Salinity Effects on Soil-Water Diffusivity

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to Mariana,
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and Patrick.

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ABSTRACT

Salt effects on water movement in unsaturated Yolo loam soil are explored by comparing soil-water diffusivity values determined by Bruce and Klute's method in soil columns treated with SAR values 0, 5 and 15 and wetted with water containing 15, 5, 2 and 0 me/l. Sorptivity values for these conditions are also compared. Total soil solution concentration estimated by electrical conductivity measurements and Na and Ca concentrations measured by flame photometry are discussed.

Salt effects on soil-water diffusivity were more pronounced at larger values of water content. Movement of water in Ca-saturated samples was significantly affected only when the soil solution concentration was smaller than approximately 2 me/l. Soil samples treated with SAR 5 presented reductions in soil-water diffusivity when the solution concentration was equal to or smaller than approximately 3.5 me/l and the water content larger than 0.35 cm^3/cm^3. The soil-water diffusivity was also affected when the solution concentration was equal to or smaller than approximately 2 me/l and the water content larger than 0.30 cm^3/cm^3. Soil-water diffusivity of samples treated with SAR 15 was affected basically at all values of water content when the soil solution concentration was equal to or smaller than approximately 3.5 me/l. When such concentration was as large as 5 me/l, reductions in soil-water diffusivity were apparent only for water contents larger than 0.25 cm^3/cm^3.

Chemical analyses of soil solution after infiltration revealed that most soluble salts in the soil column were carried near the wetting front. Significant displacement of Na by Ca occurred in soils treated with SAR 5 and 15. Although Bruce and Klute's method does not apply for chemically unstable and swelling soils, the slope of the plot of distance to the wetting front versus square root of time fitted the Boltzman variable for the water content of wetting front satisfactorily. This fact suggests good reliability of reported soil-water diffusivity values.

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LIST OF SYMBOLS

x	Distance reached by the wetting front
t	time
λ	Scaled variable ($\lambda = xt^{-1/2}$)
θ	water content
θi	Initial water content
θo	Water content at the water source
θwf	Water content at the wetting front
D	Soil-water diffusivity
K	Hydraulic conductivity
J	Water flux
H	Total water potential
h	Matric potential
S	Sorptivity

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INTRODUCTION

Recent surveys indicate that 2.9 million of the 10.1 million irrigated acres in California are affected by salt accumulation (USDA, 1982). Use of saline and sodic waters, inadequate drainage, and dissolution of minerals from the soil are the main causes of this problem.

Clearly, a relationship exists between crop yield and soil salinity. Salt effects on plants are related to ion toxicity or water absorption. The presence of salts in the root zone increases the osmotic potential thereby decreasing the water availability to plants. Changes in soil physical properties due to presence of sodium can also affect water availability by decreasing soil permeability. In addition, the use of waters with very low salt concentration also reduces water transmission if insufficient salt is released by the soil (Shainberg et al., 1981 a, b).

Basic mechanisms reponsible for changes in soil structure due to the presence of salts are swelling and detachment of clay particles from larger soil aggregates. Swelling of clay particles results in a reduction of the cross sectional area available for flow (Quirk and Schofield, 1955), while detachment of clay particles results in movement and blockage of conducting pores. Evidence of these phenomena are provided by Felhendler et al. (1974), Chen and Banin (1975), Frenkel et al. (1978), Oster and Schroer (1979) and Shainberg et al. (1981 a, b).

The extent to which these mechanisms affect soil structure depends on the relative concentration of sodium and the soil solution concentration. The salinity effects are more pronounced in soils predominated by very active clays, such as montmorillonite as compared with illite and kaolinite.

An early study into the effect of sodium on soil physical properties was conducted by A. E. Harris (1931). He reported that the rate of water percolation in a heavy, calcareous, alkali soil decreased when the percentage of sodium to total bases increased. Later, M. Fireman and G. B. Bodman (1939) emphasized the importance of the effect of total solution concentration on permeability of two Californian soils. An increase of permeability was reported when saline water was used rather than distilled water. In 1944, M. Fireman identified that some soils remained moderately permeable when leached with water containing large amount of sodium due to flocculation of soil particles by salts in solution. In 1955, J. P. Quirk and R. K. Schofield used the term "threshold concentration" to designate the concentration of salt causing a 10 to 15% decrease in soil permeability. They reported threshold concentrations of 250 me/l for a Na-saturated soil. Three years later, D. W. Henderson reported reduction in hydraulic conductivity values caused by increases in sodium percentage, decreases in salt concentration, or both. The qualitative response of all soils were similar .

An early attempt to understand the effects of sodium and solution concentration on unsaturated soils was made by Gardner et al. (1959). They studied the effects of exchangeable sodium percentage (ESP) and electrolyte concentration on the soil-water diffusivity function, defined by Childs and Collis-George (1950) as the product of hydraulic conductivity and the slope of the soil-water characteristic curve. Gardner et al. (1959) reported that reduction in soil-water diffusivity values at high ESP levels and low salt concentration was more pronounced at higher water contents. After the pioneering work of Gardner, Christenson and Ferguson (1966), Kutilek (1974) and Russo and Bresler (1977) described the effects of saline and sodic waters on soil-water diffusivity. Except for Gardner et al. (1959), who used their own method, all others used the method proposed by Bruce and Klute (1956). In this method the soil-water diffusivity is determined from infiltration experiments in effective semi-infinite horizontal soil columns.

Christenson and Ferguson (1966) monitored changes in ion concentration during the infiltration studies. Working with soils having ESP levels of 5.0 and 20.3 they observed a displacement of sodium from the first few centimeters of soil column and a concentration of this element at the end of the column, just behind the wetting front. The theoretical development of the method proposed by Bruce and Klute, however, does not consider the salinity effects on soil structure. Soil particles being chemically and physically heterogeneous initiate questions about the validity of the soil-water diffusivity values obtained.

The present work was conducted to study infiltration tests and measure the effects of adsorbed sodium and electrolyte concentration on soil-water diffusivity of the Yolo loam soil, a non-saline soil with approximately 20% sand, 50% silt and 30% clay, most of which is montmorillonite. The exchangeable sodium percentages and electrolyte concentrations used are typically of those found in irrigation projects from the western United States. This research also describes the effects of salts on sorptivity values for the soil columns studied and the movement of sodium and calcium ions during infiltration of water in unsaturated soils. Finally, there is a discussion about the assumptions involved in methods available for soil-water diffusivity determinations.

LITERATURE REVIEW

Selection of soil-water diffusivity for studying effects of salt on water movement in unsaturated soils is based on its smaller range in variation as compared to hydraulic conductivity. The following review describes the main mechanisms of salt effects on soil hydraulic properties and the method used for soil-water diffusivity determinations. The text also discusses the limitations of the method and some suggestions for its improvement.

The arrangement of clay particles in soil can tremendously change hydraulic properties of soil matrix. Such arrangement, formally denominated soil structure, can be largely affected by the ion present on clay particles and also on the amount of ions present in soil solution. The negatively charged clay platelet and the diffuse ion atmosphere are commonly designated as the diffuse double layer; an electric layer with variable thickness depending upon type and amount of ions present. The term diffuse is related to forces tending to diffuse the cations from near the platelet to the bulk solution where the relative concentration is smaller. Another force, electrostatic in nature, tends to keep the cations attracted to the negative platelet. This force obeys Coulomb's law, and as such is inversely related to the square of the distance between the cation and the surface of platelet and directly related to the valence of the cation. Calcium, due to its double valence can be strongly attracted to the negative surface of clay. Among elements of same valence the size of the hydrated radius is the parameter which governs the attraction force. For example, potassium is closely attracted to the platelets compared to sodium, due to the distance between the charges imposed by its shorter hydrated radius.

