Review

Managing salt affected soils: Issues and strategies

Mahanta K. K.[1]*, **Kansal M. L.**[2] **and Mishra G. C.**[2]

[1]Central Soil Salinity Research Institute, RRS, Canning Town, South 24 Parganas, W.B., PIN 743329, India.
[2]Department of WRD&M, Indian Institute of Technology, Roorkee, Uttarakhand, PIN 247667, India.

Improper land and water management has amplified the degradation of soil across the world. In saline soil, high concentration of soluble salts results in high soil permeability, thus, making soil physical conditions favorable for leaching. But the presence of excess Na^+ ions as in the sodic soil, makes the reclamation process more complex because of the poor hydraulic conductivity and infiltration rate. The problem in the sodic soil is for the swelled electric double layer on the clay surface. More monovalent ions are required to balance the fixed deficit charges on the clay surface than the multivalent ions. Hence, the thickness of electric double layer in sodic soil is more than the non-sodic soil where multivalent ions are dominant. Most of the previous studies on reclamation of salt affected soils are field studies. A few analytical models were attempted without involving the interaction of ions and geometry of soil, hence failed. The electric double layer has hardly been taken into account for solving the reclamation problem of the sodic soil. As Na^+ and Ca^{2+} ions are ions of concern for reclamation of the sodic soil, the interactions among these ions need to be considered through the electric double layer theory.

Key words: Salt affected soil, saline, sodic, electric double layer, reclamation.

INTRODUCTION

The history of agriculture has it that experienced irrigated agriculture cannot survive in perpetuity without adequate salt balance and drainage. Of the world's cultivated lands (1.5×10^7 km^2), about 23% are saline while saline and sodic soils cover about 10% of total potentially arable land and exist over 100 countries (Szabolcs, 1989).

Buringh (1978) stated that the world is losing at least ten hectare of arable land every minute, because of soil erosion, three from soil salinization, one from other soil degradation processes and one from non-agricultural uses. Water present in the soil and constituting its liquid phase always contain ions of various salts. The ionic composition and their concentrations in soil solution affect soil physical properties (Keren, 2000). The proportion of ions in soil solution is drastically altered due to irrigation and application of agricultural inputs such as fertilizer and pesticides. Soil physicochemical properties are adversely affected by the presence of excess Na^+ ions in the soil water.

SOURCES OF SALTS AND THE EFFECTS OF SALTS ON CROP YIELD

The primary sources of salts are: (i) irrigation water, (ii) salts present in parent materials of soil, (iii) capillary rise of ground water, and (iv) application of fertilizers, pesticides and other inputs (Bolt and Bruggenwert, 1978; Rhoades and Loveday, 1990). Irrigation water is a major source of soluble salts which may contain salts from 0.1 to 4 metric tons per 1000 m^3. Generally, irrigation water is applied to the soil at annual application rates of 10,000 to 15,000 m^3 ha^{-1}. Thus, about 0.1 to 60 metric tons of salt per hectare is added to the soil in irrigated areas annually (Rhoades, 1974; ILRI, 1979). If these salts are not removed from the crop root zone (Figure 1), salinization is inevitable.

Because of the high solubility of Na salts in nature and precipitation of calcium carbonate at high pH values, both the salinization (high salt content) and alkalinization (high pH) result in sodification (high ESP) of the soil (FAO/UNESCO, 1973). Figure 2 shows the effect of

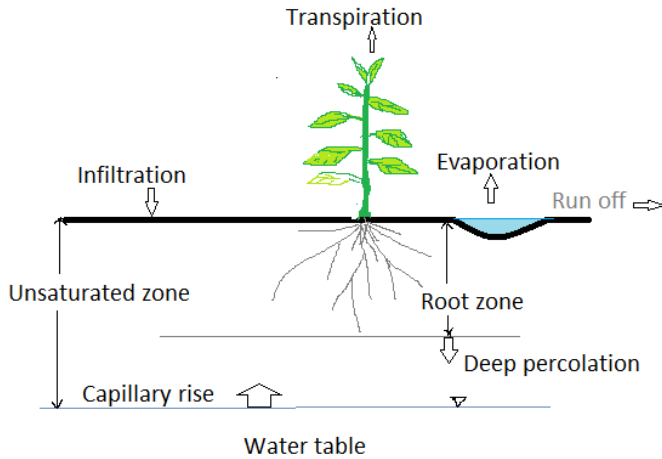*Corresponding author. E-mail: kkmahanta@yahoo.com.

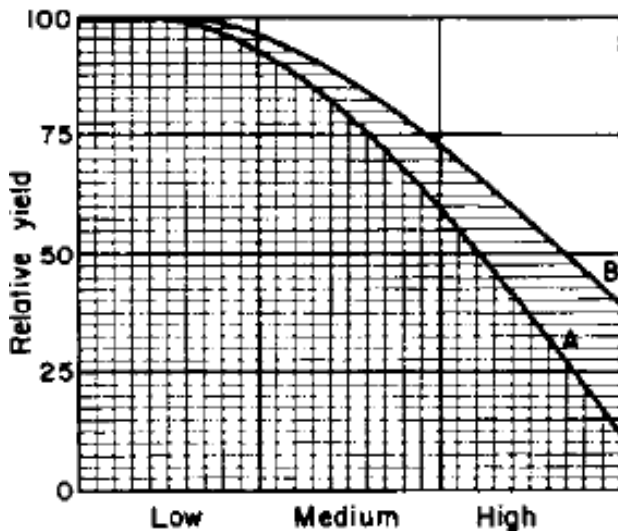**Figure 1.** Different processes which occur in salt affected soils.

