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Article

Hydraulic Property and Solute Breakthrough from Salt Accumulated Soils under Various Head Pressures

Sanghun Lee, Doug-Young Chung[1]*, Seon-Woong Hwang, Kyeong-Bo Lee,
Chang-Hyu Yang, and Hong-Kyu Kim

National Institute of Crop Science, Rural Development Administration, Iksan, 570-080, Korea
[1]College of Agricultural and Life Science, Chungnam National University, Daejeon, 305-764, Korea

Salt accumulated soil should be reclaimed to lower salt level for crop production. This study was carried out to investigate the characteristics of water flow and transport of mono and divalent solutes on salt accumulated soils with different head pressures. Saturated hydraulic conductivity was measured by constant and falling head methods with maintaining different head pressures. Saturated hydraulic conductivity was influenced by bulk density and organic matter contents in soils, but it had different elusion patterns between saline and sodic soil. While the quantity of water necessary for reclamation could be varies with soil type, it was considered that the supply of one pore volume of water was affordable and economic. Additional head pressure significantly increased the volume of leachate at a given time and it was more effective at low organic matter soils. The results indicate that additional head pressure would be one of the best irrigation practices on desalination method for salt accumulated soils.

Key words: Saturated hydraulic conductivity (Ksat), Salt accumulated soil, Saline/sodic, Head pressure, Breakthrough curve

Introduction

Continuous salt buildup in agricultural soils has reduced its productivity and threatens agricultural sustainability. In Korea, it has been increased areas of greenhouse cultivation in near of big cities due to the massive demands for fresh vegetables. Greenhouse soils may be plagued by salt damages because it has been cultivated with heavy application of chemical fertilizers and organic compost for massive production and quick rotation for multiple cropping (Joo et al., 2009). Salt accumulated soils are generally divided into saline and sodic soils depending on the amounts and kinds of salts present. Saline soils are dominated by large quantities of soluble salts, while sodic soils are dominated by exchangeable sodium. Each soil has different impacts on plant development. Salinity causes a reduction in the water uptake by osmotic effect, while sodicity affects plants negatively through its influence on physical and hydrological properties of soils. In addition, both soil types can affect crop growth and yield reduction due to nutritional disorders and toxic effects (Lauchli and Epstein, 1990).

The leaching of excessive salts from the vadose zone is the reclamation process in salt accumulated soils. The movement of water and solute through saturated porous media is of great interest in reclamation. During this process, sufficient water supply can wash-out the soluble salts from root zone, otherwise remained salts will affect crop development and yield. Excessive water may create drainage problems as well as wasting of water. Water movement velocity can be a major factor affecting reclamation time and solute transport in the soil-water saturated system. Therefore, it is important to decide the optimum quantity and to increase velocity of water flow during the reclamation process.

In Korea, some researchers has been tried to remove the salts from salts accumulated soils. For instance, it was conducted to investigate the effects of watering on salt eluviation from greenhouse soils (Jung, et al., 1975) and conducted to obtain quantitative information on the movement of applied nutrients under different soil moisture regimes (Ryu, et al., 1994). There was

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*Corresponding author : Phone: +82428216739
E-mail: dychung@cnu.ac.kr

also the evaluation of water requirement for desalinization of tidal saline soil (Oh, 1990). Ryu et al. (2010) evaluated the effect of gypsum on elution patterns and salt distribution from reclaimed saline soil. However, desalinization problem is complicate and most solutions were neither economical nor effective. Furthermore, little is known of the extent to which soil head pressure can be modified. Therefore, this experiment was undertaken to evaluate the effect of head pressure of water application on leaching of salts from salt-accumulated soils. The specific objectives were 1) to identify the time required for leaching the soils for infiltration rate, 2) to observe how efficiently the infiltrating water displaces salts in saturated sandy clay loam soils, and 3) to determine the effects of bulk density and organic matter (OM) contents on saturated hydraulic conductivity and water distribution patterns in a soil with different head pressures.