The resultant diffuse layer of an individual platelet has an exponential form for the cation concentration distribution. Such distribution depends directly on the cation valence and on the potential per unit of mass, and inversely on the absolute temperature. The overlapped ionic atmosphere between two clay platelets has a parabolic distribution. Since divalent cations are more attracted by the surface, the thickness of the diffuse double layer in a monovalent saturated clay is larger compared to a divalent saturated clay.

Repulsion forces between clay platelets tend to increase the size of the clay particle thereby decreasing the radius of soil pore. Depending upon the magnitude of this force and on the configuration of platelets the resultant arrangement can be irreversible. Small clay particles can be detached from aggregates and settled in pores restrictions (Nielsen et al., 1986). This phenomenon can be caused by irreversible swelling or by weakening of the bonds between clay particles imparted by the presence of sodium. For this reason, the increase in concentration of soil solution as a reclamation procedure to enlarge a reduced soil pore may not bring the pore's radius to its original size. Reductions in hydraulic conductivity of soils with low ESP values, where no appreciable swelling is expected, are suggested by McNeal et al. (1966) to be a result of movement and clogging of conducting pores by migration of detached clay particles. Emerson and Bakker (1973) suggested that the concentration gradient between the solutions in large and small pores may induce rupture of clay particles thereby decreasing hydraulic conductivity. In contrast, Pupisk and Shainberg (1979) noted the possibility of clay particles to be leached from coarse soils resulting in an increase in hydraulic conductivity. More complete descriptions of diffuse double layer are given by Van Olphen (1977), Babcock (1963), and Bolt (1979).

The effects of concentration of soil solution and type of cation adsorbed to clay particles can be more predominant on those soils with more active clay types. Montmorillonite and vermiculite, both 2:1 phillosilicate minerals, can expand easily, and thus have a greater effect on soil hydraulic properties. A soil dominated by kaolinite and sesquioxides is virtually insensitive to changes in the composition of soil solution (McNeal and Coleman, 1966).

Soil permeability depends both on exchangeable sodium percentage (ESP) present in clay particles and total concentration of the soil solution (Quirk and Schofield, 1955). Henderson (1958) measured the effects of exchangeable sodium and total concentration of irrigation water on hydraulic conductivity of Yolo loam soil. The values observed decreased rapidly with decreases in concentration of soil solution. These changes occurred mostly at concentration values lower than 20 me/l. For concentration of 5 me/l the hydraulic conductivity of soil with ESP 5 was twice as large as that of the soil with ESP 10.

Differences in hydraulic conductivity reductions imparted by the presence of low concentrated soil solution in different soils were hypothesized by Shainberg et al. (1981 a) as a result of the different mineral dissolution rates. Hydraulic conductivity of a fine loamy soil (Fallbrook soil) mixed with sand and treated with a solution of SAR 20 decreased faster relative to two other soils (Pachappa and Gila). This difference occurred for effluent volumes larger than 100 ml, corresponding to approximately 1 pore volume according to their experimental descriptions. Shainberg et al. (1981b) suggested that well weathered soils are very susceptible to changes in hydraulic properties when wetted with waters of low salt concentration. In this manner, it can be concluded that prolonged rainfall might cause infiltration problems in chemically stable soils (Biggar, 1983).

Salinity effects on soil water retention curves have not been extensively reported. Kutilek (1974) observed that the volume of water retained by a Na-saturated clay was larger than that retained by the same clay when it was saturated with calcium. The changes were noticed for water content values larger than that corresponding to the wilting point. Russo and Bresler (1977) reported that the amount of water retained by a Na saturated soil increased as the concentration of soil solution decreased to values smaller than 10 me/l. Although the changes observed were more pronounced at larger water content values, they occurred for water content as low as approximately 0.15 cm^3/cm^3, corresponding to 1000 cm of water suction. Jayawardane and Beattie (1978) determined the soil-water characteristic curves of soils treated with solutions of different SAR values. Data reported for two soils showed an increase in the amount of water retained by the soil pores when the concentration of soil solution decreased. The changes observed were larger in those soils treated with higher SAR values and they occurred for suction values smaller than 50 cm of water. One of the soils treated with a solution of SAR 40 apparently did not release any water when it was saturated with a solution of 10 me/l and submitted to negative pressures up to an equivalent of 50 cm of water head. The soils used in their experiment were reported to contain approximately 6% free iron oxides. A third soil, with less than 1% free iron oxides, presented similar changes in the retention curves but to a much less extent. MCNeal et al. (1968) observed the hydraulic conductivity of Hawaian soils with approximately 15% Fe_2O_3 and suggested that the ions able to stabilize soil structure are usually ions most easily extracted. This suggestion might explain why Jayawardane and Beattie (1978) observed different behaviors in the water retention characteristics of the soils they studied. An increase in water retained by some soils was probably caused by extraction of soil stabilizing agents (free iron oxides).

One of the first attempts to study changes of hydraulic properties caused by sodium and/or low concentration of the soil solution in unsaturated soils was made by Gardner et al. (1959). They used a wetting source of essentially zero hydraulic head which allowed the soil used to have a water content of 0.65 cm^3/cm^3. Weighted-mean diffusivity values of approximately 3.5 and 2.0 cm^2/min were reported for a solution of 10 me/l in soils with ESP 0 and 5, respectively. The weighted-mean diffusivity was defined for sorption as

$$\bar{D} = \frac{5}{3\,(\theta_o - \theta_i)^{5/3}} \int_{\theta_i}^{\theta_o} (\theta - \theta_o)^{2/3} D(\theta)\, d\theta$$

where θ_o is the water content at the source, θ_i is the initial water content of the soil and $D(\theta)$ is the soil-water diffusivity. A good description of the method used by Gardner et al. (1959) can be found in Kirkham and Powers (1972). Beyond the method used by Gardner et al. to measure the soil-water diffusivity, other methods have been suggested in the soil physics literature. Among these methods, the mostly widely used is the method proposed by Bruce and Klute (1956).

Christenson and Ferguson (1966) also studied the effects of salts and clay type on unsaturated water flow. Using an apparatus similar to that of Nielsen et al. (1962) and the method proposed by Bruce and Klute (1956), they reported soil-water diffusivity and soluble salt concentration in a montmorillonite soil with ESP 5.5 and 13.6, and in a Dickite soil with ESP 5.0 and 20.3. For the same water content value, diffusivity values reported were smaller when the soils were wetted with distilled water as compared to 15 me/l of $CaCl_2$. Reported differences were more pronounced for water content values larger than approximately 0.45 cm^3/cm^3. With respect to the soluble salt concentration, an accumulation of ions at the end of the column just behind the wetting front was reported in all soil columns studied. They suggested that this movement of Na and Ca ions may have been associated with dissolution of some Ca compounds in the soil and it also could be attributed to presence of soluble salts in the soil column before the infiltration process. That small movement of Ca occurred in the

Na-saturated soil was suggested by them to be a result of preferential retention of Ca over Na by the clay particles. In a general pattern, sodium was displaced from the beginning and transported to the end of the soil column.