Figure 2. Relative yields of tolerant native (B) and high yielding dwarf (A) rice varieties in sodic conditions (Abrol et al., 1988).

sodicity on the crop yield.

CHARGES ON THE CLAY SURFACE AND ION EXCHANGE IN THE SOIL SYSTEM

In case of the clay minerals, the lower valence cations isomorphically substitute the higher valence cations which take place during the formation of clay minerals. The deficit of charges thus created are compensated by adsorption of the cations (for example, Ca^{2+}, Mg^{2+}, K^+, Na^+ etc.) on the exterior surface (Bolt, 1978; Grim, 1953). The exchangeable ions in the soil are held around outside of the silica-alumina clay mineral structural unit. Generally, the exchange reaction does not affect the structure of the silica-alumina packet. The attraction of the cations to a negatively charged clay micelle, generally, increases with the increase in valence of the cations. Thus monovalent cations are replaced more easily than the divalent or trivalent cations. The order of preference of the cations in exchange reactions is as follows: $Al^{3+}>Ca^{2+}>Mg^{2+}>K^+>Na^+>Li^+$ (Jenny, 1932, 1936).

For quantifying the exchangeable ions in the soil system, two different modeling approaches are advocated (FAO/UNESCO, 1973). The first model is known as the electric double layer (EDL) theory. The second model advocates that the exchangeable ions are adsorbed on the clay surfaces in a non-rigid monolayer fashion at particular adsorption sites. Through a study of cation exchange phenomena, it is required to evaluate the relative energies with which the clay soil attracts the cations (for example, Na^+, Ca^{2+}) in the soil water. Subsequently, it becomes possible to predict the changes in the relative amounts of these exchangeable ions during the reclamation or upon the use of irrigation water of a specific quality. The diffuse double layer theory can be quantitatively applied to a mixture of monovalent and divalent cations to deduce the ion exchange (FAO/UNESCO, 1973). The flow of water in the soil profile depends on the soil hydraulic conductivity, which further depends on the EDL thickness at the clay surface (Schmitz, 2006). The double layer thickness varies according to concentration of ions and their valences.

Electric Double Layer (EDL) on the Clay Surface

The diffuse character of the counterions in soil water was first recognized by Gouy (1910) and Chapman (1913). The electric double layer consists of the layer of charges on the clay surface and the layer of attracted counterions in the soil water. In the diffuse double layer model, the concentration of cations decreases and the concentration of anions increases with the distance from the clay surface till the concentrations of both the cations and anions are equal in the bulk solution, where the potential is zero (Figure 3).

In most textbooks, the Poisson equation is expressed in electrostatic units (Newman, 1987; Mitchell, 1976; van Olphen, 1977) as: $\dfrac{d^2\phi(x)}{dx^2} = -\dfrac{4\pi\rho(x)}{\varepsilon_r}$ where $\phi(x) = $ potential at a distance x from the clay surface; $\rho(x) = $ volumetric charge density; and ε_r = relative static permittivity which is the dielectric constant of the medium. When expressed in SI units, the Poisson equation (van Olphen, 1977) is: $\dfrac{d^2\phi(x)}{dx^2} = -\dfrac{\rho(x)}{\varepsilon}$

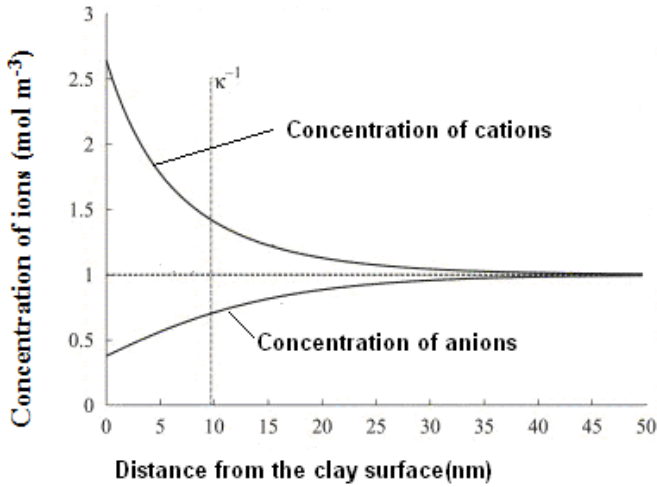where ε = static permittivity of the medium.

Figure 3. The distribution of concentrations of cations and anions in the soil water with respect to the distance from the clay surface
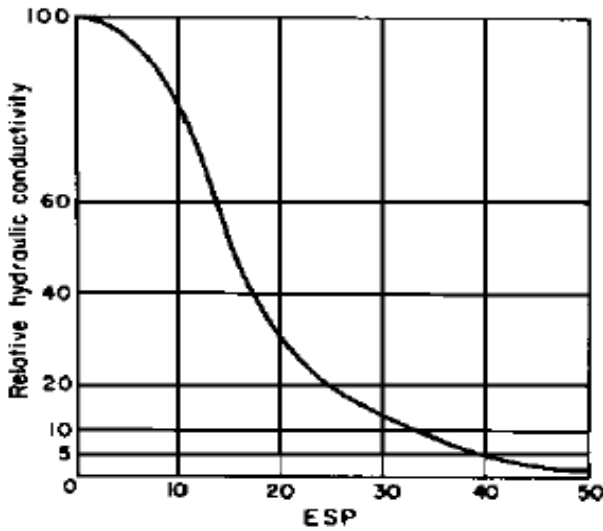

Figure 4. Schematic diagram showing the relative hydraulic conductivity of a soil as affected by increasing ESP (Abrol et al., 1988).