Materials and Methods

Soil preparation and analysis Nonsan series soil (Fine loamy, mixed, mesic, Typic Hapludults) was collected from A horizon (0-15 cm) at Nonsan area, Chungnam in Korea. The area has temperate monsoon clmate, and the average temperature is 25.5°C in August and -1.9℃ in January with mean annual precipitation of 1350 mm. Soils used in this experiment were air-dried and passed through a 2mm sieve prior to physical and chemical analysis. Saline and sodic soils with different salt compositions were prepared from Nonsan series soil using combination of 1 M NaCl, 1 M $CaCl_2$, and 1 M $MgCl_2$ stock solutions. The soils were placed on a filter paper in a funnel and repeatedly leached with these solutions, and then soils were air-dried at 30℃ in a dry-oven for 72h. This process was repeated until the desired combination of electrical conductivity (EC) and sodium adsorption ratio (SAR) was achieved to make sodic (EC<4 dS/m and SAR>13) and saline (EC>4 dS m^{-1} and SAR<13) soil. The physical and chemical properties of the soils used in this experiment were given in Table 1.

Soil pH was determined in a 1:5 soil/water suspension using 5g of soil with pH meter (HI 9321, Hanna) and EC was measured by saturated paste extract method with conductivity meter (Model 162, Orion). Organic matter content was measured by Walkley-Black method. Particle size distribution was analyzed by using ASTM 152H hydrometer after dispersion with 5% sodium hexametaphosphate. For various OM contents on sandy clay loam soil, air dried cow manures passing through a 0.5 mm sieve were added at 3%, 5% (wt/wt) ratio, respectively.

Saturated Hydraulic Conductivity Soil columns that had 50 mm in diameter by 250 mm in height were packed with 150 mm soil samples adjusted bulk densities. Then, soil columns were saturated with deionized water from bottom of the column by capillarity rise in order to get steady state flux before introducing solution to be studied. Saturated Hydraulic conductivity (K_{sat}) was measured by constant and falling head method with different head pressure. In case of 0 kPa head pressure, K_{sat} was determined by constant head method. In columns where continuous ponding was provided, water was supplied by maintaining a constant head at the soil surface through a Mariotte bottle arrangement. In case of inputting the falling head pressure onto soil column, which had one pore volume (PV) solution to the inlet of the column at the falling head pressures ranging from 50 to 150 kPa using the pneumatic pump throughout the experiment. Leachate was collected in the centrifuge tubes placed on an automatic Linear fraction collector (LC200, Buchler) with a constant interval for the measuring the volume of effluent. When the elution was finished, soil columns were cut

Table 1. Physical and chemical properties of Nonsan, saline, and sodic soils used in this study.

	pH	EC	Soluble cation				Exch. Cation				PSD[†]			SAR
			Na	K	Ca	Mg	Na	K	Ca	Mg	Sand	Silt	Clay	
	(1:5)	dS m^{-1}	--------- cmol$_c$ kg^{-1} ----------				--------- cmol$_c$ kg^{-1} ----------				--------- % ---------			
Nonsan	4.6	0.3	0.26	0.10	0.12	0.04	0.22	0.33	2.02	0.89	54	20	26	0.6
Saline	5.2	5.8	3.15	0.10	0.96	0.22	4.80	0.42	3.22	2.11	-	-	-	9.2
Sodic	6.9	1.5	1.89	0.02	0.02	0.00	13.51	0.41	2.27	1.66	-	-	-	30.5

[†] PSD, particle size distribution

with 2.5 centimeter intervals and mass water contents (θ_m) and solutes were determined.

