydraulic conductivity, this in turn can be determined as described as:

$$K_{(h)} = S_e^{1/2} \left[1 - (-S_e^{1/m_i})^{m_i} \right]^2 \quad \text{Equation 19}$$

explains van Genuchten (1980), where S_e is the relative water saturation in the soil, and m_i is an empirical parameter which depends on the soil type. By substituting Equations 17 and 19 into Equation 18, the resultant relationship, according to Simunek et al. (1996) is:

$$K = r K_{Sat}^{Max} S_e^{1/2} \left[1 - (-S_e^{1/m_i})^{m_i} \right]^2 \quad \text{Equation 20}$$

Equation 20 is useful to predict the reduction of K_{Unsat} at higher water content, particularly in clayey soils. However, Equation 20 does not account for the rapid increase or decrease of K_{Unsat} at moderate and low water content, especially in coarser or finer textured soils. Nonetheless, under irrigation, water is usually applied to maintain the soil-water content at a relatively high level. Hence, Equation 20 satisfies the needs to quantify solute and water movement.

4. Sodicity Management under Irrigation Water

Improvements observed during the amelioration process in the soil physical properties under sodic conditions have been attributed mainly to an increase in Ca^{2+} levels, both in the soil solution and on the exchange complex (Qadir et al., 2006). Maintaining sufficient levels of Ca^{2+} involves the addition of amendments to either the irrigation water or soil. The amendments can be categorised in two groups. The first group includes those that work as an independent source of Ca^{2+} , such as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and calcium chloride ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$). The second group includes those used to promote the dissolution of domestic Ca^{2+} available within the soil (especially calcareous soils) (Hussain et al., 2001). Examples for those amendments are sulphuric acid (H_2SO_4), sulphur (S), and ferric sulphate ($\text{Fe}_2(\text{SO}_4)_3$) (Qadir et al., 2006).

Marginal irrigation water containing relatively high sodium concentration can be managed by blending (Qadir & Oster, 2004). Mixing saline-sodic water by the ratio of 1:1 with good quality water reduces the water salinity to 50 per cent and the SAR to about 71 per cent. Irrigation water containing high levels of bicarbonates have been ameliorated using sulphuric acid. Applying gypsum to irrigation water is useful in terms of reducing the water sodicity and the bicarbonate concentrations (Ayers & Westcot, 1985). Using blending concurrently with amelioration could provide appropriate management to saline-sodic irrigation water.

4.1. Use of Sulphur Acid Generators (SAG_s)

SAG_s are a recently introduced technology to treat saline-sodic waters. Sulphur (S) is burnt to produce sulphur dioxide gas (SO_2) in a chamber, which is dissolved in a fraction (10-15 per cent) of irrigation water to form sulphuric acid (H_2SO_4). H_2SO_4 neutralises carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions in water resulting in a decrease in residual sodium concentration (RSC) of the treated water (Doneen, 1975). Theoretically, this will not ameliorate water salinity and SAR (Amrhein, 2000). Evaluations by Zia et al. (2006) using sulphuric acid generators (SAGs) did not find any significant physical soil benefits.

Gale et al. (2001) treated the irrigation water with a sulphuric acid (5 per cent) and did not find any significant differences in the water quality, soil properties or crop (lucerne) responses. They conclude that the use of acid injection or sulphur burners should be preceded by a thorough evaluation of irrigation water quality and soil properties in terms of economical achievement.

It should be noted that H_2SO_4 has been used to reclaim sodic soils. Gale et al. (2001) suggest that the main effect of sulphur in the treatment of a sodic soil is not through direct acidification, but rather by dissolving lime and releasing Ca^{2+} , which replaces sodium and allows it to be leached from the soil. In this case, excess water must be applied to leach sodium, which is often difficult in poorly drained soils.