Kutilek (1974) studying soil water diffusivity values of Na-kaolinite and Ca-kaolinite reported that differences between values obtained for both clays decreased as water content decreased. For a Na-vertisol the maximum value of soil-water diffusivity occurred at a water content smaller than that corresponding to the wilting point. The author attributed this fact to the flux of water vapor. Russo and Bresler (1977), using the method proposed by Bruce and Klute (1956), measured the soil-water diffusivity of solutions with 2 to 50 me/l for soils with different concentrations of Na and Ca. A single value of diffusivity was reported for a Ca-saturated soil when the concentration of the wetting solution was larger than 2 me/l. In general , the changes in soil-water diffusivity values decreased as the concentration of soil solution increased, the water content decreased or the ratio $Na/\sqrt{Ca}$ decreased. The soil-water diffusivity and hydraulic conductivity values reported for a soil with $Na/\sqrt{Ca}$ ratio equal to 10 showed different behaviors. While the hydraulic conductivity was roughly constant for any concentration at water contents less than 0.30 cm^3/cm^3, the soil-water diffusivity for a wetting solution concentration of 2 me/l was always below those values obtained for a solution of 50 me/l for any water content value. This fact can be attributed to changes in water retention by the soil pores.

The use of soil-water diffusivity for analyzing the effects of sodium and solution concentration on unsaturated soils has been preferred over hydraulic conductivity due to its smaller variation. For example, hydraulic conductivity values obtained by Russo and Bresler (1977) varied approximately from 10^{-10} to 10^{-2} cm/min while the soil-water diffusivity varied approximately from 10^{-3} to 10^{1} cm^2/min. The soil-water diffusivity term was originally suggested by Childs and Collis-George in

1950 and the concept comes from the combination of the following equations:

$$J = -K[\theta]\,\frac{\partial H}{\partial x} \qquad [1]$$

$$\frac{\partial \theta}{\partial t} = -\,\frac{\partial J}{\partial x} \qquad [2]$$

where J is the flux of water, K[θ] is the hydraulic conductivity, H is the total water potential, t is time, x is distance and θ is the soil-water content. Combining equations 1 and 2 we have for horizontal infiltration the following expression:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K[\theta]\frac{dh}{dx}\right] \qquad [3]$$

where h is the matric potential. Recognizing a functional relation between h and θ, equation 3 becomes:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left\{\left[K[\theta]\frac{dh}{d\theta}\right]\frac{\partial \theta}{\partial x}\right\} \qquad [4]$$

in which the term inside brackets represents the soil water diffusivity. Finally, substituting the diffusivity we have:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D[\theta]\frac{\partial \theta}{\partial x}\right] \qquad [5]$$

Solution of this non-linear partial differential equation requires knowledge of function D(θ). To determine it, Bruce and Klute (1956) proposed an experimental solution based on horizontal infiltration in a soil column. Boundary conditions applicable to their procedure are:

$$\theta = \theta_i \qquad x > 0 \qquad t = 0$$

$$\theta = \theta_o \qquad x = 0 \qquad t \geq 0$$

where θ_i is the initial water content in the soil and θ_0 is the water content at the water source end of the soil column. Using the Boltzman transformation, Bruce and Klute changed equation 5 into the ordinary differential equation:

$$-\frac{\lambda}{2}\frac{\partial\theta}{\partial\lambda} = \frac{\partial}{\partial\lambda}\left[D[\theta]\frac{\partial\theta}{\partial\lambda}\right] \qquad [6]$$

where λ is equal to $xt^{-1/2}$. Integration with respect to λ yields:

$$-\int_{\theta_i}^{\theta_x}\frac{\lambda}{2}\,\partial\theta = D[\theta_x]\left[\frac{\partial\theta}{\partial\lambda}\right]_{\theta_x} - D[\theta_i]\left[\frac{\partial\theta}{\partial\lambda}\right]_{\theta_i} \qquad [7]$$

Since the initial water content in the soil column is constant ahead of the wetting front, the second term on the right hand side of equation 7 is zero and the soil-water diffusivity can be written as follows:

$$D[\theta_x] = -\frac{1}{2}\left[\frac{\partial\lambda}{\partial\theta}\right]_{\theta_x}\int_{\theta_i}^{\theta_x}\lambda\,\partial\theta \qquad [8]$$

The integral and derivative in this expression are obtained graphically from the plot of θ versus λ for a constant value of infiltration time. Equation 8 can also be expressed in terms of x and t by substituting $xt^{-1/2}$ for λ. Thus we have:

$$D[\theta_x] = -\frac{1}{2t}\left[\frac{\partial X}{\partial \theta}\right]_{\theta_x} \int_{\theta_i}^{\theta_x} X\,\partial\theta \qquad [9]$$

The experimental procedure required to determine the plots necessary for evaluating both integral and derivative of equation 9 requires measurement of the time variation of the water content profiles during infiltration.

Both methods proposed for soil-water diffusivity determinations have limitations. The method proposed by Gardner (1956) assumes a negligible impedance of the membrane used in the pressure outflow apparatus. A small change in pressure was assumed such that the soil-water diffusivity would not vary significantly in the interval of time between two consecutive pressure values. To accomplish this, Jackson et al. (1963) pointed out that the pressure changes might have to be so small that they would not be practical. One difficulty leading to the method proposed by Bruce and Klute is the evaluation of $\partial x/\partial\theta$ or $\partial\lambda/\partial\theta$ graphically. The evaluation of the slope of the function $\lambda(\theta)$ is particularly sensitive for values near θ_o or θ_i. Suggestions for evaluation of $\partial\lambda/\partial\theta$ near saturation are given by Clothier and Wooding (1983). Numerical techniques assuming a linear function between two consecutive points eliminate the dependence of the $\partial\lambda/\partial\theta$ values on the curve fitting procedure. The use of larger initial water contents in the soil columns provides easier evaluation of $\partial\lambda/\partial\theta$ near θ_i. The uniform distribution of the larger water content in the soil could be achieved by use of a microwave oven (Horton, 1982). Another option, the use of very long columns, would be compromised by long times required for the infiltration process and difficulties in packing homogeneous long soil columns.

Modifications of Bruce and Klute or Gardner's methods have been proposed by the literature. Miller and Elrick (1958) improved Gardner's method by assuming a value for the membrane impedance. More improvements on these methods were given by Ritjema (1959), Gardner (1960), Kunze and Kirkham (1962) and Klute (1965). Whisler et al. (1968) modify Bruce and Klute's method by using gamma ray absorption to measure the water content as a function of time at a fixed position in a horizontal soil column. Selim et al. (1970) compared the modifications proposed by Whisler et al. (1968) and found that both methods are equally reliable.