Kinetic Adsorption and Desorption Isotherms Kinetic adsorption and desorption isotherms were carried out to determine the adsorption/desorption kinetics of base salts on Nonsan series and the time to reach equilibrium for adsorption and desorption isotherms. A soil was packed into soil columns (15 mm in diam by 40 mm in height) and solution was passed through the column. Oven dried soils were equilibrated with 25 mL of solution by shaking 8 hrs on a reciprocal shaker. The suspensions were centrifuged (3,000 × *g*) for 10 min and filtered with filter paper (Whatman, No. 1442). Analysis of cations was conducted by atomic absorption spectrophotometer (6800A, Shimazu). Amounts of adsorbed and desorbed cations were estimated from the differences between the amount added and remained in solution. Soil columns were packed with Nonsan series soil at adjusted bulk densities. And, introduction solution at concentration 10 $\text{mmol}_c\ \text{kg}^{-1}$ is continuously introduced into a steady state flow regime at the upstream end of a column. The leachate was collected in centrifuge tubes on an automatic linear fraction collector with a constant time interval. All experiments were carried out in a constant laboratory temperature (25℃±3℃) to ensure that thermally induced variations in aqueous properties. All the analyses were conducted in duplicate. Least significant different were used to separate means when significant F values were observed in statistical analysis.

Theoretical Backgrounds The mass of fluid diffusion is proportional to the concentration gradient, which can be expressed as Fick's first law. Given that the rate of salt dissolution is diffusion controlled, Ficks first law of diffusion can be used to derive the first order rate expression (Berner, 1971).

$$\frac{dC}{dt} = \frac{DA}{L}(C_S - C)$$

which has the integrated form

$$\int_0^c \frac{1}{C_S - C} dC = \int_0^t k \cdot dt$$

$$\log(1 - \frac{C}{C_S}) = -\frac{kt}{2.3}$$

where, C is the concentration of the uniformly mixed bulk solution into which the solid is dissolving (mol cm^{-3}), C_s is the concentration at the surface of the solid particle which is its equilibrium solubility (mol cm^{-3}), t is time (sec), and *k* (apparent rate constant) = D × A/L, where D ($\text{cm}^2\ \text{sec}^{-1}$) is the diffusion coefficient, A is the total surface area of the solid per unit volume of water ($\text{cm}^2\ \text{cm}^{-3}$), and L (cm) is the width of the stagnant boundary layer (film) surrounding the dissolving particle through which diffusion occurs. In this column study, the concentration of effluent was assumed to be proportional to the concentration C at any time t. The initial salinity of the soil, measured by the EC of the initial volume of effluent obtained from the soil column, was assumed to be proportional to C_s. For salt removal from soil columns, Equation is written

$$\log(1 - \frac{EC}{EC_i}) = -\frac{kt}{2.3}$$

where the apparent rate constant *k* includes the conversion from units of concentration to units of electrical conductivity. Because the column effluent samples were obtained at equal time increments and the moisture flow was maintained constant, the amount of drainage in PV was assumed proportional to time of reaction. An advantage of using the PV of draining water as a parameter rather than the PV of applied water is that it allows the direct comparison of water requirement for reclamation of soils by eliminating the initial difference in water storage between soils. The equation used to describe the column effluent concentration during saline soil reclamation was

$$\log(1 - \frac{EC}{EC_i}) = -\frac{k(PV)}{2.3}$$

Results and Discussion

Saturated hydraulic conductivity Saturated hydraulic conductivity (K_{sat}) of saline and sodic soil with 0, 50, 100, and 150 kPa head pressure was shown in Figure 1. Saturated hydraulic conductivity in saline soil had been sharply decreased until one pore volume of water was leached from soil, while K_{sat} in sodic soil was gently decreased over time. It may be inferred that the effect of compaction into the closed-system, and the pore distribution was more stable in sodic soils due to the

