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Development of a sodic soil reclamation model based on electric double layer theory

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ABSTRACT

A sodic soil reclamation model is developed based on the electric double layer (EDL) theory. The computed EDL thickness (β) being very small in comparison to the interparticle distance, with reduction of β there is insignificant increase in the hydraulic conductivity. Simulation results indicated that the sodium adsorption ratio (SAR) is reduced to acceptable level (SAR<13) only up to a depth of 0.3 m with infiltration of 10 pore volumes of gypsum solution in a fine loamy soil.

***Keywords* :** Eelectric double layer, gypsum, reclamation, sodic soil.

Crop is affected when salts accumulate in the root zone beyond a permissible limit (Abrol *et al*., 1988). In sodic soil, presence of excess sodium (Na) ions destroys the favorable physical conditions by causing dispersion of clay particles, hampering infiltration rate and soil permeability (Anandarajah, 2003). Hence, leaching of sodic soil is more challenging than leaching of saline soil (So and Aylmore, 1993; Gupta and Ranade, 1987).

During the formation stages of clay, isomorphic substitutions in the lattice interior cause existence of residual negative charges on the surface (Butt and Graf, 2003). These charges are balanced by the cations present in the soil water (Bolt, 1978). The electrostatic forces that exist between the charges on the clay surface and the cations present in the soil water form the EDL at the clay surface (Butt and Graf, 2003). Larger EDL obstructs more pore space affecting the hydraulic conductivity (K) of soil. The EDL thickness (β) is computed using the solution of Poisson-Boltzman (P-B) equation (Mahanta *et al*., 2012; Voyutsky, 1978; Mahanta *et al*., 2014)

Chemical amendments such as gypsum are required to augment the reclamation process in sodic soil (ILRI, 1979; Oster, 1982; Naorem *et al*., 2017). The reclamation of sodic soil requires the replacement of Na^+ ions in the EDL by incoming Ca^{2+} ions and leaching (Mahanta *et al*., 2015). The infiltration of Ca^{2+} ions causes redistribution of Na^+ and Ca^{2+} ions in the soil water. Calcium ions are attracted more towards the clay surface because of higher valence than the Na^+ ions, thus replace the existing Na^+ ions. Less number of Ca^{2+} ions is required to neutralize the residual charges on the clay surface than Na^+ ions, thus reduce β and facilitate leaching of sodium ions.

The previous studies on the reclamation of the sodic soil are mainly confined to the experimental approach, where true scenario *i.e*. taking into account of the EDL has hardly been considered. A conceptual model is developed here taking into account the interaction of Ca^{2+} and Na^+ ions through EDL theory. The model is simulated for study of reclamation of a fine loamy sodic soil.

MATERIALS AND METHODS

The root zone depth is conceptualized to be comprised of reservoirs connected in series as shown in fig. 1. Each of the reservoirs has thickness equal to D. The initial soil moisture in the root zone is θ_f. The pore volume (PV) in each reservoir is equal to $(\theta_s - \theta_f)D$. For estimation of $\tilde{K}$, prior estimation of bulk concentrations of Ca^{2+} and Na^+ ions is prerequisite. The bulk concentration is the concentration of ion at infinite distance from the clay surface, where potential is zero. A saturation extract is made using distilled water and the bulk concentrations of sodium (C_{bNa^+}) and calcium ($C_{bCa^{2+}}$) are determined in the laboratory (Rhoades, 1982).

Laboratory test was also conducted in the year 2010 using a permeameter on a core sample applying distilled water and C_{bNa^+} and C_{bNa^+} in the effluent from the permeameter at the time of test are recorded. Known Ca^{2+} concentration of gypsum solution, which may contain nominal amount of sodium as present in the natural water, is applied on the surface. It is required to find the temporal and spatial distributions of the C_{bNa^+} and C_{bNa^+} in the root zone as several volumes infiltrate.

When cumulative infiltration equals J number of PV, the wetting front reaches a depth equal to JD and the number of reservoirs which get saturated is J. During the advancement of the wetting front in the J^{th} reservoir, all the $(J-1)^{th}$ reservoirs are conceptualized to be one reservoir with a harmonic mean hydraulic conductivity $K^*_{hm}(1,J)$ having a thickness of $(J-1)D$.

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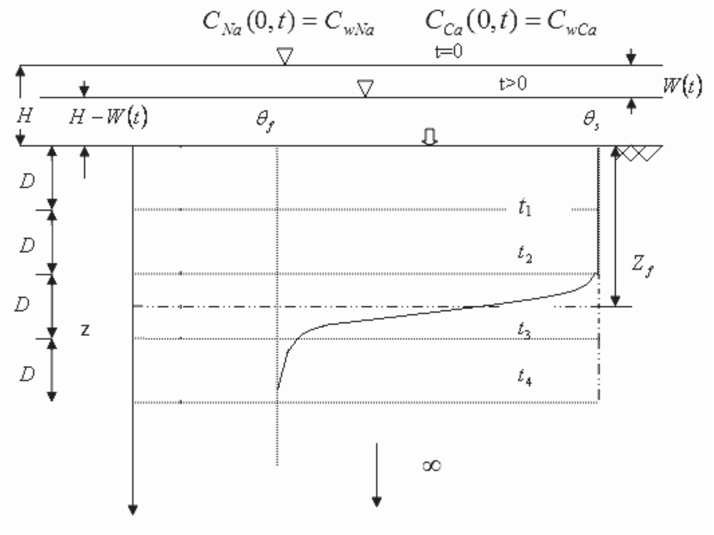