Experimental considerations of horizontal infiltration studies used in soil-water diffusivity measurements are discussed by Nielsen et al. (1962) and reviewed by Kirkham and Powers (1972). Equations involved in the theoretical analysis of Bruce and Klute's method fail according to Nielsen et al. (1972) due to inhomogeneity of the wetting fluid, variation of the soil pore geometry, physical or chemical heterogeneity of soil particles and movement of air. An example of temperature effects on infiltration studies is reported by Fry (1968). Reported changes in a clay soil temperature due to the release of heat by the wetting process were as high as 4^{o}C. Although some of these limitations are present in any infiltration experiment, the soil-water diffusivity has been used to study the salinity effects on unsaturated soils. More complete studies can be done by additionally measuring the soil-water characteristic curves. According to equation 4, a distinction would then be possible between contributions of hydraulic conductivity and soil-water retention to changes in soil-water diffusivity.

MATERIAL AND METHODS

The soil used in this study was collected from the 30 to 60 cm depth at the UC Davis near location number 157. Huntington et al. (1981), classified this soil as Yolo loam, moderately-fine textured substratum; a deep and well drained soil formed in alluvium derived from sedimentary rocks. This soil survey reported that at least 95% of this soil passed a mesh size of 0.5 mm. The amount of organic matter detected was not more than 3%. Chemically it contained 25 me/100g of (Ca + Mg) equally distributed, 0.4 me/100g of sodium and 0.4 me/100g of potassium. When leached with distilled water this soil yielded a solution with an electrical conductivity of 0.3 mmho/cm. Its texture was approximately 21% sand, 50% silt and 29% clay. X ray diffraction analyses reported by Morkoc (1980) reveal that 80% of the clay fraction is montmorillonite.

The soil was air dried, sieved through a 2 mm mesh size and divided into 3 subsamples. Each subsample was treated with a volume of solution, corresponding to twice the mass of soil, having 1.0 N of $NaCl + CaCl_2$. The sodium adsorption ratio (SAR) of the solution used, defined as $Na/(Ca+Mg)^{1/2}$, was 0.0, 5.0 or 15.0 . After the mixture was stirred for 24 hours and allowed to settle for one more day, the supernatant liquid was removed and the saturated paste placed in large Büchner funnels.

After free drainage of the solution, vacuum was applied to extract the remaining solution and to remove excess of salts. Distilled water was applied intermittently to the soil in the funnel and the EC (electrical conductivity) of effluent was measured periodically by using an EC meter model RC1B manufactured by Industrial Instruments Inc.. When the drainage process became very slow, even with vacuum applied, a solution of 50% methanol was applied to enhance the clay particle flocculation. Then, the soil was leached periodically by centrifuging at 2400 rpm.

After the leaching procedure, soil samples were air dried and sieved through 1 mm mesh size. One hundred grams of each sample were saturated with distilled water and shaken for 1 hour at 150 rpm. The mixture was placed in small Büchner funnels and the soil solution extracted by vacuum at 25 mm Hg. The filtrate was analyzed to determine the electrical conductivity.

To measure sodium and calcium in soil samples, 20 grams of each sample were combined with 150 ml of neutral normal ammonium acetate (NH_4Ac) in a 250 ml Erlenmeyer flask. The mixture was shaken for one hour at 150 rpm and transferred to a Büchner funnel where the filtrate was collected by applying a vacuum of 25 mm Hg. An 5 ml aliquot of the extract was diluted to 100 ml and analyzed for sodium and calcium by using a flame photometer model Beckman DU. The standard solutions used in this analysis were prepared with NaCl and $CaSO_4$.

Columns were prepared with glass rings of 2.0 , 1.0 and 0.5 cm wide and 5.0 cm of internal diameter. These rings were set together with cellophane tape, which covered approximately half of the rings' perimeter. The columns were 20 cm long consisting of seven 2.0 cm rings, five 1.0 cm rings and two 0.5 cm rings. Acrylic housings with a porous plate or a screen were attached to the ends of the tube formed by the glass rings. The porous plate has a diameter of 5 cm and thickness of 5 mm. According to the manufacturer (ACE Glass Inc.) it is classified as having porosity "B" and its maximum pore size diameter ranges from 0.07 to 0.10 mm which gives a bubbling pressure equivalent to a water pressure head of -28 cm.

A view of the column presented by figure 1 shows an extra 2 cm ring attached to the screen end of column to improve soil uniformity. The soil was compacted by using a 4 cm diameter rubber stopper attached to a 30 cm long bar having a diameter of 4 mm. This rubber stopper apparatus weighted approximately 60 grams. The packing procedure was executed by using both ends of this apparatus, 10 times each end, for every tablespoon of soil.

After packing, the soil column was wetted with a solution of same SAR as the solution used to treat the soil. For a given soil, treated with a given SAR, 4 columns were prepared and wetted with solution concentration of 0, 2, 5 or 15 me/l. The time required for the wetting front to reach every division line between rings was measured.

As soon the wetting front reached a distance of 20 cm, the stopcock in the buret was closed and the soil column was sectioned into 14 parts, one per ring. The content of each ring was transferred to a beaker, weighed and placed in a constant temperature room to air dry for one week. At the 5th day when the soil was apparently dry, it was stirred and allowed to dry two more days. Then, the air dried soil weight was determined and part of the sample was oven dried to determine the amount of water remaining in the samples after the air drying process.

The other part of each ring's content was used for EC, Na and Ca measurements. These parts were combined to yield 5 sections of 25 grams each. In this manner, the soil column was divided in 4.0 cm sections. Each 2.0 cm ring contributed with 12.5 grams of soil, while 1.0 cm and 0.5 cm rings contributed with 6.25 and 3.12 grams of soil respectively. Each of these samples were dispersed in 50 ml of distilled water and shaken for one hour at 150 rpm. The mixture was transferred to a Büchner funnel and the filtrate was vacuum extracted at a suction corresponding to 25 mm Hg. Finally, the extract was analyzed for EC, Na and Ca.

concluded that swelling was the only mechanism responsible for retarding the wetting front of the solution with 5.0 me/l in the soil treated with SAR 5 and 5.0 and 15.0 me/l in the soil treated with SAR 15. Decreases in the rate of wetting front movement of solutions with 2.0 and 0.0 me/l were caused not only by swelling, but also by blockage of conducting pores by he detached clay particles.

Values of distance and square root of time plotted in figures 2, 3 and 4 for soils treated with SAR 0, 5 and 15, respectively, are linear; thereby suggesting that the Boltzman transformation for this case is acceptable. This kind of plot, however, used by many authors to check the homogeneity of the packing procedure, must be used in a more rigorous fashion. This work used a linear regression to describe the data. Slope of lines shown in figures 2, 3 and 4, determined from linear regression, are given in table 8. The residuals obtained for distance, i.e., measured minus calculated values, were plotted in figures 5, 6, 7 and 8 for soils wetted with 15, 5, 2 and 0 me/l, respectively. It is expected that the larger deviations occurred at the beginning of soil column were caused mainly by initial contact of porous plate with the soil column. According to Corey (1977), the small intercept on the square root of time axis might be a result of disregarding the resistance to flow through the barrier where the water is admitted and through the contact region between the barrier and the soil. Such resistance, which depends on the flux rate, and thus on time, is probably a reason for the larger residuals obtained at the beginning of the soil column.

Another possible cause might be the distorted configuration of the wetting front observed at the beginning of some soil columns. This fact appeared to have retarded the movement of water by imposing a non-linear configuration to the wetting front, which became linear as soon it reached 2.0 cm of distance.