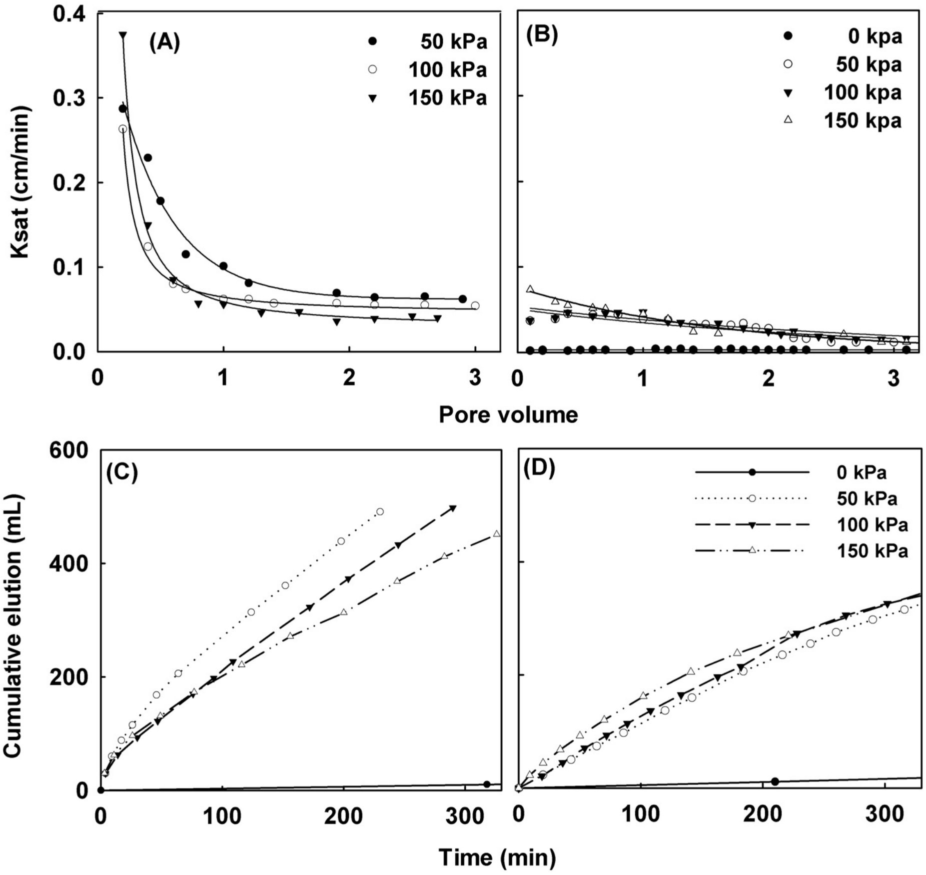

Fig. 1. The changes of saturated hydraulic conductivity of (A) saline and (B) sodic soils and cumulative amounts of eluted from (C) saline and (D) sodic soils under 0, 50, 100, and 150 kPa head pressure.

dispersion of clay particle. Time required to get same volume of leachate was about 100-fold faster with additional head pressures compare to 0 kPa in both saline and sodic soils. In saline soil, total amounts of elution were decreased with increasing the head pressure, but the total leachate was slightly increased with increasing the head pressure in sodic soil (Fig. 1). This data indicates that increasing head pressure significantly increased the volume of elution than in control (0 kPa), but it was more effective in saline soil. In general, K_{sat} was affected with the factor of air pocket on soil, form and concentration of dissolved solute in soil water, soil expansion, configuration types and distribution of soil pore, microbial activity and physical structure of soil (Kim, et al., 1997; Pupisky and Shainberg, 1979). It is probably that sodic soil had more undrained soil structures and micropores than saline soil. Saturated hydraulic conductivity obtained in this study is comparable with other researches (Kim, 1997; Kim and Hong, 1999; Ryu et al., 2010). For instance, Ryu et al. (2010) observed that the maximum K_{sat} on silty loam saline soil was 0.6 cm hr^{-1} with 0.8% gypsum application. Saturated hydraulic conductivity was five-fold increased with additional head pressure, which would reduce the time to washout salts into soils.