4.2. Use of Gypsum Amendment

Calcium sulphate dihydrate, which is known as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) has been widely used as a Ca^{2+} source to replace sodium on the soil exchange complex. Among the other amendment materials, gypsum is comparatively cheap, generally available, and easy to apply (Qadir et al., 2006). The application of gypsum to soils increases the soil solution salinity and exchangeable Ca^{2+} levels. Both of these actions reduce the inter-particle swelling pressures and the potential for dispersion.

Surface application of gypsum generally increases infiltration rates and reduces dispersion, but the process is sometimes slow because the gypsum solubility is low. Mixing the gypsum into the soil surface layers accelerates the reclamation process because the Ca^{2+} is physically placed where it can react. Leaching removes gypsum from the upper part of the soil profile where the major problems of dispersion and hard setting are located. Thus, periodic applications are necessary to both maintain adequate electrolyte to prevent dispersion and slumping, and to slowly reduce the ESP level (Chartres et al., 1985; Greene & Ford, 1985).

Gypsum has also been dissolved in irrigation water to improve water quality by increasing the electrical conductivity, reducing the SAR and reducing the RSC. Davidson and Quirk (1961) conclude dissolved gypsum, at a concentration of Ca^{2+} up to 10 mmol_c/L , is sufficient to maintain flocculation of colloidal clay which has an ESP of about 20 per cent.

However, gypsum has low solubility (Kernebone et al., 1986). The solubility of gypsum is estimated to be about 0.30g/100ml of water at 25 $^\circ\text{C}$ (USSL Staff, 1954). The solubility of gypsum increases to produce an additional two to four mmol_c/L in flowing irrigation water (Ayers & Westcot, 1985; Doneen, 1975).

Gypsum solubility is highly affected by its particle size, temperature, and the water salinity. Fine gypsum particles are quicker to dissolve (Mater et al., 1990). The solubility of gypsum increases with increases in temperature. The optimal temperature for maximum gypsum solubility is between 35 $^\circ$ and 50 $^\circ$ C (Mater et al., 1990). Furthermore, the solubility of gypsum increases with increasing electrolyte concentration.

For example, the solubility of gypsum increases sharply with an increase in NaCl concentration at low salinity concentrations (Figure 17). Furthermore, the solubility of gypsum tends to further increase in the presence of bicarbonates. This is because bicarbonates in water have a tendency to increase water pH and decrease the solubility of calcite (CaCO_3) (Mater et al., 1990). Wallace (2003) explains that if soil or irrigation water contains bicarbonate ions, the soluble Ca^{2+} in gypsum reacts with bicarbonates to form insoluble Ca^{2+} carbonate. Subsequently, the pH decreases to the range of 7.5 to 7.8. Chorom and Rengasamy (1997) found the direct application of gypsum to alkali soil in laboratory plots reduced the soil pH from 9.38 to 7.89.

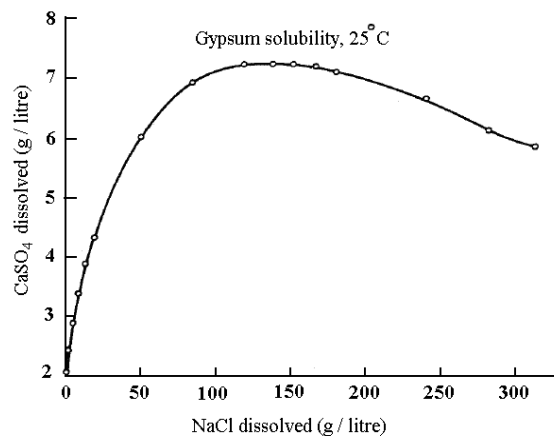


Figure 17. Solubility of gypsum in aqueous solutions of different NaCl concentrations at 25° C, and one atmospheric pressure (Source: Shternina, 1960).