Fig. 1: Reservoirs of equal size connected in series.

$$K^*_{hm}(1,J)=\frac{(J-1)D}{D/K(1,J)+D/K(2,J)+...+D/K(J-1,J)}=\frac{J-1}{\sum_{I=1}^{J-1}1/K(I,J)} \tag{1}$$

The hydraulic conductivity in the J^{th} reservoir while the wetting front moving in it is $K^*(J,J)$. The equivalent $K^*(2,J)$ is taken as $K^*(J,J)$.

The Green and Ampt equation (1911) for two layered soil (Mahanta, 2010; Mahanta *et al.*, 2012) is :

$$\frac{\left\{1-\left(\theta_s-\theta_f\right)\right\}K^*(2,J)\,t_{JD}}{\left(\theta_s-\theta_f\right)}$$

$$=D+\left[(J-1)D\left\{\frac{K^*(2,J)}{K^*_{hm}(1,J)}-1\right\}-\frac{\left\{H+H_f\right\}}{\left\{1-\left(\theta_s-\theta_f\right)\right\}}\right]\ln\left[\frac{\left\{H+H_f\right\}+JD\left\{1-\left(\theta_s-\theta_f\right)\right\}}{\left\{H+H_f\right\}+(J-1)D\left\{1-\left(\theta_s-\theta_f\right)\right\}}\right]$$

$$+\ \frac{\left\{1-\left(\theta_s-\theta_f\right)\right\}K^*(2,J)\,t_{(J-1)D}}{\left(\theta_s-\theta_f\right)} \tag{2}$$

H_f is the capillary pressure head at the wetting front (m); H is the depth of water applied at the surface in the beginning (m) and t is the time.

The temporal and spatial variations of C_{bNa^+} and $C_{bCa^{2+}}$ with passage of integer pore volumes have been computed applying mass balance of the ions in a series of reservoirs. The passing time of integer pore volume is obtained applying Green and Ampt infiltration theory.

Formulation of model

Initial and boundary conditions

The initial condition is: $C_{Na^+}(I, J) = C^*_{bNa^+}$; $C_{Ca^{2+}}(I, J) = C^*_{bCa^{2+}}$ for $J = 0$ for all I ; J represents the PV and linked to time t . $J = 0$ means $t = 0.$ I represents reservoir number and linked to depth z. Boundary conditions: $C_{Na^+}(0, J) = C_{wNa}$; $C_{Ca^{2+}}(0, J) = C_{wCa}$ for all J . $I = 0$ means the water reservoir is on the surface.

Mass balance

As infiltration progresses, each reservoir is subjected to two situations; a) there is inflow but no outflow and b) there is both inflow and outflow. The reservoir which is getting saturated by the wetting front has inflow component but no outflow component. The reservoir which is already saturated, has both inflow and outflow components.

i) Mass balance in a reservoir when there is inflow but no outflow

The I^{th} reservoir is in an unsaturated state for $J - 1 = I$. For $J = I$ the saturation front is moving in the reservoir. The mass balance equations for Na and Ca carried out over the time period in which one pore volume saturates the reservoir are as follows.

For Na :

$$\frac{D\theta_f}{d_f}\int_0^{d_f} C^*_{bNa^+}(I,J-1)e^{\frac{-FZ_1\phi(x,J-1)}{RT}}dx + D(\theta_s-\theta_f)\left\{\frac{\bar{C}_{bNa^+}(I-1,J-1)+\bar{C}_{bNa^+}(I-1,J)}{2}\right\}$$

$$= \frac{D\theta_s}{d_s}\int_0^{d_s} C_{bNa^+}(I,J)e^{\frac{-FZ_1\phi(x,J)}{RT}}dx \tag{3}$$

The average concentrations $\bar{C}_{bNa^+}(I-1,J-1),\ \bar{C}_{bNa^+}(I-1,J)$ are given by:

$$\bar{C}_{bNa^+}(I-1,J-1) = \frac{1}{(d_s-d_f)}\int_{d_f}^{d_s} C_{bNa^+}(I-1,J-1)\,dx \tag{4}$$

$$\bar{C}_{bNa^+}(I-1,J) = \frac{1}{(d_s-d_f)}\int_{d_f}^{d_s} C_{bNa^+}(I-1,J)\,dx \tag{5}$$

An alternate way of computing average concentration of the influent is:

$$\bar{C}_{bNa^+}(I-1,J-1) = \frac{1}{(d_s-\beta(I-1,J-1))}\int_{\beta(I-1,J-1)}^{d_s} C_{bNa^+}(I-1,J-1)\,dx \tag{6}$$

$$\bar{C}_{bNa^+}(I-1,J) = \frac{1}{(d_s-\beta(I-1,J))}\int_{\beta(I-1,J)}^{d_s} C_{bNa^+}(I-1,J)\,dx \tag{7}$$

where $\beta(I-1, J)$ is thickness of EDL in the $(I-1)^{th}$ reservoir when J^{th} PV has passed through this reservoir, and $\beta\ (I-1, J-1)$ is thickness of EDL in the $(I-1)^{th}$ reservoir when $(J-1)^{th}$ PV has passed through the reservoir. As the soil water in the double layer is immobile, the average concentrations of Na and Ca ions have been computed for the distance from β to d_s using equations (6) and (7).