Water content values measured in the first half of the soil column just after the infiltration process show that use of lower concentrated wetting solutions did not result in a significant increase of the soil capacity to hold water. Data listed on table 10, 11 and 12 show an increase of less than 2% in the water content when it was wetted with distilled water instead of 15 me/l at a suction corresponding to 3.0 cm of water. The water content profiles plotted in figures 13 through 24 show slight smaller values at end part of column for soils treated with SAR 5 and wetted with distilled water and treated with SAR 15 and wetted with 5, 2 or 0 me/l. The smaller values observed, more noticeable in tables 13 and 14, were accompanied by a relative faster wetting-front advance at the end of the infiltration process. This increase in wetting front advance rate may be due in part to vapor diffusion phenomena. This kind of behavior can be observed in infiltration experiments of long duration (Grismer et al., 1986).

The use of $\lambda(\theta_{wf})$ values to predict the water distribution in soil columns was successful. Taking the time the wetting front took to reach 14.0 cm for every column, the water content distribution was calculated and plotted in figures 13 through 24. According to Nielsen et al. (1962), this prediction would not be good if the curves presented in figures 2, 3 and 4 were not linear. In fact, the best predicted water content profiles were those calculated for soil columns with smaller residuals on the distance versus square root of time curves. Satisfactory predictions would not would not have occurred had there not been close agreement between vertical lines and $\lambda(\theta_{wf})$ as shown in figures 9 through 12. Values plotted in figures 25, 26 and 27 for SAR 0, 5 and 15, respectively show that significant reductions in soil-water diffusivity can be caused by an increase of sodium content in soil and/or a decrease of soil solution concentration. The soil-water diffusivity values obtained near saturation behaved similarly to hydraulic conductivity values reported by Henderson (1958) for the same soil at approximated equal conditions of saturation. The reductions observed were shorter when the water content in soil was lower. The soil-water diffusivity of the Ca-saturated soil was significantly changed only when distilled water was used to wet the soil. The soil-water diffusivity of the soil treated with SAR 5 changed also when 2 me/l were used as the wetting solution, while in the soil treated with SAR 15 it was affected also when 5 me/l were used as the wetting solution. Relative larger changes of soil-water diffusivity, at larger water contents in Ca-saturated soils wetted with solutions of low concentration, can be attributed to the rupture of soil particles by diffusion of solution from non-conducting pores. In soils with larger contents of sodium like the one treated with SAR 15, swelling is expected to be the main mechanism responsible for reducing the soil-water diffusivity.

Sorptivity values plotted in figure 43 show that soil solutions with low salt concentrations can significantly affect the infiltration of water in soils. Although the changes in sorptivity values were larger in soils treated with solution with SAR 5 or 15, significant reductions were observed also in Ca-saturated soil samples.

Determinations of the concentration of soluble salts in soil columns after the infiltration process reveal that most of the salt leached from an unsaturated soil profile moves just behind the wetting front. Increases in concentration of soluble salts with distance observed in figures 28 through 31 were caused by dispersion of the wetting solution due to differences in velocity distribution inside pores and also by molecular diffusion of the high concentrated solution already present in soil. The existence of stagnant zones with soluble salts might have increased the velocity of salt movement. According to results presented in table 2, the concentration of solution in these pores was as high as approximately 28, 35 or 63 me/l for soils treated with SAR 0, 5 or 15, respectively. The high gradient of concentration expected between micro and macropores when distilled water was used to wet the soil might have contributed significantly to the rupture of soil particles due to movement of soil solution by chemical diffusion. The breaking of aggregates by this phenomenon, originally suggested by Emerson and Bakker (1973), might have contributed to the release and accumulation of salts near the wetting front.

Values of concentration plotted in figure 31 describe the concentration of soluble salts after the infiltration of distilled water. Undoubtedly, a large fraction of soluble salts remained in the soil after the leaching and drying processes. These data agree well with data from table 2 and show that the amount of soluble salt remaining was larger for soils treated with solutions with higher SAR values. These soils were exactly those more difficult to leach even with the use of the methanol solution.

Figure 28 illustrates that the concentration of soluble salts measured after the infiltration process was slightly less than that of the input concentration. This may be due to dilution errors involved on EC_{25} determinations or by estimation errors in calculating total concentration from EC values. This phenomenon has been observed by Morkoc (1980) for chloride concentration in a similar soil (Yolo silt loam). For the present work, the differences observed between measured and input concentrations were as large as 14%, according to values shown in tables 17, 18 and 19. Significant or not, these differences were negative in the whole soil column, except near the wetting front. Disregarding errors in the chemical analysis or in the total concentration estimations, the hypothesis of anion exclusion by the inlet end suggested by Morkoc (1980) would not apply. Na and Ca analysis determined by flame photometry, if correct, show however that the equation used to estimate total concentration from EC values might not have been appropriate. Values presented in tables 17, 18 and 19 show that the sum of Na and Ca concentrations results in a concentration larger than the input concentration (15 me/l).

Variations between the total concentration and the sum of Na and Ca concentrations, noticeable in tables 17, 18 and 19, are attributed to dilution errors in both chemical analysis and/or estimation errors from use of inappropriate equation.

Assuming the lack of a third element in the soil solution, the differences observed in the last column of tables 17, 18 and 19 are a consequence of the use of different methods for chemical analyses. Disregarding these differences, the Na and Ca concentrations were plotted in figures 37 through 42. In the soil treated with SAR 0 (see figure 32), where no sodium was expected to be present, we observe that approximately 0.6 me/l of Na was released by the soil or was already present in the soil pores prior to the infiltration process. This may be attributed to incomplete displacement of Na by Ca during the treatment of soil or by an incomplete removal of excess of soluble salts by the leaching procedure.

Differences between the amounts of Na or Ca added to the soil column by the wetting solution and the measured soluble concentration after infiltration are plotted in figures 38 through 42. In figure 38 we observe that the amount of Na released by the soil treated with SAR 5 increased when solutions of lower concentrations were used to wet the soil. Similar behavior was observed in the soil treated with SAR 15 as shown in figure 39. Ca concentrations for 0 me/l presented in figure 40 show that approximately 1.0 me/l of calcium was present in soil after the infiltration process. Adsorption of Ca by the soil occurred however, when 2, 5 or 15 me/l was used to wet the soil treated with SAR 0. The adsorbed Ca probably displaced the Na amount measured in the soil columns wetted with solutions with SAR 0 (figure 32). The amount of Ca adsorbed by the soil treated with SAR 5 and SAR 15 was larger when 15 me/l was used as the wetting concentration. Disregarding errors in chemical analysis, this observation can be attributed to increased availability of Na for chemical changes in these soils. Calcium, being a divalent element is preferred over sodium in the exchange phase of clay particles.

Disregarding variations in water content imparted by errors in gravimetric analysis and variations in wetting front advance, observed changes in soil-water diffusivity were caused by the presence of sodium in the clay particles, low concentration of soil solution, and to a less extent by chemical instability of the system. Displacement of sodium by calcium, as well as, prior existence of soluble salt and release of salts by the soil could have affected the movement of soil solution. Although these facts, associated with swelling and detachment of clay particles, can invalidate Bruce and Klute's method, they appeared to have little net effect on calculated values of soil-water diffusivity. Differences in diffusivity functions, therefore, may be attributed to the effects of soil salinity.

TABLE 1 - Exchangeable Na and Ca concentration in the soil samples used for the infiltration studies.