At equilibrium, the local concentrations of the ions are related to the local electric potential by the Boltzman equations: $n_- = n_-^0 e^{\frac{F\upsilon_- \phi}{RT}}$ and $n_+ = n_+^0 e^{\frac{-F\upsilon_+ \phi}{RT}}$ where n_-^0 and n_+^0 are the concentrations of the anions and cations in the solution outside the range of diffuse double layer; F = Faraday's number; n_+ and n_- are the local concentrations of the cations and anions, respectively; R = gas constant; T = absolute temperature; υ_+ and υ_- are the absolute values of their valences; and $\rho(x) = F\sum \upsilon_i n_i$ where υ_i and n_i are the valence and

concentration of ions of type i, respectively (Yeung, 1992; Voyutsky, 1978).

Assuming $\upsilon_+ = \upsilon_-$, and $n_-^0 = n_+^0 = n$, and combining the Poisson equation and the Boltzman equation, the Poisson-Boltzman equation can be written as:

$$\frac{d^2\phi(x)}{dx^2} = \frac{8\pi n \upsilon F}{\varepsilon} \sinh\left(\frac{F\upsilon\phi(x)}{RT}\right).$$

Applying the boundary conditions: at $x = 0$, $\phi(x) = \phi(0)$; at $x = \infty$, $\phi(x) = 0$, and after some approximations in the derivations, Gouy (1910) and Chapman (1913) have given a solution of the Poisson-Boltzman equation as: $\phi(x) = \phi(0)e^{-\kappa x}$ where

$$\kappa = \sqrt{\frac{8\pi n \upsilon^2 F^2}{\varepsilon RT}} \text{ cm}^{-1}$$ and κ^{-1} is the thickness of the EDL.

Appelo and Postma (2005) has derived an analytical solution to Poisson-Boltzman equation as:

$$\psi(x) = \frac{1}{b} \ln\left[\tanh\left\{ \frac{-bax}{2} + \frac{1}{2}\ln\left(-\frac{e^{b\psi_0}+1}{e^{b\psi_0}-1} \right) \right\} \right] \text{ where}$$

$$b = \frac{F}{2RT} \text{ and } a = \sqrt{\frac{8RTC_b}{\varepsilon}}.$$ Mahanta et al. (2012) has supplemented this solution with a method to compute the EDL thickness for single type of ions. The computation of EDL for two types of ions has also been devised (Mahanta et al., 2014).

In the clay-water system, a quantitative treatment of the EDL is most useful in dealing with the problem of counter-ions exchange (FAO/UNESCO, 1973).

SOIL HYDRAULIC CONDUCTIVITY IN RELATION TO SALTS

Hydraulic conductivity of soil is a function of both soil water and soil characteristics. The soil permeability depends on the soil texture, mineralogy, ESP of the soil, and the salt concentration of the percolating solution (Anandarajah, 2003; Mandal et al., 2008). However, saturated hydraulic conductivity ($\tilde{K}$) can be maintained even at high ESP levels provided the EC of the percolating water is above a critical (threshold) level (Quirk and Schofield, 1955). Conversely, when low electrolyte concentration water was applied, an ESP equal to 5 was enough to cause a two orders of magnitude decrease in the $\tilde{K}$ of 71 Australian soil (McIntyre, 1979). McNeal and Coleman (1966) found that an increase in the SAR and decrease in the electrolyte concentration of the percolating solution induced a decrease in the soil permeability. Abrol et al. (1988) found that there is a decrease in the soil relative hydraulic conductivity when the ESP is increased (Figure 4).

Frenkel et al. (1978) while studying the effect of clay type and content, ESP, and electrolyte concentration on the clay dispersion and soil hydraulic conductivity, concluded that the sensitivity of soil to the excessive exchangeable sodium and low electrolyte concentration increases with the clay content and bulk density. In flocculating soil colloids, the Mg^{2+} ions are less efficient than the Ca^{2+} ions (Rengasamy et al., 1986), although the US Salinity Laboratory Staff (1954) grouped Ca^{2+} and Mg^{2+} together as both the ions improve the soil structure.

SALIENT FEATURES OF THE SALT AFFECTED SOILS

The electrical conductivity (EC), exchangeable sodium percentage (ESP), and pH are the basic parameters used for classifying salt affected soils. The salinity of the soil is usually characterized by means of EC of the saturation extract (EC_e) obtained by suction-filtration of a water-saturated paste of soil. According to US Salinity Laboratory's classification (US Salinity Laboratory Staff, 1954), the salt affected soils are categorized into three types:

Saline soil: The soil is characterized as saline if EC_e >4 dS m^{-1} at 25°C and ESP<15. The pH, in general, is below 8.5. The dominant ions are Cl^- and SO_4^{2-}. Sodium content is less than 50% of soluble cations. Most of the salts in the soil solution have a positive effect on the soil structure. Therefore, water infiltration rate is not a major concern with the saline soil (United States Salinity Laboratory Staff, 1954).

Saline-sodic soil: The saline-sodic soil is high in sodium and other salts with EC_e >4 dS m^{-1}, SAR >13, and ESP >15. The soil pH can be above or below 8.5. They can have the characteristics of either a saline or sodic soil, depending on whether Na or Ca dominates. The Na$^+$ in the solution are present as neutral salts as $NaCl$ and Na_2SO_4. If the pH value is above 8.5, then HCO_3^- and CO_3^{2-} ions are present in the soil solution.