Gouy (1910) and Chapman (1913) had initiated the study of the diffuse characters of concentrations of cations away from the clay surface (Van Olphen, 1977). Inside the EDL, the cations are heavily concentrated (Mahanta and Mishra, 2016). The β (Yeung, 1992; Butt and Graf, 2003) is given by:

$$\beta = \frac{1}{\kappa} = \sqrt{\frac{\varepsilon RT}{2F^2\left\{Z_1^2 C_{bNa^+} + Z_2^2 C_{bCa^{2+}}\right\}}} \tag{8}$$

Voyutsky (1978) has derived this equation for computation of β . Thus, β can be determined if the bulk concentrations of Na^+ and Ca^{2+} ions in soil water are known.

The first term in the left side in Eq. (3) is the initial mass (mole) present in the I^{th} reservoir. The upper limit of integration is d_f represents initial soil moisture. The integrand is the variation of the concentration (mol m^{-3}) in the soil water with distance from the clay surface. x is the distance from the clay surface. The second term represents the total mass (mole) of Na ions those have entered into the reservoir from the $(I-1)^{th}$ reservoir. It may be noted that, an average value of the concentrations in the influent of each PV has been considered. The last term on the right hand side of Eq. (3) represents the mass in the reservoir when the reservoir gets completely saturated. The upper limit of integration is d_s as the reservoir gets completely saturated.

Similarly, the mass balance equation for Ca is:

$$\frac{D\theta_f}{d_f}\int_0^{d_f} C^*_{bCa^{2+}}(I,J-1)e^{\frac{-FZ_2\phi(x,J-1)}{RT}}dx + D(\theta_s-\theta_f)\left\{\frac{\bar{C}_{bCa^{2+}}(I-1,J-1)+\bar{C}_{bCa^{2+}}(I-1,J)}{2}\right\}$$

$$= \frac{D\theta_s}{d_s}\int_0^{d_s} C_{bCa^{2+}}(I,J)e^{\frac{-FZ_2\phi(x,J)}{RT}}dx \tag{9}$$

$$\bar{C}_{bCa^{2+}}(I-1,J-1)=\frac{1}{(d_s-d_f)}\int_{d_f}^{d_s}C_{bCa^{2+}}(I-1,J-1)\,dx \tag{10}$$

$$\bar{C}_{bCa^{2+}}(I-1,J)=\frac{1}{(d_s-d_f)}\int_{d_f}^{d_s}C_{bCa^{2+}}(I-1,J)\,dx \tag{11}$$

Computation of $C^*_{bNa^+}$ and $C^*_{bCa^{2+}}$ from measured bulk concentrations of ions in the saturation extract is an inverse problem and are known. The two unknowns C_{bNa^+} (I, J) and $C^*_{bCa^{2+}}$ (I, J) are solved from Eq. (3) and Eq. (9) using Taylor series expansion and iteration procedure. Eq. (3) and Eq. (9) are implicit in respect of both these unknowns as the potential $\varphi(x,J)$ is a function of both C_{bNa^+} (I, J) and $C^*_{bCa^{2+}}$ (I, J). When bulk concentrations in the I^{th} reservoir for J^{th} PV are to be determined, the bulk concentrations in $(I-1)^{th}$ reservoir for J^{th} PV have already been determined. Equations (3) and (9) are explicit with respect to the reservoirs; in other words, while C_{bNa^+} (I, J) and $C^*_{bCa^{2+}}$ (I, J) are being solved C_{bNa^+} $(I-1, J)$ and $C_{bCa^{2+}}$ $(I-1, J)$ have solved a priori.

ii) Mass balance when the reservoir is already saturated and there is both inflow and outflow

The equations of mass balance for Na^+ and Ca^{2+} ions in I^{th} reservoir when PV of water enters are:

$$\frac{D\theta_s}{d_s}\int_0^{d_s}C_{bNa^+}(I,J-1)e^{\frac{-FZ_1\phi(x,J-1)}{RT}}dx+D(\theta_s-\theta_f)\left\{\frac{\bar{C}_{bNa^+}(I-1,J-1)+\bar{C}_{bNa^+}(I-1,J)}{2}\right\}$$

$$-D(\theta_s-\theta_f)\left\{\frac{\bar{C}_{bNa^+}(I,J-1)+\bar{C}_{bNa^+}(I,J)}{2}\right\}=\frac{D\theta_s}{d_s}\int_0^{D_s}C_{bNa^+}(I,J)e^{\frac{-FZ_1\phi(x,J)}{RT}}dx \tag{12}$$

$$\bar{C}_{bNa^+}(I,J-1)=\frac{1}{(d_s-d_f)}\int_{d_f}^{d_s}C_{bNa^+}(I,J-1)\,dx \tag{13}$$

$$\bar{C}_{bNa^+}(I,J)=\frac{1}{(d_s-d_f)}\int_{d_f}^{d_s}C_{bNa^+}(I,J)\,dx \tag{14}$$

$$\frac{D\theta_s}{d_s}\int_0^{d_s}C_{bCa^{2+}}(I,J-1)e^{\frac{-FZ_2\phi(x,J-1)}{RT}}dx+D(\theta_s-\theta_f)\left\{\frac{\bar{C}_{bCa^{2+}}(I-1,J-1)+\bar{C}_{bCa^{2+}}(I-1,J)}{2}\right\}$$