SAR used to treat the soil	Na (me/100g)	Ca (me/100g)	Na/Ca %
0.0	0.17	24.00	0.71
5.0	1.11	23.44	4.74
15.0	2.97	21.86	13.59

TABLE 2 - Electrical conductivity values of the last effluent obtained from the leaching process and from the soil solution extracted (1:1) from the sieved soil.

SAR used to	EC_{25} (µmho/cm)	
treat the soil	Effluent	Extract
0.0	18.9	141.5
5.0	19.5	177.2
15.0	35.5	317.8

TABLE 3 - Bulk density values of soil columns used on the infiltration tests.

SAR used to treat the soil	Wetting solution concentration (me/l)			
	15.0	5.0	2.0	0.0
0.0	1.32	1.32	1.33	1.33
5.0	1.33	1.33	1.33	1.34
15.0	1.37	1.36	1.36	1.36

TABLE 4 - Time (min) required for the wetting front to reach a distance of 20 cm.

SAR used to treat the soil	Solution concentration (me/l)			
	15.0	5.0	2.0	0.0
0.0	535	504	667	1070
5.0	663	942	1408	3485
15.0	1340	4449	11671	26652

TABLE 5 - Square root of time values ($\min^{1/2}$) versus distance for soil columns wetted with different concentrations of a solution with SAR 0.

Distance (cm)	Concentration (me/l)			
	15.0	5.0	2.0	0.0
2.0	2.40	2.32	2.55	3.46
4.0	4.94	4.75	5.23	6.98
6.0	7.46	7.03	7.93	10.29
8.0	9.78	9.24	10.47	13.60
10.0	12.12	11.43	13.03	16.86
12.0	14.34	13.57	15.57	20.08
14.0	16.53	15.74	18.17	23.24
15.0	17.64	16.83	19.41	24.82
16.0	18.73	17.95	20.68	26.45
17.0	19.81	19.03	21.97	28.09
18.0	20.85	20.13	23.26	29.57
19.0	21.96	21.21	24.53	31.13
19.5	22.52	21.86	25.21	31.95
20.0	23.13	22.45	25.83	32.72

TABLE 6 - Square root of time values ($min^{1/2}$) versus distance for soil columns wetted with different concentrations of a solution with SAR 5.

Distance (cm)	Concentration (me/l)			
	15.0	5.0	2.0	0.0
2.0	2.52	3.41	3.79	5.90
4.0	5.18	6.86	7.57	12.11
6.0	7.71	10.08	11.40	18.28
8.0	10.32	13.15	15.14	24.40
10.0	12.89	16.13	18.81	30.57
12.0	15.41	19.07	22.61	36.54
14.0	17.97	21.95	26.29	42.36
15.0	19.25	23.39	28.12	45.16
16.0	20.54	24.86	29.97	47.99
17.0	21.85	26.29	31.79	50.74
18.0	23.14	27.75	33.67	53.48
19.0	24.43	29.18	35.46	56.11
19.5	25.07	29.92	36.45	57.63
20.0	25.76	30.69	37.52	59.03

TABLE 7 - Square root of time values ($min^{1/2}$) versus distance for soil columns wetted with different concentrations of a solution with SAR 15.

Distance (cm)	Concentration (me/l)			
	15.0	5.0	2.0	0.0
2.0	4.29	5.59	7.31	10.31
4.0	8.33	12.14	18.17	26.50
6.0	12.13	18.94	29.75	43.42
8.0	15.70	25.36	41.34	62.58
10.0	19.31	31.82	52.98	80.93
12.0	22.88	38.27	63.79	98.91
14.0	26.37	45.17	75.53	117.02
15.0	28.14	48.20	81.91	126.45
16.0	29.84	51.83	87.41	134.44
17.0	31.49	55.20	92.13	141.38
18.0	33.26	59.10	97.87	148.68
19.0	34.94	62.97	103.00	156.24
19.5	35.79	64.95	105.52	159.58
20.0	36.60	66.70	108.03	163.25

Table 8: Slope values of distance versus square root of time curves

Concentration (me/l)	SAR 0	SAR 5	SAR 15
15.0	0.855	0.778	0.537
5.0	0.890	0.643	0.306
2.0	0.773	0.534	0.185
0.0	0.606	0.335	0.122

Table 9: Sorptivity values (cm/min$^{1/2}$) of soil columns treated with SAR 0, 5 and 15 and wetted with 15, 5, 2 and 0 me/l.

Concentration (me/l)	SAR 0	SAR 5	SAR 15
15.0	0.331	0.305	0.213
5.0	0.343	0.254	0.112
2.0	0.289	0.207	0.071
0.0	0.235	0.128	0.047

TABLE 10- Volumetric water content (cm^3/cm^3) at the end of infiltration process in the soil column treated with SAR 0.

Distance (cm)	Concentration of the wetting solution (me/l)			
	15.0	5.0	2.0	0.0
2.0	0.438	0.458	0.447	0.462
4.0	0.447	0.451	0.443	0.461
6.0	0.453	0.453	0.450	0.464
8.0	0.452	0.451	0.446	0.461
10.0	0.455	0.445	0.446	0.454
12.0	0.443	0.443	0.433	0.441
14.0	0.439	0.439	0.429	0.432
15.0	0.428	0.425	0.413	0.430
16.0	0.422	0.415	0.401	0.419
17.0	0.411	0.408	0.393	0.393
18.0	0.394	0.392	0.374	0.378
19.0	0.369	0.368	0.353	0.356
19.5	0.355	0.338	0.341	0.344
20.0	0.305	0.306	0.283	0.295
>20.0	0.048	0.048	0.048	0.048

TABLE 11- Volumetric water content (cm^3/cm^3) at the end of infiltration process in the soil column treated with SAR 5.

Distance (cm)	Concentration of the wetting solution (me/l)			
	15.0	5.0	2.0	0.0
2.0	0.459	0.460	0.461	0.468
4.0	0.461	0.463	0.463	0.470
6.0	0.460	0.461	0.468	0.470
8.0	0.459	0.460	0.467	0.460
10.0	0.454	0.453	0.456	0.448
12.0	0.446	0.444	0.447	0.436
14.0	0.439	0.430	0.432	0.420
15.0	0.432	0.424	0.422	0.410
16.0	0.422	0.417	0.410	0.389
17.0	0.410	0.400	0.394	0.370
18.0	0.393	0.379	0.369	0.345
19.0	0.369	0.355	0.343	0.314
19.5	0.358	0.336	0.316	0.288
20.0	0.306	0.296	0.280	0.258
>20.0	0.042	0.042	0.042	0.042

TABLE 12- Volumetric water content (cm^3/cm^3) at the end of infiltration process in the soil column treated with SAR 15.

Distance (cm)	Concentration of the wetting solution (me/l)			
	15.0	5.0	2.0	0.0
2.0	0.445	0.463	0.487	0.490
4.0	0.450	0.463	0.473	0.488
6.0	0.455	0.463	0.474	0.480
8.0	0.461	0.458	0.461	0.463
10.0	0.455	0.448	0.448	0.444
12.0	0.450	0.433	0.437	0.424
14.0	0.435	0.416	0.411	0.401
15.0	0.427	0.402	0.401	0.391
16.0	0.416	0.384	0.381	0.365
17.0	0.403	0.362	0.352	0.343
18.0	0.384	0.336	0.330	0.322
19.0	0.356	0.306	0.297	0.296
19.5	0.336	0.283	0.279	0.260
20.0	0.290	0.242	0.249	0.256
>20.0	0.039	0.039	0.039	0.039

TABLE 13 - Soil-water Diffusivity versus water content in soil columns wetted with 15 me/l of solution with SAR 0.0, 5.0 and 15.0.