Non-saline sodic soil: The sodic soil is high in exchangeable Na as compared to Ca and Mg with EC_e <4 dSm^{-1}. Soil pH is usually greater than 8.5. The hydraulic conductivity as well as infiltration rate is often low, adversely affecting the water, solutes and air movement. Consequently, wet soil condition is generally accompanied by O$_2$ deficiency. This deficiency causes reduction in root respiration and total root volume, increased resistance to transport of water and nutrients through the roots, formation of toxic compounds in soils and plants.

Hence, reclamation actions are essential to maintain suitable conditions in soil for the plant growth.

RECLAMATION OF THE SALT AFFECTED SOILS

The reclamation methods are location specific and depend upon type and severity of the salt problem, viz. salinity or sodicity; time available for reclamation, soil type, irrigation water quality and availability, sensitivity of crops to be grown and economical viability.

i.) Reclamation of saline soil: Saline soil is reclaimed by leaching. The effective amelioration (Szabolcs, 1989) of the saline soils are: a) to keep the water table below the critical depth by drainage, b) to reduce the salt content in the root zone. Leaching with good quality and quantity of water is only effective if the saline soil.

ii.) Reclamation of Sodic Soil: For sodic soil, the adsorbed Na$^+$ ions has to be exchanged against the Ca^{2+} ions, which is effectuated by applying Ca salts and leaching with water of a low SAR value (Kamphorst and Bolt, 1978; Wang et al., 1998). After prolonged irrigation with good quality water, even without special measures, soil eventually become desodicated; however, the process may take a very long time (FAO/UNESCO, 1973; ILRI, 1979). To augment the reclamation process in the sodic soil, Ca^{2+} ions are directly or indirectly added to the soil system through any of the chemical amendments, viz., gypsum ($CaSO_4.2H_2O$), calcium chloride, pyrite, sulfur, sulphuric acid, limestone, iron sulphate, aluminum sulphate, calcium polysulphide etc. A suitable amendment can be chosen according to its accessibility, market price, and time available for reclamation. Gypsum is helpful to reduce swelling and dispersion of the soils through two mechanisms: 1) concentrations of ions in the soil water increases, which results in reduction of thickness of EDL; and 2) Ca$^+$ ions from the gypsum replace the Na$^+$ ions that are held on the clay surface.

Leaching

The leaching is intended to dissolve and transport the soluble salts downward below the crop root zone. The leaching requirement may be defined as the fraction of irrigation water that must be leached through the root zone to control the soil salinity at any specified level (US Salinity Laboratory Staff, 1954). The leaching requirement depends on: i) the salt concentration of the irrigation water, ii) the amount of water extracted from the soil by the crop through evapotranspiration, and iii) the salt tolerance of the crop (Hillel, 1998). To achieve the same degree of leaching, Miller et al. (1965) found that intermittent ponding requires less water than continuous ponding. For similar results in leaching, coarse textured soil requires less water than the fine textured soil. The

water requirement for peat > clay loam > sandy loam (Hoffman, 1980). For sandy loam soil, nearly 0.3 cm of water per unit depth of root zone is required as compared to 0.68 cm for the clay loam soil (Jury et al., 1979).

Infiltration study by Green and Ampt approach

Infiltration can be either measured in the field or estimated using the mathematical models that range from the empirical to physically based models. The Richards and the Green-Ampt models are the most commonly used physically based infiltration models. The Green and Ampt (1911) model is still considered useful for its simplicity and reasonably accurate predictions (Youngs and Aggelides, 1976). The flexibility of the Green-Ampt equation for describing infiltration under varied initial, boundary, and soil profile conditions makes it a useful tool for modeling the infiltration through both the uniform and layered soils.

Gypsum for reclamation of salt affected soils

Gypsum is used for sodic soil reclamation since long time (U.S. Salinity Laboratory Staff, 1954; Oster and Frenkel, 1980). The solubility of gypsum in water is 0.26% at 25°C. The dissolution reaction of gypsum is: $CaSO_4.2H_2O\left(solid\right)\rightarrow Ca^{2+}+SO_4^{2-}+2H_2O$.
Based on solubility of gypsum, Dutt (1964) and Dutt et al. (1972) predicted that 52 to 73 cm of irrigation water was required to dissolve 16.5 to 24 metric tons/ha of applied gypsum. Hira and Singh (1980) observed that gypsum dissolution increased with an increase in the exchangeable Na content of the soil. The effectiveness of gypsum for sodic soil reclamation has been studied by many investigators (Keren and Shainberg, 1981; Lange et al., 2005; Amezketa et al., 2005; Sakai et al., 2009). Comparative analyses of crop response due to irrigation with poor-quality water and gypsum application have been extensively studied by various researchers (Ilyas et al., 1997; Yaduvanshi and Sharma, 2008). Gypsum has also been used in agriculture as a soil stabilizing agent, nutrient source for Ca, and ameliorant to counter the subsoil acidity (Sumner, 1993; Levy and Sumner, 1998). Some more studies on the effect of gypsum on the soil properties are enlisted in Table 1. The efficiency of the gypsum amendment depends on several factors, viz. type of application, solubility, particle size, and soil water composition. A shallow mixing of gypsum with the soil is better than the deeper mixing (Oster, 1982; Singh, 1994).

Gypsum requirement

The amount of gypsum required for the reclamation of the salt affected soil depends on the initial and desired final exchangeable Na$^+$ fraction, cation exchange capacity

(CEC), bulk density, and the depth of soil to be reclaimed. From the condition of electroneutrality, the exchange must be equivalent (Bolt, 1978). In making this calculation, a final ESP of 10 is considered as it will not result in any noticeable peptisation of the soil (FAO/UNESCO, 1973). The gypsum requirement is estimated as:

Gypsum requirement in meq/100 g of soil = $CEC\left(ESP_i-ESP_f\right)/100$

where ESP_i = initial ESP of soil (meq/100gm of soil); ESP_f = final ESP desired after the reclamation (meq/100 g of soil).