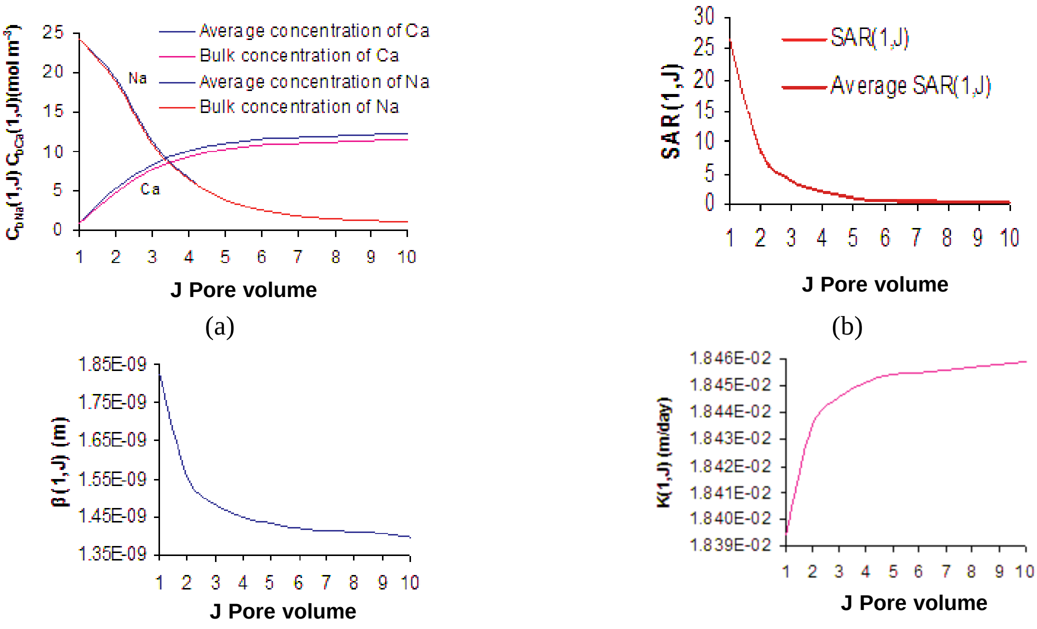
$$-D(\theta_s-\theta_f)\left\{\frac{\bar{C}_{bCa^{2+}}(I,J-1)+\bar{C}_{bCa^{2+}}(I,J)}{2}\right\}=\frac{D\theta_s}{d_s}\int_0^{D_s}C_{bCa^{2+}}(I,J)e^{\frac{-FZ_2\phi(x,J)}{RT}}dx \tag{15}$$

$$\bar{C}_{bCa^{2+}}(I,J-1)=\frac{1}{(d_s-d_f)}\int_{d_f}^{d_s}C_{bCa^{2+}}(I,J-1)\,dx \tag{16}$$

$$\bar{C}_{bCa^{2+}}(I,J)=\frac{1}{(d_s-d_f)}\int_{d_f}^{d_s}C_{bCa^{2+}}(I,J)\,dx \tag{17}$$

$$\bar{C}_{bCa^{2+}}(I,J-1)=\frac{1}{(d_s-\beta(I,J-1))}\int_{\beta(I,J-1)}^{d_s}C_{bCa^{2+}}(I,J-1)\,dx \tag{18}$$

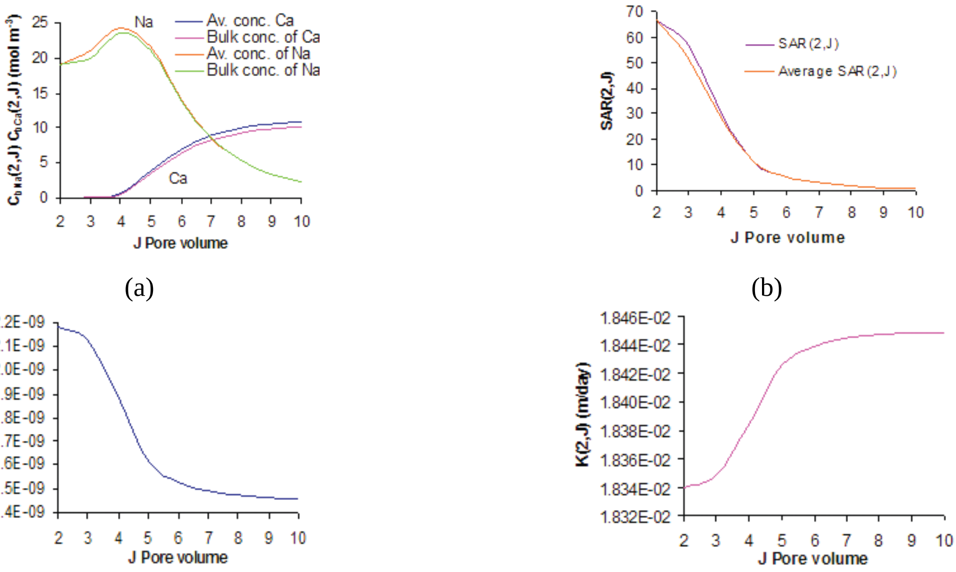
$$\bar{C}_{bCa^{2+}}(I,J)=\frac{1}{(d_s-\beta(I,J))}\int_{\beta(I,J)}^{d_s}C_{bCa^{2+}}(I,J)\,dx \tag{19}$$