Water Content (cm^3/cm^3)	Soil-water Diffusivity (cm^2/min)		
	SAR 0	SAR 5	SAR 15
0.150	1.26×10^{-3}	4.97×10^{-4}	6.64×10^{-4}
0.175	2.20×10^{-3}	1.02×10^{-3}	8.88×10^{-4}
0.200	3.14×10^{-3}	1.70×10^{-3}	1.49×10^{-3}
0.225	5.55×10^{-3}	2.82×10^{-3}	2.63×10^{-3}
0.250	7.66×10^{-3}	4.32×10^{-3}	4.59×10^{-3}
0.275	1.70×10^{-2}	1.01×10^{-2}	1.17×10^{-2}
0.300	2.88×10^{-2}	2.01×10^{-2}	2.13×10^{-2}
0.325	6.49×10^{-2}	4.81×10^{-2}	3.86×10^{-2}
0.350	1.07×10^{-1}	1.09×10^{-1}	6.31×10^{-2}
0.375	1.91×10^{-1}	2.11×10^{-1}	1.01×10^{-1}
0.400	3.96×10^{-1}	3.34×10^{-1}	1.73×10^{-1}
0.425	8.51×10^{-1}	5.64×10^{-1}	3.07×10^{-1}
0.450	1.90×10^{0}	2.26×10^{0}	1.31×10^{0}

TABLE 14 - Soil-water Diffusivity versus water content in soil columns wetted with 5 me/l of solution with SAR of 0.0, 5.0 and 15.0.

Water Content (cm^3/cm^3)	Soil-water Diffusivity (cm^2/min) SAR 0	SAR 5	SAR 15
0.150	1.01×10^{-3}	9.13×10^{-4}	5.29×10^{-4}
0.175	1.82×10^{-3}	1.30×10^{-3}	8.90×10^{-4}
0.200	3.41×10^{-3}	3.08×10^{-3}	1.43×10^{-4}
0.225	4.92×10^{-3}	4.65×10^{-3}	2.37×10^{-3}
0.250	1.14×10^{-2}	7.99×10^{-3}	4.18×10^{-3}
0.275	2.34×10^{-2}	1.64×10^{-2}	7.31×10^{-3}
0.300	5.32×10^{-2}	3.25×10^{-2}	1.28×10^{-3}
0.325	9.24×10^{-2}	5.69×10^{-2}	1.84×10^{-2}
0.350	1.64×10^{-1}	9.33×10^{-2}	2.78×10^{-2}
0.375	2.54×10^{-1}	1.46×10^{-1}	4.21×10^{-2}
0.400	4.00×10^{-1}	2.37×10^{-1}	6.16×10^{-2}
0.425	8.41×10^{-1}	4.34×10^{-1}	8.99×10^{-2}
0.450	4.73×10^{0}	1.37×10^{0}	1.89×10^{-2}

TABLE 15 - Soil-water Diffusivity versus water content in soil columns wetted with 2 me/l of solution with SAR of 0.0, 5.0 and 15.0.

Water Content (cm^3/cm^3)	Soil-water Diffusivity (cm^2/min)		
	SAR 0	SAR 5	SAR 15
0.150	4.75×10^{-4}	5.74×10^{-4}	2.28×10^{-4}
0.175	1.58×10^{-3}	7.78×10^{-4}	4.83×10^{-4}
0.200	3.66×10^{-3}	1.51×10^{-3}	8.43×10^{-4}
0.225	6.04×10^{-3}	2.14×10^{-3}	1.67×10^{-3}
0.250	9.39×10^{-3}	5.97×10^{-3}	2.59×10^{-3}
0.275	1.88×10^{-2}	1.32×10^{-2}	4.73×10^{-3}
0.300	3.82×10^{-2}	2.87×10^{-2}	7.08×10^{-3}
0.325	7.39×10^{-2}	4.80×10^{-2}	1.01×10^{-2}
0.350	1.56×10^{-1}	7.66×10^{-2}	1.29×10^{-2}
0.375	2.56×10^{-1}	1.08×10^{-1}	1.69×10^{-2}
0.400	4.20×10^{-1}	1.71×10^{-1}	2.36×10^{-2}
0.425	8.87×10^{-1}	2.68×10^{-1}	3.27×10^{-2}
0.450	**	5.47×10^{-1}	4.49×10^{-2}

** : The water content at the inlet end was less than 0.450 cm^3/cm^3

TABLE 16 - Soil-water Diffusivity versus water content in soil columns wetted with distilled water.

Water Content (cm^3/cm^3)	Soil-water Diffusivity (cm^2/min)		
	SAR 0	SAR 5	SAR 15
0.150	8.09×10^{-4}	2.19×10^{-4}	3.45×10^{-4}
0.175	1.16×10^{-3}	6.29×10^{-4}	4.55×10^{-4}
0.200	1.58×10^{-3}	1.60×10^{-3}	6.16×10^{-4}
0.225	2.37×10^{-3}	2.90×10^{-3}	1.03×10^{-3}
0.250	5.29×10^{-3}	5.12×10^{-3}	1.45×10^{-3}
0.275	9.26×10^{-3}	1.08×10^{-2}	1.90×10^{-3}
0.300	1.73×10^{-2}	1.76×10^{-2}	2.97×10^{-3}
0.325	4.02×10^{-2}	2.57×10^{-2}	4.33×10^{-2}
0.350	8.27×10^{-2}	3.31×10^{-2}	5.70×10^{-2}
0.375	1.43×10^{-1}	4.72×10^{-2}	7.49×10^{-2}
0.400	2.20×10^{-1}	6.98×10^{-2}	9.92×10^{-2}
0.425	3.33×10^{-1}	1.21×10^{-1}	1.15×10^{-2}
0.450	9.51×10^{-1}	2.42×10^{-1}	1.46×10^{-2}

TABLE 17 - Soluble Sodium and Calcium concentrations and estimated total soluble concentration after infiltration in the soil treated with solution of SAR 0 .

Wetting conc. (me/l)	Distance (cm)	Na	Ca (me/l)	C	(Na+Ca)-C
15.0	0-4	0.16	13.10	13.79	-0.53
15.0	4-8	0.67	14.32	14.69	0.30
15.0	8-12	0.76	13.26	13.96	0.06
15.0	12-16	0.73	14.11	14.46	0.38
15.0	16-20	0.91	25.49	23.44	2.96
5.0	0-4	0.30	3.82	5.02	-0.90
5.0	4-8	0.54	3.85	5.05	-0.66
5.0	8-12	0.49	3.73	5.24	-1.02
5.0	12-16	0.50	4.02	5.51	-0.99
5.0	16-20	0.75	8.86	10.22	-0.61
2.0	0-4	0.51	0.96	3.24	-1.77
2.0	4-8	0.61	1.11	3.75	-2.03
2.0	8-12	0.68	1.06	3.83	-2.09
2.0	12-16	0.63	1.18	4.07	-2.26
2.0	16-20	1.33	5.92	8.28	-1.03
0.0	0-4	0.82	0.66	2.18	-0.70
0.0	4-8	0.62	0.71	2.13	-0.80
0.0	8-12	0.87	0.95	2.29	-0.47
0.0	12-16	0.64	1.06	2.55	-0.85
0.0	16-20	1.09	4.15	5.45	-0.21

TABLE 18 - Soluble Sodium and Calcium concentrations and estimated total soluble concentration after infiltration in the soil treated with solution of SAR 5 .