Effect of gypsum application on hydraulic conductivity and infiltration rate

Gypsum adds Ca to the soil water, which in turn, reduces the amount of exchangeable Na in the exchangeable complex (Quirk and Schofield, 1955). The gypsum-saturated irrigation water improves the infiltration rate due to the fast exchange reaction with the soil exchangeable Na and the increase in electrolyte concentration of the soil water (Anjos, 1993; Oster and Schroer, 1979). Shainberg et al. (1982) used a laboratory column study to compare the hydraulic conductivities of two sodic soils having an ESP of 20 and leached with the distilled water after adding equivalent amounts of CaCl$_2$ and gypsum. A higher hydraulic conductivity was found in the gypsum-treated soil than that with CaCl$_2$, which was attributed to the slow release of Ca^{2+} into the displacing water of slightly soluble gypsum as compared with the rapid leaching of highly soluble CaCl$_2$.

Eltaif and Gharaibeh (2007) investigated the influence of solute concentration of two types of electrolyte solutions, viz., single-ion (Na) and mixed-ion (Na–Ca) systems on the hydraulic and other physical properties of a clay soil. The saturated soil hydraulic conductivity ($\tilde{K}$) declined noticeably while using a lower solute concentration in a single ion system. The improvement of some physical properties in the mixed-ion solution treatment was attributed to the presence of Ca^{2+} ions. Silveira et al. (2008) evaluated the effects of the addition of gypsum in the irrigation water on the physical and chemical properties of soil with different levels of salinity and sodicity and found that, the soil leaching with gypsum-saturated water resulted in an increase in the amounts of exchangeable calcium and decrease in soil pH, EC, and ESP. Chawla and Abrol (1982) conducted a laboratory experiment to evaluate the effect of gypsum fineness for reclamation of the soil with ESP of 35 and 80. The treatments with the coarser particles had a lower initial hydraulic conductivity that was maintained or increased with time.

Table 1. Experiments on the effectiveness of gypsum on soil properties.

Investigators	Research work	Findings
Amezketa et al. (2005)	Effectiveness of mined-gypsum, and the byproduct of coal-gypsum and lacto-gypsum to control crusting in sodic soil	These three types of gypsum materials were equally effective in the soil reclamation process, whereas lacto-gypsum was less efficient in the prevention of crusting in sodic soil.
Yu et al. (2003)	Effect of surface application of granular polyacrylamide, PAM (10 and 20 kg ha^{-1}) and gypsum (2 and 4 Mg ha^{-1}) on the infiltration rate (IR) and soil erosion	Spreading gypsum at the soil surface doubled the final infiltration rate (IR) compared with that of control and reduced erosion slightly. Spreading a mixture of 20 kg ha^{-1} PAM and 4 Mg ha^{-1} gypsum increased the final IR of the two soils by four times and reduced erosion to 30 percent as compared to that in the control.
Shainberg et al. (1982)	Laboratory column study to compare the hydraulic conductivities of two sodic soils (ESP 20) leached with distilled water to which equivalent amounts of CaCl$_2$ and gypsum had been added	A higher hydraulic conductivity was found in the gypsum treated soil as compared to that of CaCl$_2$, which was ascribed to the slow release of Ca^{+2} ions into the displacing water of slightly soluble gypsum amendment as compared with the rapid leaching of Ca^{+2} ions by highly soluble CaCl$_2$.
Rengasamy et al. (1986)	Effectiveness of Ca^{2+} and Mg^{2+} ions in flocculating the soil colloids	The Mg^{2+} ions are less efficient than the Ca^{2+} ions in flocculating the soil colloids.
Ayers and Westcot (1985)	Effects of poor quality irrigation water on the soil chemical properties	In spite of different levels of applied gypsum, sodic irrigations caused an appreciable build up of ESP.

Modeling studies for management of salt affected soils

A number of models have been proposed to describe the relationships between the structure of the porous material as reflected by its pore size distribution and permeability (Kozeny, 1927; Marshall, 1958). Lagerwerff et al. (1969) used the diffuse double layer theory to predict the variations in the saturated hydraulic conductivity ($\widetilde{K}$) using the Kozeny-Carman equation for the soil exposed to various chemical conditions. Further, in order to estimate hydraulic conductivity decrease during expansion of soil matrix, Lagerwerff and his coworkers coupled the prediction of the clay swelling with the Kozeny-Carman equation for the viscous flow through porous media (Reeve and Luthin, 1957). However, the approach of Lagerwerff et al. (1969) has the limitation that the value of the surface area required in the Kozeny-Carman equation is not the surface area of the entire soil matrix, but only that of the major flow channels through the matrix. Such a surface area value is a reasonable parameter for the uniform materials of nearly uniform pore size distribution (Carman, 1937). Mahanta and Mishra (2014) have given a method to compute the pore size taking into account the electric double layers. Dahiya et al. (1980) studied a multicompartment model to describe the transport of reactive solutes in the soil under unsaturated flow conditions. For an 80 percent reduction in the soil profile salinity, 0.4 cm leaching water per cm depth was required to be passed through the soil which corresponded to 1.14 pore volume displacement. When leached in the presence of gypsum, the SAR was reduced to a greater extent in the lower depths which would otherwise have been achieved by passing additional quantities of water. Assuming an equilibrium chemistry and piston flow approach for the movement of soil water, Oster and Frenkel (1980) theoretically evaluated the sodic soil reclamation. Since the exchange phase acted as a sink for Ca^{2+} until both the gypsum dissolution and exchange reaction reached equilibrium, the effective solubility of gypsum was increased when mixed with a sodic soil.