(a) (b)

(c) (d)

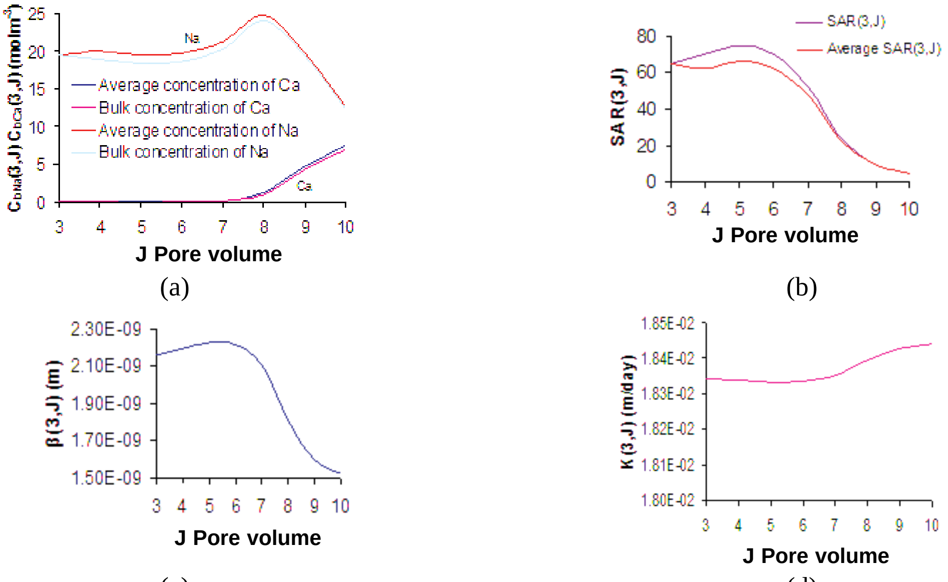
Fig. 2: The variations of (a) $C_{bNa^+}(1,J)$, $\bar{C}_{bNa^+}(1,J)$ and $C_{bCa^{2+}}(1,J)$, $\bar{C}_{bCa^{2+}}(1,J)$ and (b) *SAR(1,J)* and $\overline{SAR(1,J)}$ (c) β (1, *J*) (d)*K* (1, *J*) with the passage of successive PV through 1st reservoir; concentrations in applied water : $C_{bNa^+}(0,J)$ = 1 mol m^{-3} and $C_{bCa^{2+}}(0,J)$ = 10 mol m^{-3}; bulk concentrations in saturation extract are: C_{bNa+} = 25 mol m^{-3}, C_{bCa2+}= 1 mol m^{-3}; corresponding bulk concentrations in soil water at field capacity: C_{bNa+} (1, 0) = 19.529 mol m^{-3}, C_{bCa2+} (1, 0) = 0.094 mol m^{-3}; and σ = – 0.058 Cm^{-2}. Using reported values of cation exchange capacity (CEC) and specific surface (S) (Sumner, 2000; Manchanda and Khanna, 1981), Mahanta *et al*. (2012) has computed σ = -0.058 Cm^{-2} for a fine loamy sodic soil.



(a) (b)

(c) (d)

Fig. 3: The variations of (a) C_{bNa+} (2, *J*), $\bar{C}_{bNa^+}(2,J)$ and C_{bCa2+} (2, *J*), $\bar{C}_{bCa^{2+}}(2,J)$ (b) *SAR(2,J)* and $\overline{SAR(2,J)}$ (c) β (2, *J*) (d) *K* (2, *J*) with the passage of successive PV through the reservoir; concentrations in applied water C_{bNa+} (0, *J*) = 1 mol m^{-3}, and C_{bCa2+}(0, *J*) = 10 mol m^{-3}; bulk concentrations in saturation extract are : C_{bNa^+} = 25 mol m^{-3}, $C_{bCa^{2+}}$ = 1 mol m^{-3}; corresponding bulk concentrations in soil water at field capacity : C_{bNa^+} (2, 1) = 19.529 mol m^{-3}, $C_{bCa^{2+}}$ (2, 1) = 0.094 mol m^{-3}; and σ = –0.058 Cm^{-2}.