Saturate hydraulic conductivity of Nonsan series soils under different head pressures was influenced by soil OM contents (Fig. 2). Without OM addition, increasing head pressure had higher K_{sat} until 2.5 pore volume water were leached. The difference between K_{sat} with different head pressures was decreased with increasing OM content. This data indicate that additional head pressure was effective in low OM content, although total volume of leachate was higher with higher head pressure. Interior of the soil column behavior occurred in responses for compression index, air-filled porosity, and K_{sat}. These responses were typified in Nonsan series soil by a soil property response to OM. Interior of the soil column behavior in the Nonsan series soil yielded a decreased compression index, and increased air-filled porosity and K_{sat}, with increased OM contents at low levels. Thus, the native soil, which has low OM

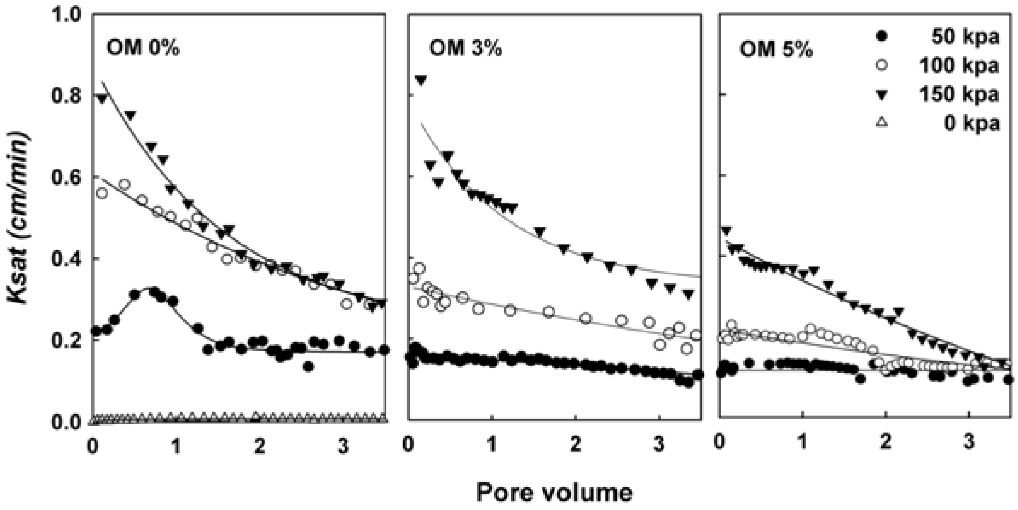

Fig. 2. The changes of saturated hydraulic conductivity of the Nonsan series soils with different organic matter contents under 0, 50, 100, and 150 kPa head pressures.

Table 2. Water holding capacities of Nonsan series soil amended with different amounts of organic matter.

Soil	Pressure (kPa)					
	0	33	50	100	150	1500
	--		%, w/w	--		
Nonsan	52.1†	23.4	20.2	18.4	15.5	11.6
Nonsan + 1% OM	52.5	23.3	21.2	19.6	18.1	13.4
Nonsan + 3% OM	58.4	27.4	25.1	23.6	21.7	16.8
Nonsan + 5% OM	68.5	34.5	31.3	30.0	27.7	24.1

contents, exhibited maximum values of soil compressibility and minimum values of air-filled porosity and K_{sat}. At high OM contents, favorable changes in soil properties observed at low OM were diminished or even reversed. For low OM contents, the trend of reduced compression index, and increased air-filled porosity and K_{sat} continued. Thus, minimum values of soil compressibility and maximum values of air-filled porosity and K_{sat} were observed at lowest OM contents. Saturated hydraulic conductivity with 0 kPa head pressure was decreased with increasing soil OM contents. It was probably due to the effect of OM which had high water holding capacity. Water contents of Nonsan series soil were increased with increasing OM, and the increasing ratio of water holding capacity was proportional to the OM content (Table 2).