5. Soil Hydraulic Changes due to Sodicity in Modelling Water-Solute Movement

There are limitations of the models that can handle water and solute movement associated with soil chemical reactions under sodic conditions (Qadir et al., 2006). Simulation of soil-water flow and chemical processes under highly sodic conditions requires a consideration of the effect of soil structural degradation on water and solute transport under variable water content conditions. Modelling of unsaturated water and solute flow, coupled to equilibrium major ion chemistry, has been carried out by a number of researchers (e.g. Robbins et al., 1980a; Russo, 1986; Seetharam et al., 2007; Wagenet & Hutson, 1987; Yeh & Tripathi, 1991). In most of these models, the main assumptions are:

- a) The chemical reactions are in an equilibrium state; and
- b) The pH with soil depth is either assumed constant or related to fixed concentrations of CO₂ with soil depth.

Simunek and Suarez (1994) developed a two-dimensional model (UNSATCHEM 2D) with unsaturated water flow and major ion chemistry in which CO₂ production and transport is considered. However, the change of soil structure was ignored in all aforementioned models. Furthermore, evaluation of these models in either laboratory or in field conditions is limited (Suarez & Simunek, 1997).

Simunek et al. (1996) developed a model (UNSATCHEM) that takes into consideration the change of physical properties as a result of the chemical conditions of the soil-water. The reduction of K_{Sat} was used as an indicator of soil degradation due to sodicity. The magnitude of reduction of K_{Sat} has been related mathematically to the level of sodicity and salinity in the soil solution. Simunek et al. (1996) assume a relationship between the reduction of K_{Unsat} and reduction of K_{Sat} . The reduction of K_{Unsat} can be described at corresponding combined levels of sodicity and salinity. The soil chemical reactions model provides a temporal and spatial quantitative prediction of major cation concentrations (i.e. Ca⁺², Mg⁺², and Na⁺) during water and solute movement. The cation concentrations predicted are used to calculate the chemical parameters required, such as SAR or ESP and electrolyte concentration, which allow prediction of both soil sodicity and salinity. This, in turn, can be used to determine the reduction of K_{Unsat} using the reduction function.

6. Conclusions

Degradation of soil permeability can produce complex problems related to waterlogging and aeration, along with the potential to develop salinity problems. It is necessary to maintain a sufficient soil permeability to leach the salt out of the root zone. High relative sodium concentrations result in adverse effects. The structural stability of soils which have reactive clay is dependent on the interaction between the sodicity and salt concentration in the soil solution. The primary processes responsible for soil structural degradation are clay swelling and dispersion.

The processes of spontaneous swelling and dispersion that affect the saturated hydraulic conductivity can be explained using both TEC and TC concepts. The reduction of K_{Sat} at the values below the TEC occurs mainly due to swelling, while dispersion is the main cause below the TC. However, each soil has a specific relationship for TEC and TC due to differences in clay mineralogy, pH, soil texture, climatic conditions, and organic matter. Irrigation practices also cause temporal changes in soil-water (e.g. initial water content, rate and ageing of wetting) under sodic conditions, which also have a significant effect on K_{Sat} .

The effect of sodicity is more complicated in unsaturated soils. Sodicity results in a change in soil pore size distribution. The number of macroscopic pores is reduced as a result of clay swelling and dispersion. However, the number of smaller soil pores increases. Hence, K_{Sat} decreases while K_{Unsat} may increase at moderate to low water contents.

The management of soil sodicity is usually carried out using amendments. The amendments may be added to either the irrigation water or directly to the soil. Amendments may either counter the effect of rising sodium levels or stabilise soil structure. The use of soil amendments, such as gypsum, is often necessary for successful management. Blending with better quality water is also common in irrigation systems using saline-sodic water.

Modelling may be used to evaluate management strategies for the use of saline-sodic water. The effect of sodicity on soil physical properties has been presented in the UNSATCHEM model, in which the soil chemical conditions are related to the physical conditions. The effect of sodicity was incorporated into the UNSATCHEM using a hydraulic conductivity reduction function that includes clay swelling (McNeal, 1968) and pH (Simunek et al., 1996). However, there has been limited research using this model

and the assumption underpinning the reduction function parameters have not been evaluated for different soils. Therefore, there is a need to validate this model and approach before it can be used to investigate different water quality and irrigation management options.

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– NOTES –



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