(a) (b)

(c) (d)

Fig. 4: The variations of (a) C_{bNa+} (3, *J*), $\bar{C}_{bNa^+}(3,J)$ and C_{bCa2+} (3, *J*), $\bar{C}_{bCa^{2+}}(3,J)$ (b) SAR(3,J) and $\overline{SAR(3,J)}$ (c) β (3, *J*) (d) *K* (3, *J*) with the passage of successive PV through 3rd reservoir; concentrations in applied water C_{bNa+} (0, *J*) = 1 mol m^{-3}, and C_{bCa2+}(0, *J*) = 10 mol m^{-3}; bulk concentrations in saturation extract are C_{bNa+} = 25 mol m^{-3}, C_{bCa2+} = 1 mol m^{-3}; corresponding bulk concentrations in soil water at field capacity: C_{bNa^+} (3, 2) = 19.529 mol m^{-3}, $C_{bCa^{2+}}$ (3, 2) = 0.094 mol m^{-3}; and σ = 0.058 Cm^{-2}.

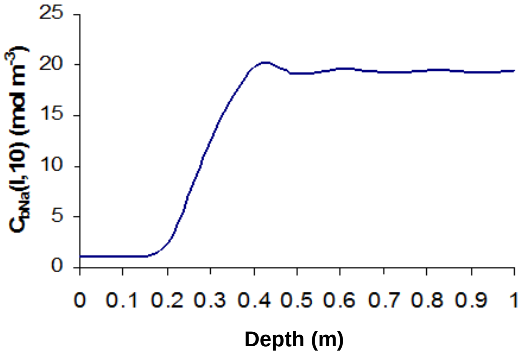
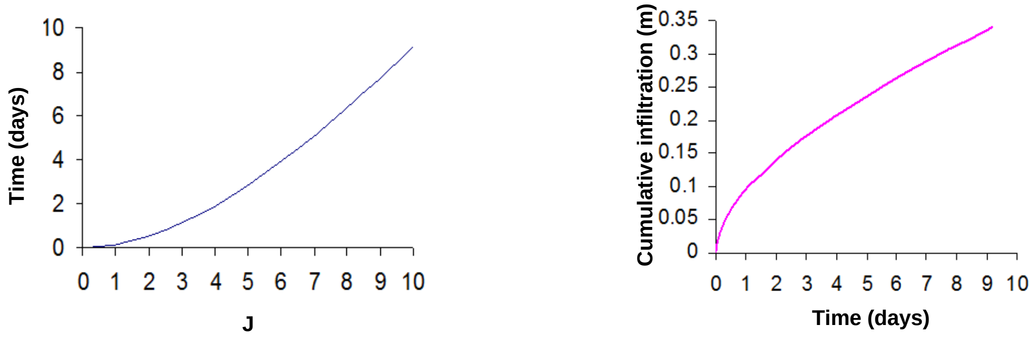


Fig. 5: The variation of C_{bNa+} (*I*, 10) after the passage 10th PV through the reservoir;



(a) (b)

Fig. 6: The (a) time for infiltration of different PVs (b) cumulative infiltration, *W*(*t*) with respect to time in fine loamy soil; concentrations in applied water are: C_{bNa+} (0, *J*) = 1 mol m^{-3}, and C_{bCa2+} (0, *J*) = 10 mol m^{-3}; bulk concentrations in saturation extract are: C_{bNa+} = 25 mol m^{-3}, $C_{bCa^{2+}}$ = 1 mol m^{-3}; and σ = –0.058 Cm^{-2}, θ_s = 0.47, θ_f = 0.129; and H = 0.5 m

Equations (18) and (19) have been used for accounting the average concentrations of C_{bNa^+} (I, J) and $C_{bCa^{2+}}(I, J)$, solved from Eq. (12) and Eq. (15) using Taylor series expansion and iteration. $\varphi(x)$ and β have been computed using the solution of linearized P-B-Boltzman equation.

RESULTS AND DISCUSSION

Leaching of Na in fine loamy soil : The following data have been used for studying the leaching of Na ions in fine loamy soil. The initial moisture content, $\theta_f = 0.129$ m^3/m^{-3} ; the moisture content at saturation, $\theta_s = 0.47$ m^3/m^{-3} ; the saturated hydraulic conductivity, $K_s = 0.0184$ $m.day^{-1}$.

According to Quirk (1986), Quirk and Schofield (1955) and Keren and O'Connor (1982), the sodium adsorption ratio (SAR) corresponding to J^{th} infiltrated PV of gypsum solution is:

$$SAR(I,J) = \frac{Na^+}{\sqrt{Ca^{2+}}} = \frac{C_{bNa^+}(I,J)}{\sqrt{C_{bCa^{2+}}(I,J)}}$$

An average SAR could be defined as:

$$\overline{SAR(I,J)} = \frac{\bar{C}_{bNa^+}(I,J)}{\sqrt{\bar{C}_{bCa^{2+}}(I,J)}} .$$

The average bulk concentrations are the average of the concentrations in the pore space beyond the EDL adjacent to the clay surface. Variations of $SAR(I, J)$ and $\overline{SAR(1,J)}$ in the first reservoir with infiltrated PVs of gypsum solution are presented in Fig. 2(b). The average bulk concentrations $\bar{C}_{bNa^+}(I,J) > C_{bNa^+}(I,J);$ and $\bar{C}_{bCa^{2+}}(I,J) > C_{bCa^{2+}}(I,J)$, where as the average $\overline{SAR(I,J)} < SAR(I,J)$. In the first reservoir there is very little difference in them. Prior to application of gypsum solution, the $SAR(I, J)$ is 26.45. The $SAR(I, J)$ is reduced due to leaching of Na^+ ions. In the first reservoir the sodium absorption ratio reduces from 26.45 to 8.5 after passage of two PV through the reservoir. In sodic soil, the SAR is more than 13. The purpose of reclamation is to reduce the high SAR to a value less than 13. For SAR-values between 2 and 30, the SAR and ESP are approximately equal under equilibrium conditions (ILRI 1979).