Water distribution patterns Figure 3 shows the distribution patterns of mass water contents of soil column packed with different head pressure and bulk density. Soil water contents were decreased from soil surface to the bottom regardless of head pressure and bulk density. It may be inferred that the puddling effect between the top soil and the solution. Solution nearby the soil surface of the soil column was strongly affected to the physical combining due to the head pressure. Thus, it made soil easy to bind with solution. Another factor was the down-flow of air porosity from top soil to bottom of the soil column. As a result, difference of water contents between top soil and bottom soil was increased with increasing head pressure. In water content curves of the soil column packed with different bulk density, there was no significant difference on water contents in topsoil (Fig. 3). However, the difference of the water content was increased with increasing soil depth from surface. It was also due to the effect of puddling caused by inputting the head pressure. Water contents of the soil with same OM contents were decreased with increasing the bulk density. In general, OM in soil causes the decreased bulk density, increased water holding capacity as OM content increased. Superimposed on this general response was a linear reduction in water holding capacity with increased

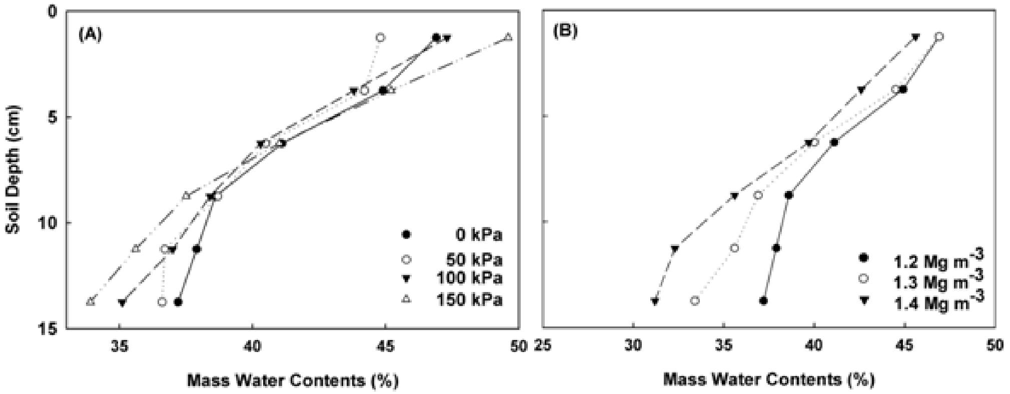

Fig. 3. Distribution patterns of mass water contents of soil column packed with different (A) head pressure and (B) bulk density after elution was completed.

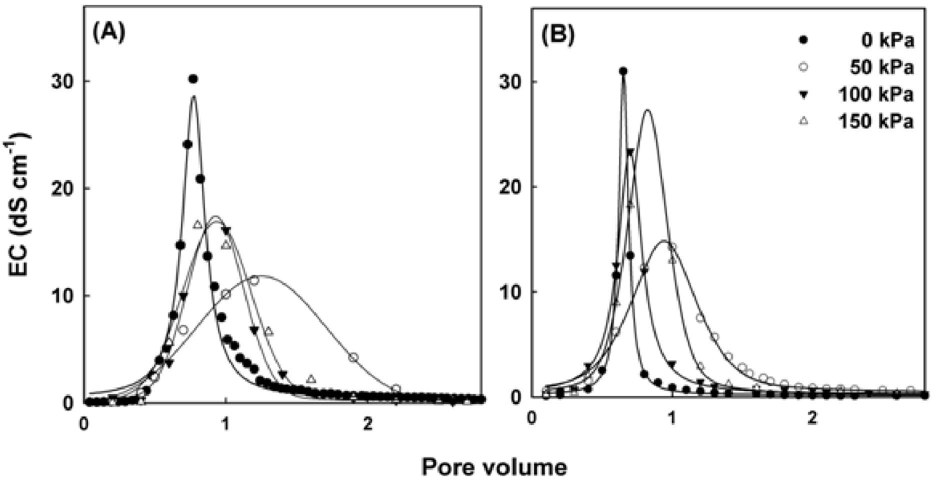

Fig. 4. The changes of electrical conductivity (EC) of elution obtained from (A) saline and (B) sodic soil under 0, 50, 100, and 150 kPa head pressure.