To assess the effects of spatial variability in soil properties and temporal variability in irrigation

water quality, a number of simulations are carried out by Kaledhonkar et al. (2006) using an analytical and numerical model (UNSATCHEM). The alternate use of alkali groundwater and canal water is the cause for temporal variability of irrigation water quality, which significantly influences the ESP-values that develop in the topsoil. The equilibrium model, which assumes the rate of gypsum dissolution, is rapid enough to maintain a saturated condition, were field tested by Dutt et al. (1972) in Arizona and by Tanji et al. (1972) in California. Both these studies indicated a good agreement between the predicted and measured results for the case of sodic soil reclamation with gypsum.

Reservoirs connected in series model

In the reservoirs connected in series model, Van der Molen (1957) assumed that the soil is homogenous and the volume of each reservoir is same. Each reservoir receives the outflow from the overlying one where mixing is complete. The salt concentration of the Nth reservoir is given by (ILRI, 1979).

$$C_N = C_i + (C_0 - C_i)e^{\frac{-ft}{T}}\sum_{n=0}^{n=N-1}\left(1+\frac{f^n t^n}{n!T^n}\right)$$

Where C_i = salt concentration of the irrigation water used for leaching; C_0 = original salt concentration of the reservoir solution; f = leaching efficiency; t = time; $T = v/Q$ = ratio of the volume of reservoir to the flow rate at which the soil moisture is replaced; v = volume of reservoir; and Q = rate of inflow. Since the interaction of ions with the soil is not considered in this model, this model is suitable for the desalinization study.

However, all the models discussed above are not useful as interaction of ions present in the soil water with the soil is not considered. Mahanta (2010) has developed a model for sodic soil reclamation taking into account the electric double layer. By neglecting the residual deficit charge on clay surface, that model can also simulate the reclamation of saline soil.

DISCUSSIONS AND CONCLUSIONS

Approximate solution of the Poisson-Boltzman equation given by Gouy (1910) and Chapman (1913) neglects the higher order terms while expanding the exponential terms appearing in the derivation. As EDL thickness is the main factor deciding the flow of water and consequently leaching of excess salts through the sodic soil, its accurate quantification is required. The exact EDL thickness for two types of ions may be computed by the method given by Mahanta et al. (2014).

From the literature review, the following conclusions can be drawn:

i.) The methods for reclaiming the salt affected soils are location specific and vary depending upon the type of salt affected soil, the extent of reclamation required, crop to be cultivated, time available for reclamation, and economical aspects.

ii.) Amendment is essential to augment the reclamation process in the sodic soil. For reclaiming the sodic soil, shallow mixing of gypsum is better than deep mixing.

iii.) Lagerwerff et al. (1969) used the diffuse double layer theory to predict the variations in the $\tilde{K}$ using the Kozeny-Carman equation for the soils exposed to various chemical conditions. The limitation of the approach used by Lagerwerff et al. (1969) is that

the surface area value required in the Kozeny-Carman equation is not the surface area of the entire soil matrix, but only that of the major flow channels through the matrix.

iv.) The thickness of the EDL is dependant on the nature and the concentrations of ions in the bulk solution. The diffuse double layer theory can be quantitatively applied to a mixture of monovalent and divalent cations to deduce the ion exchange (FAO/UNESCO, 1973). The hydraulic conductivity of the soil is dependant on the thickness of the EDL. When the thickness of the EDL is more, the effective pore space and hydraulic conductivity are less and vice versa.

v.) The Green and Ampt infiltration model is more convenient due to its simplicity than the Richards model for computing the infiltration into the soil.

vi.) The reservoirs connected in series model advocated by Van der Molen (1957) does not take into account the interaction of the ions in the soil water with the clay soil.

There is need of more study on reclamation of the sodic soil taking into account Na^+ and Ca^{2+} ions; and the electric double layer theory.

REFERENCES

Abrol IP, Yadav JSP, Massoud FI (1988). Salt–affected soils and their management. Soils Bulletin 39, FAO, Rome.

Amezketa E, Aragues R, Gazol R (2005). Efficiency of sulphuric acid, mined gypsum, and two gypsum by-products in soil crusting prevention and sodic soil reclamation. Agron. J., 97: 983-989.

Anandarajah A (2003). Mechanism controlling permeability change in clays due to changes in pore fluid. J. of Geotech. and Geoenviron. Eng., 129(2): 163-172.

Anjos IM (1993). Recuperação de um solo salino-sódico: efeito de diferentes níveis e formas de aplicação de gesso. Areia: UFPB, 34p. Dissertação (Mestrado).

Appelo CAJ, Postma D (2005). Geochemistry, groundwater and pollution. 2nd edition, A.A. Balkema Publishers, Leiden/London/New York/Philadelphia/ Singapore.

Ayers RS, Westcot DW (1985).

Water quality for agriculture. FAO Irrigation and Drainage Paper 29 (Rev.1), FAO of the United Nations, Rome, Italy.

Bolt GH (1978). Surface interaction between the soil solid phase and the soil solution. Soil chemistry A. Basic elements, G.H. Bolt, and M.G.M. Bruggenwert(Ed.), Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York.

Bolt GH, Bruggenwert MGM (1978). Composition of the soil. Soil Chemistry A. Basic Elements. G.H. Bolt, and M.G.M. Bruggenwert (Ed.), Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York.