The EDL thickness in the I^{th} reservoir after passage of J^{th} PV is given by

$$\beta(I,J) = \sqrt{\frac{\varepsilon RT}{2F^2\left\{Z_1^{\,2}C_{bNa^+}(I,J) + Z_2^{\,2}C_{bCa^{2+}}(I,J)\right\}}}$$

With passage of gypsum solution, β decreases. Variation of β with infiltrated PV (J) of gypsum solution is shown in Fig. 3(c) which is prominent. The graph follows a hyperbolic nature and after 7th PV, the rate of decrease is nominal. In the beginning, the decreasing trend follows a straight line with steep slope. The corresponding increase in K is shown in fig. 2(d). As pore space is 488 nm for fine loamy soil, and β is comparatively very small (= 2.16 nm), the improvement in $K(1, J)$ is nominal. After passage of 10 PV the K_s of the first reservoir increases from 1.8395×10^{-2} to 1.846×10^{-2} $mday^{-1}$. Thus, there is very nominal increase in the hydraulic conductivity attributed to the application of gypsum solution.

The variations of $C_{bNa^+}(2,J)$, $\bar{C}_{bNa^+}(2,J)$ and $C_{bCa^{2+}}(1,J)$, $\bar{C}_{bCa^{2+}}(1,J)$ with the passage of successive PV through the 2nd reservoir are shown in fig. 3(a). The average concentration of Ca as well as of Na ions in the mobile water is higher than the corresponding bulk concentration of the ions. The increasing trend in the bulk concentration or average concentration in the 2nd reservoir is due to inflow of the Na ions from the 1st reservoir as well as release of the Na ions from the EDL from the second reservoir itself.

The concentration is maximum for $J = 4$, after which the concentration decreases with passage of infiltrated PV due to flushing action of the infiltrating water. In case of Ca, the concentration of Ca ions increases with passage of infiltrated PV, as the concentration of Ca ions in the influent increases with time. The reduction of SAR as different PV infiltrates in 2nd reservoir is presented in fig. 3(b). After passage of 5 PVs, the SAR reduces to 11.2. This means 5 PVs need to be applied to reclaim 0.2 m of the top sodic soil layer. The variation of EDL in 2nd reservoir with passage of infiltrated PV is presented in fig. 3(c).

Unlike in the first reservoir, the variation of $\beta(2, J)$ with J follows a parabola up to $J = 5$, beyond which it follows an exponential decay curve. The variation of $K(2, J)$ with J is presented in fig. 3(d). The hydraulic conductivity increases from 1.834×10^{-2} to 1.844×10^{-2} after passage of 10 PV of infiltrated water. Thus there is very marginal increase in hydraulic conductivity.

The variation of SAR(3,J) and $\overline{SAR(3,J)}$ are presented in fig. 4(b). As seen from the figure, in 3rd reservoir, the SAR reduces to 9.3 after passage of 9th PV of infiltrated water. Thus, 9 PVs are required to reclaim the top 0.3 m sodic of soil. The variation of the double layer thickness, $\beta(3, J)$ with J is presented in fig. 4(c) and the corresponding variation in hydraulic conductivity $K(3, J)$ with J is presented in fig. 4(d).

In the 4th reservoir, the initial increase in Na ions is due to the higher concentration of Na ions in the influent caused due to replacement of Na ions by Ca ions and exit of Na ions from the EDL in the upper reservoirs.

The subsequent decrease is due to flushing action of the influent originating from the applied gypsum solution.

Similarly, the variations of C_{bNa+} (4, *J*), $\bar{C}_{bNa^+}(4,J)$ and $C_{bCa^{2+}}(4,J)$, $\bar{C}_{bCa^{2+}}(4,J)$ with respect to PV was studied. There are small changes in the Ca and Na concentrations due to infiltrated PVs of gypsum solution. The *SAR(4, J)* does not get reduced below 13, rather it increases with PV. There is very little change in the hydraulic conductivity even with passage of 10 PVs through reservoir 4.

The variation of $C_{bNa^+}(I,10)$ with depth after infiltration of 10 PV is shown in fig. 5. As seen in the figure, up to a depth of 0.2 m, $C_{bNa^+}(1, 10)$ $C_{bNa^+}(2,10)$ have reduced from 19.52 mol m^{-3} to 2.3 mol m^{-3}. However there is very little change in the Na concentration beyond 0.4 m depth.