sand. In addition, there were diminishing increases in water holding capacity for incremental OM additions at higher OM contents. Maximum available water values occurred at the highest OM content. Bulk density further exhibited a reversal of the general trend resulting in increased bulk densities at higher OM contents were due to greater compressibility of the OM. The primary influence of OM on bulk density and water holding capacity was similar to previous observations with soil mixes (McCoy, 1998), yet the diminished increase in water holding capacity with increasing sand was also documented for these system. Difference of the water contents between top soil and bottom soil was approximately between 10 and 15%. It was increased with increasing head pressure, but it was similar to the OM contents (data not shown).

Kinetic Adsorption and Desorption Isotherms The capacity of soils to adsorb and desorb solutes and the potential for solute movement through the soil profile depends on the adsorption properties of soil, the quantity of previously adsorbed cations, solution concentration of cations, soil pH, and soil physical properties. Figure 4 shows the elution patterns of the solute concentration in the drainage water plotted as the sum of solutes vs. pore volume of drained water. Salt concentrations in elution was relatively higher with 0 kPa head pressure because the water retention time that could react with solutes was shorter with increasing head pressures. Elution pattern of desorbed cations from the saline soil was similar to each other and it was also similar to elution patterns of electrical conductivity. The extent of Na removal will depend upon the amount of Ca and Mg in the reclamation water as well as on the exchange capacity (data not shown). The removal ratio was increased with increasing the concentration of the salts. The result is corresponding with Kim et al. (2011). The sum of cations in the drainage water after one pore volume has passed through will give estimation of how much Na is released to the leaching solution as it equilibrates with the exchange surfaces and OM in the soil. The relative solutes are equal to the cations concentration divided by cation concentration which first appears in the drainage following the introduction of the leaching experiment. The adsorption characteristics of cations on soil introduced by each cation solution (Fig. 5). Potassum adsorption was relatively high and only 10% of K was eluted at a given pore volume, while sodium adsorption was completed at 2 pore volume. Representative salt leaching data, collected under saturated moisture conditions, for the saline (EC_e = 5.8 dS m^{-1}) and sodic (EC_e = 1.6 dS m^{-1}) soils plotted as a first order kinetic process are shown in Fig. 6. All salt releases were normalized by taking the