Buringh P (1978). Food production potential of the world. In: Radhe Sinha(Ed.). The world food problem; Consensus and conflict, Pregamon press: 477-485.

Carman PC (1937). Fluid flow through a granular bed. Trans. Inst. Chem. Eng. London, 15:150-156.

Chapman L (1913). A contribution to the theory of electrocapillarity. Philosophical Magazine, Ser.6, 25(148): 475-481.

Chawla KL, Abrol IP (1982). Effect of gypsum fineness on the reclamation of sodic soils. Ag. Water Manage., 5: 41-50.

Dahiya IS, Abrol IP, Hajrasuliha S (1980). Modeling transport of reactive solutes during leaching saline-sodic soils rich in soluble carbonates. Agric. Water. Manage., 3: 3-16.

Dutt GR (1964). Effect of small amounts of gypsum in soils on the solutes in effluents. Soil Sci. Soc. Am. Proc., 28:754-757.

Dutt GR, Terkeltoub RW, Rauschkolb RS (1972). Prediction of gypsum and leaching requirements for sodium affected soils. Soil Sci., 114: 93-103.

Eltaif NI, Gharaibeh MA (2007). Effects of single and mixed ion solutions on hydraulic and physical properties of a clay soil. Water Air Soil Pollution., 181: 297–302.

FAO/UNESCO (1973). Irrigation, drainage and salinity. An international source book.

Frenkel H, Goortzen JO, Rhoades JD (1978). Effects of clay type and content, exchangeable sodium percentage and electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Sci. Soc. Am. J., 42: 32– 39.

Gouy G (1910). Sur la constitution de la charge electrque a la surface d'un electrolyte. Journal de Physique Theorique et Appliquee, Ser. 4(9):457-468 (in French).

Green WH, Ampt G (1911). Studies of soil physics, part I–the flow of air and water through soils. J. Agric. Sci., 4:1-24.

Grim RE (1953). Clay Minerology. International Series in the Earth Sciences. McGraw-Hill Book Company, Inc., NewYork, Toronto, Londan.

Hillel D (1998). Environmental soil physics. Academic press.

Hira GS, Singh NT (1980). Irrigation water requirement for dissolution of gypsum in sodic soil. Soil Sci. Soc. Am. J., 44: 930-933.

Hoffman GJ (1980). Guidelines for reclamation of salt-affected soils. Proc. Inter-American Salinity and Water Management Technology Conference. Juarez, Mexico.11–12 December 1980: 49–64.

ILRI (1979). Drainage principles and applications, II Theories of field drainage and watershed runoff, 9. Salt balance and leaching requirement. Publication 16, Wageningen, Nederlands :89-93.

Ilyas M, Qureshi RH, Quadir MA (1997). Chemical changes in a saline-sodic soil after gypsum application and cropping. Soil Technol., 10: 247-260.

Jenny H (1932). Studies on the mechanism of ionic exchange in colloidal aluminum silicates: J. Phvsical Chem., 36: 2217-2258.

Jenny H (1936). Simple kinetic theory of ionic exchange. I. Ions of equal valency: J. Physical Chem., 40: 501-517.

Jury WA, Jarrel WM, Devitt D (1979). Reclamation of saline-sodic soils by leaching. Soil Sci. Soc. Am. J., 43:1100-1106.

Kaledhonkar MJ, Keshari AK, Van Der Zee SEATM (2006). Relative sensitivity of ESP profile to spatial and temporal variability in cation exchange capacity and pore water velocity under simulated field conditions. J. Agric. Water Manage., 83:58-68.

Kamphorst A, Bolt GH (1978). Saline and sodic soils. Ch.9, Soil Chemistry A. Basic Elements. Elsevier Scientific Publishing Company, Bolt, G.H., and Bruggenwert, M.G.M. (Ed.), Developments in Soil Science 5A, Amsterdam-Oxford-New York.

Keren R (2000). Salinity. In Handbook of soil science, M.E. Sumner (Ed.), CRC press.

Keren R, Shainberg I (1981). Effect of dissolution rate on the efficiency of industrial and mined gypsum in improving infiltration of a sodic soil. Soil Sci. Soc. Am. J., 4:103-107.

Kozeny J (1927). Ueber kapillare Leitung des Wassers im Boden. Wien, Akad. Wiss. 136(2a), 271p.

Lagerwerff JV, Nakayama FS, Frere HM (1969). Hydraulic conductivity related to porosity and swelling of soil. Soil Sci. Soc. Am. Proc., 33: 3-12.

Lange ML, Webb BL, Jolley VD, Nelson SD (2005). Long term effects of surface applied amendments in reclamation of sodic soils. Western Nutrient Management. Conference 6, Salt lake City, UT: 207-212.

Levy GJ, Sumner ME (1998). Mined and by-product gypsum as soil amendments and conditioners. In A. Wallace and E.R. Terry (ed.), Handbook of soil conditioners, Marcel Dekker, New York: pp. 445-462.

Mahanta KK (2010). A study on reclamation of sodic soils. Unpublished thesis report, Dept. of WRD&M, IIT, Roorkee.

Mahanta KK, Mishra GC, Kansal ML (2012). Estimation of electric double layer thickness from linearized and nonlinear solutions of Poisson–Boltzman equation for single type of ions. Applied Clay Science, 59-60: 1–7.

Mahanta KK, Mishra GC, Kansal ML (2014). Estimation of the electric double layer thickness in the presence of two types of ions in soil water. Applied Clay Science, 87: 212-218.