Computation of infiltration

The time of infiltration of integer PVs has been computed using Green and Ampt solution for a two-layered soil system as given in Eq.(2). The variation of time with number of PV J is shown in fig. 6 (a) and variation of corresponding cumulative infiltration $W(t)$ versus time is shown in Fig. 6 (b).

The β computed is very small in comparison to the interparticle distance, hence the porosity. Therefore with reduction of EDL thickness, there is insignificant increase in the hydraulic conductivity. With infiltration of 10 pore volumes, only up to a depth of 0.3 m the SAR is reduced to acceptable level (SAR<13). Therefore, more infiltration of gypsum solution is necessary for reducing the SAR up to acceptable level in the root zone depth.

REFERENCES

Abrol, I.P., Yadav, J.S.P. and Massoud, F.I. 1988. *Salt–affected soils and their management*. *Soils Bull.* **39,** FAO, Rome.

Anandarajah, A. 2003. Mechanism controlling permeability change in clays due to changes in pore fluid. *J. Geotech. Geoenv. Eng.,* **129(2)**: 163-72.

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

Butt, H.J. and Graf, K. 2003. *Physics and Chemistry of Interfaces*. Weinheim, Wiley-VCH.

Chapman, L. 1913. A Contribution to the theory of electrocapillarity, *Philosophical Mag., Ser. 6,* **25 (148)**: 475-81.

Gouy, G. 1910. Sur la constitution de la charge electrque a la surface d'un électrolyte, *J. de Physique Théorique et Appliquée. Ser 4,* **9**: 457-68 (in French).

Green, W.H. and Ampt, G. 1911. Studies of soil physics, part I– the flow of air and water through soils. *J. Ag. Sci,* **4**: 1-24.

Gupta, R.K. and Ranade, D.H. 1987. Salt effect on water transmission parameters of a sodic clay. *J. Indian Soc. Soil Sci,* **35**: 474-79.

ILRI .1979. *Drainage Principles and Applications, II Theories of field drainage and watershed runoff, 9. Salt balance and leaching requirement*. Publication 16, Wageningen, Netherlands: 89-93.

Keren, R and O'Connor, G.A. 1982. Gypsum dissolution and sodic soil reclamation as affected by water flow velocity. *Soil Sci. Soc. Am. J.,* **46**: 726-32.

Mahanta, K.K. 2010. A study on reclamation of sodic soils. *Unpublished Thesis report*, Dept. of WRDM, IIT, Roorkee.

Mahanta K. K., Kansal M. L. and Mishra G. C. 2015. Managing salt affected soils: Issues and strategies. *Sky J. Soil Sci. Env. Manag.* **4(1)**: 1-9.

Mahanta, K. K. and Mishra, G.C. 2016. Pore-scale distributions of electrical potential, ionic concentrations and volumetric charge density of single type ions in soil-water. *J. Indian Soc.Coast. Agric. Res.,* **34(2)**: 91-93.

Mahanta, K.K., Mishra, G.C. and Kansal, M.L. 2012. Estimation of electric double layer thickness from linearized and nonlinear solutions of Poisson–Boltzman equation for single type of ions. *App. Clay Sci.,* **59-60**: 1-7.

Mahanta, K.K., Mishra, G.C. and Kansal, M.L. 2014. Estimation of the electric double layer thickness in the presence of two types of ions in soil water. *App. Clay Sci.* **87**: 212-18.

Mahanta, K.K. 2012. A Green-Ampt model for computing infiltration through multilayered salt affected soils. *J. Indian Soc. Coast. Agr. Res.* **30(1):** 63-69.

Manchanda, M.L.and Khanna, S.S. 1981. Soil salinity and landscape relationships in part of Haryana state. *J. Indian Soc. Soil Sci.,* **29(4)**: 493-503.

Naorem, A., Udayana, S.K., Kumar, G., Singh, N.A. and Selvaraj, C. 2017. Potentiality of organics in reclaiming sodic soil, *J. Crop Weed,* **13(2):**11-14.

Oster, J.D. 1982. Gypsum usage in irrigated agriculture, a review. *Fert. Res.,* **3**: 73-89.

Quirk, J.P.and Schofield, R.K. 1955. The effect of electrolyte concentration on soil permeability. *J. Soil Sci.,* **6**: 163-78.

Quirk, J.P. 1986. Soil permeability in relation to sodicity and salinity. *Phil. Trans. R. Soc. Lond. A,* **316**: 297-97.

Rhoades, J.D. 1982. *Cation Exchange Capacity, Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties*. Agronomy Monograph No.9, 2nd. ed., ASA and SSSA, Madison, WI: 149-58.

So, H.B. and Aylmore, L.A.G. 1993. How do sodic soils behave? The effects of sodicity on soil physical behavior. *Aust. J. Soil Res.,* **31**:761-77.

Sumner, M.E. (Ed) .2000. *Handbook of Soil Science*. CRC Press, Boca Raton London New York Washington, D.C.

Van Olphen, H. 1977. *An Introduction to Clay and Colloidal Chemistry*. Wiley Interscience, New York.

Voyutsky, S . 1978. *Colloid Chemistry*. Mir Publishers, Moscow.

Yeung, A.T. 1992. Diffuse double layer equations in SI units. *J. Geotech. Eng.,* **118(12):** 2000-05.