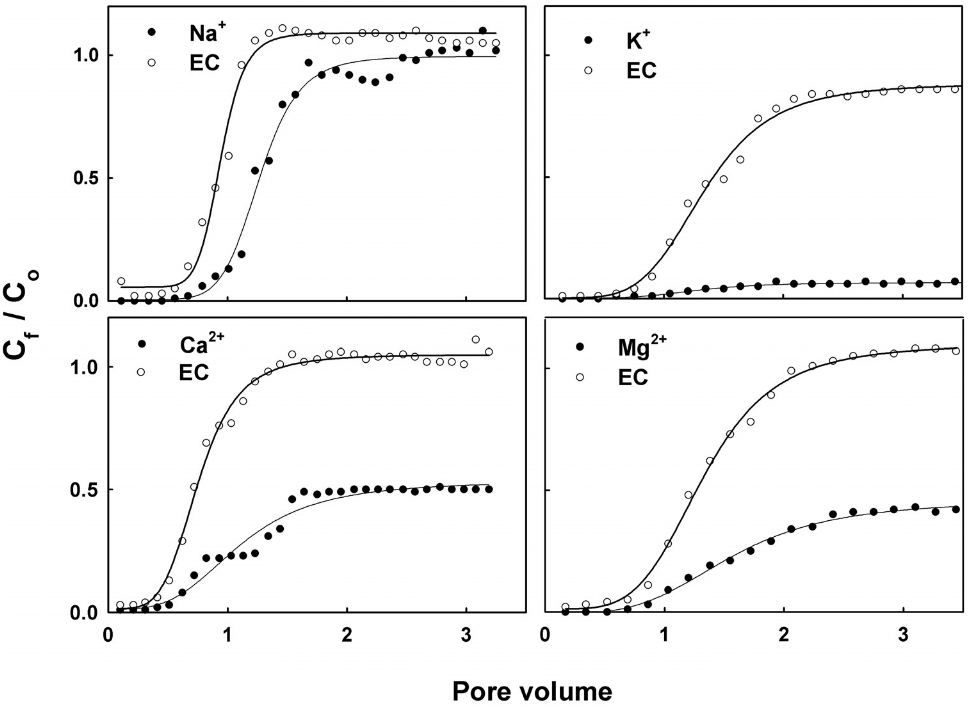

Fig. 5. Breakthrough curves of cations from Nonsan series soil.

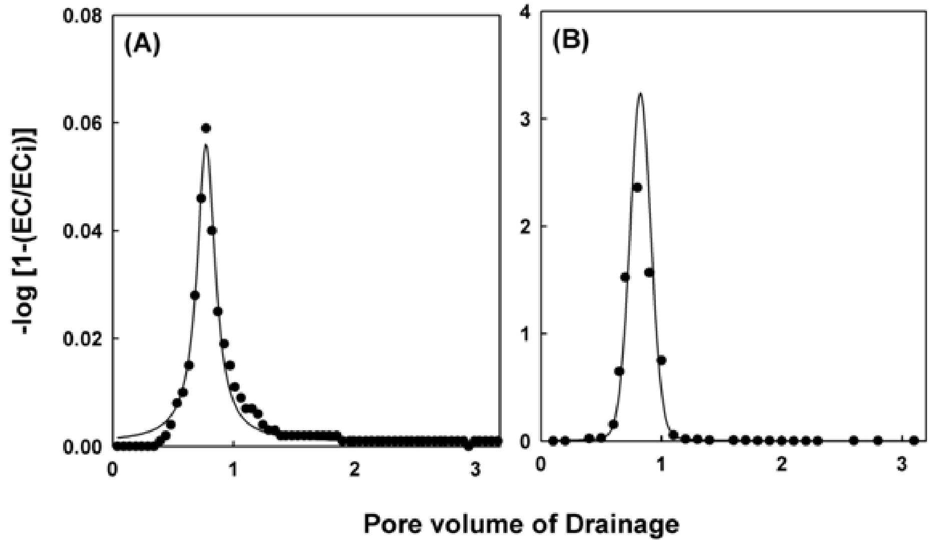

Fig. 6. Salt release from (A) saline and (B) sodic soil, plotted as a first order kinetic process against pore volume of effluent under saturated soil regime.

salinity of the effluent at 1 pore volume as EC_i. The data corroborated previous studies that showed salt release from a saline soil could be described by a multiple slope, first order equation. We speculated that the multiple slope salt release data represents a transport limiting process where rapid dissolution and transport of accessible salt was followed by as lower removal of less accessible salt. Electrical conductivity of saline soil was reduced to about 0.5 dS m^{-1} and the reduction rate of soluble salts was 90%. The SAR of sodic soil was reduced to about 8, which mean the reduction efficient was about 75%. This data referred that one pore volume of irrigation water was required to account for the bulk of the salt removed. However, total amounts of residual salts in soils was not affected the head pressures in both saline and sodic soils, but head pressure only affects the salt elution patterns and K_{sat}.

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Conclusions

In this experiment, the supply of low salted irrigation water was reclaimed salt accumulated soils. Additional head pressure significantly increased the volume of leachate at a given time and it was more effective at low OM soils. Additional head pressure would be effective to increase infiltration rate when downward movement of water is difficult. The results from this study indicates that the supply one pore volume of water would be best economic for reclamation of salt accumulated soils.

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