Mahanta KK, Mishra GC (2014). Determination of interplate distance between two clays and initial bulk concentrations: an inverse problem. Int. J. Res. in Agric. Sci., 1(5): 287-292, ISSN (Online): 2348–3997

Mandal UK, Bhardwaj AK, Warrington DN, Goldstein D, Tal AB, Levy GJ (2008). Changes in soil hydraulic conductivity, runoff, and soil loss due to irrigation with different types of saline–sodic water. Geoderma, 144: 509–516.

Marshall TJ (1958). A relation between permeability and size distribution of the pores. J. Soil Sci., 9:1-8.

Mclntyre DS (1979). Exchangeable sodium, subplasticity and hydraulic conductivity of some Australian soils. Aust. J. Soil Res., 17: 308-312.

McNeal BL, Coleman NT (1966). Effect of solution composition on soil hydraulic conductivity. Soil Sci. Soc. Am. Proc., 30: 308-312.

Miller RJ, Bigger JW, Nielsen DR (1965).Chloride displacement in a Panoche clay loam in relation to water movement and distribution. Water Resour. Res., 1: 63-73.

Mitchell JK (1976). Fundamentals of soil behavior. John Wiley & Sons, Inc., New York, London, Sydney, Toronto.

Newman ACD (Ed) (1987).Chemistry of clays and clay minerals. Minerological society monograph no.6, Longman Scientific and Technical, Mineralogical Society.

Oster JD, Frenkel H (1980).The chemistry of the reclamation of sodic soils with gypsum and lime. Soil Sci. Soc. Am. J., 44:41-45.

Oster JD (1982). Gypsum usage in irrigated agriculture: a review. Fertilizer Res., 3: 73-89.

Oster JD, Schroer FW (1979). Infiltration as influenced by water quality. Soil Sci. Soc. Am. J., 43: 444-448.

Quirk JP, Schofield RK(1955). The effect of electrolyte concentration on soil permeability. J. Soil Sci., 6: 163-178.

Reeve RC, Luthin JN (1957). Drainage investigation methods. I. Methods of measuring soil permeability. J. Soil Sci., 6: 163-178.

Rengasamy P, Greene RSB, Ford GW (1986). Influence of magnesium on aggregate stability in sodic red-brown earths. Aust. J. Soil Res., 24: 229–237.

Rhoades JD, Loveday J (1990). Salinity in irrigated agriculture, Irrigation of Agricultural Crops. Agronomy Monograph No.30, Madison, Wisconsin, USA

Rhoades JD (1974) Drainage for salinity control. In Drainage for Agriculture, Edited by JV Schilfgaarde, Number 17 in the Series Agronomy, American Society of Agronomy, Inc., Madison,Wisconsin, USA:433-461.

Sakai Y, Shitara S, Sadakata M (2009). Salt transport in alkali soil reclamation by gypsum and prediction of Na leaching in field in China. J. Water and Environ. Technol., 7(2):121-131.

Schmitz RM (2006). Can the diffuse double layer theory describe changes in hydraulic conductivity of compacted clays? Geotechnical and Geological Eng., 24:1835–1844.

Shainberg I, Keren R, Frenkel H (1982). Response of sodic soils to gypsum and calcium chloride application. Soil Science Society of America Proceedings, 46:113-117.

Silveira KR, Ribeiro MR, Oliveira LB, Heck RJ, Silveira RR (2008). Gypsum-saturated water to reclaim alluvial saline sodic and sodic soils. Sci. Agric. (Piracicaba, Braz.), 65(1):69-76.

Singh KN (1994). Crops and agronomic management. Salinity Management for Sustainable Agriculture (25 years of research at CSSRI), CSSRI, Karnal, India.

Sumner ME (1993). Sodic soils: new perspectives. Aust. J. Soil Res., 31: 683–750.

Szabolcs I (1989). Salt-affected soils. CRC press, Boca Raton, FL.

Tanji KK (1995) The salinization of land and water resources: human causes, extent, management and case studies. In: Centre for Resources and Environment Studies, The Australian National University. CAB International , Wallingford.

United States Salinity Laboratory Staff (1954). Diagnosis and improvement of saline and alkali soils. L.A. Richards (Ed.), United

States Department of Agriculture, Agriculture Handbook No. 60, Oxford and Ibh Publishing Co. New Delhi, Bombay, Calcutta.

Van der Molen WH (1957). The exchangeable cations in soils flooded with sea water. Versl. Landbouwk, Ondrez. 63.17. The Hauge, 167p.

Van Olphen H (1977). An introduction to clay and colloidal chemistry. Wiley Interscience, New York.

Voyutsky S (1978). Colloid chemistry. Mir Publishers, Muscow.

Wang S, Kitamura Y, Yano T (1998). Reclamation of gypsiferous and nongypsiferous sodic soils by leaching. Soil Phys. Cond. Plant Growth, Jpn., 80: 21-32.

Yaduvanshi NPS, Sharma DR (2008). Tillage and residual organic manures/chemical amendment effects on soil organic matter and yield of wheat under sodic water irrigation. Soil & Tillage Res., 98:11–16.

Yeung AT (1992). Diffuse double layer equations in SI units. J. Geotech. Eng., 118(12): 2000-2005.

Youngs EG, Aggelides S (1976). Drainage to a water table analyzed by the Green-Ampt approach. J. of Hydrol., 31: 67-79

Yu J, Lei T, Shainberg I, Mamedov AI, Levy GJ (2003). Infiltration and erosion in soils treated with dry PAM and gypsum. Soil Sci. Soc. Am. J., 67:630–636.