Wetting conc. (me/l)	Distance (cm)	Na	Ca	C	(Na+Ca)-C
			(me/l)		
15.0	0-4	10.87	1.32	12.87	-0.68
15.0	4-8	9.59	3.21	13.56	-0.76
15.0	8-12	9.92	4.04	15.21	-1.25
15.0	12-16	10.21	3.82	14.19	-0.16
15.0	16-20	14.84	8.02	25.46	-2.60
5.0	0-4	5.91	0.45	5.84	0.52
5.0	4-8	5.86	0.60	6.16	0.30
5.0	8-12	6.14	0.65	6.17	0.62
5.0	12-16	6.48	0.74	6.44	0.78
5.0	16-20	10.99	3.54	14.55	-0.02
2.0	0-4	3.45	0.18	3.32	0.31
2.0	4-8	3.73	0.24	3.33	0.64
2.0	8-12	3.83	0.24	3.66	0.41
2.0	12-16	4.25	0.32	3.85	0.72
2.0	16-20	8.53	1.57	10.17	-0.07
0.0	0-4	2.30	0.06	1.88	0.48
0.0	4-8	2.74	0.15	2.52	0.37
0.0	8-12	3.07	0.19	2.71	0.55
0.0	12-16	3.78	0.24	3.22	0.80
0.0	16-20	7.92	1.57	8.35	1.14

TABLE 19 - Soluble Sodium and Calcium concentrations and estimated total soluble concentration after infiltration in the soil treated with solution of SAR 15 .

Wetting conc. (me/l)	Distance (cm)	Na	Ca	C	(Na+Ca)-C
			(me/l)		
15.0	0-4	14.87	0.35	14.28	0.94
15.0	4-8	14.35	0.34	13.87	0.82
15.0	8-12	14.91	0.53	14.20	1.24
15.0	12-16	15.18	0.62	14.54	1.26
15.0	16-20	29.75	1.86	34.67	-3.06
5.0	0-4	6.42	0.12	5.88	0.66
5.0	4-8	6.79	0.15	6.21	0.73
5.0	8-12	7.28	0.19	6.66	0.81
5.0	12-16	7.79	0.21	7.05	0.95
5.0	16-20	19.20	0.92	19.92	0.20
2.0	0-4	4.03	0.06	3.42	0.67
2.0	4-8	4.26	0.06	3.61	0.71
2.0	8-12	4.98	0.06	4.19	0.85
2.0	12-16	5.45	0.10	4.67	0.88
2.0	16-20	14.28	0.23	13.25	1.26
0.0	0-4	2.66	0.03	2.03	0.66
0.0	4-8	3.20	0.03	2.44	0.79
0.0	8-12	3.67	0.06	2.93	0.80
0.0	12-16	4.38	0.11	3.57	0.92
0.0	16-20	10.55	0.18	8.54	2.19

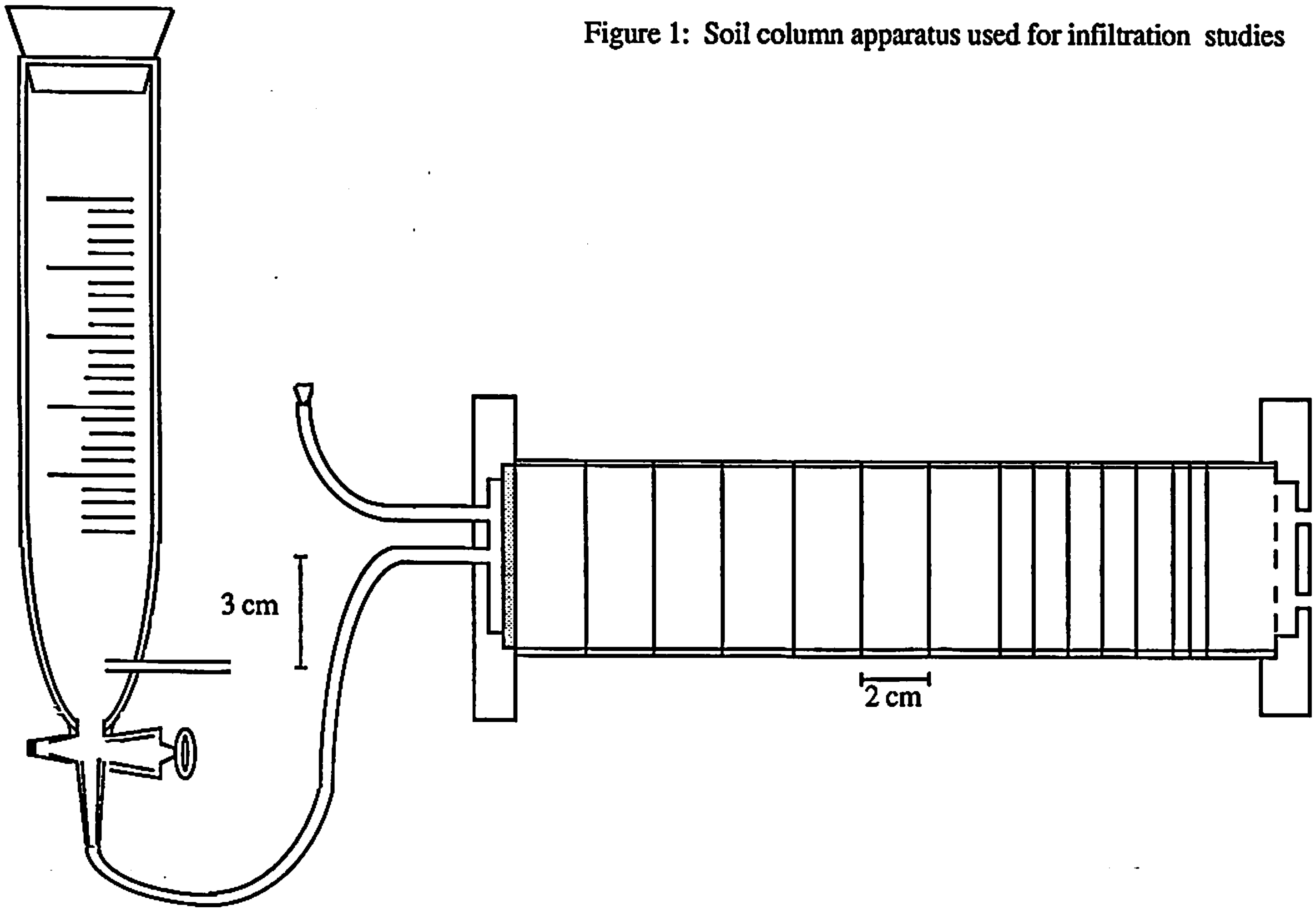


Figure 1: Soil column apparatus used for infiltration studies

Figure 2: Distance versus square root of time for soil columns treated with solution of SAR 0

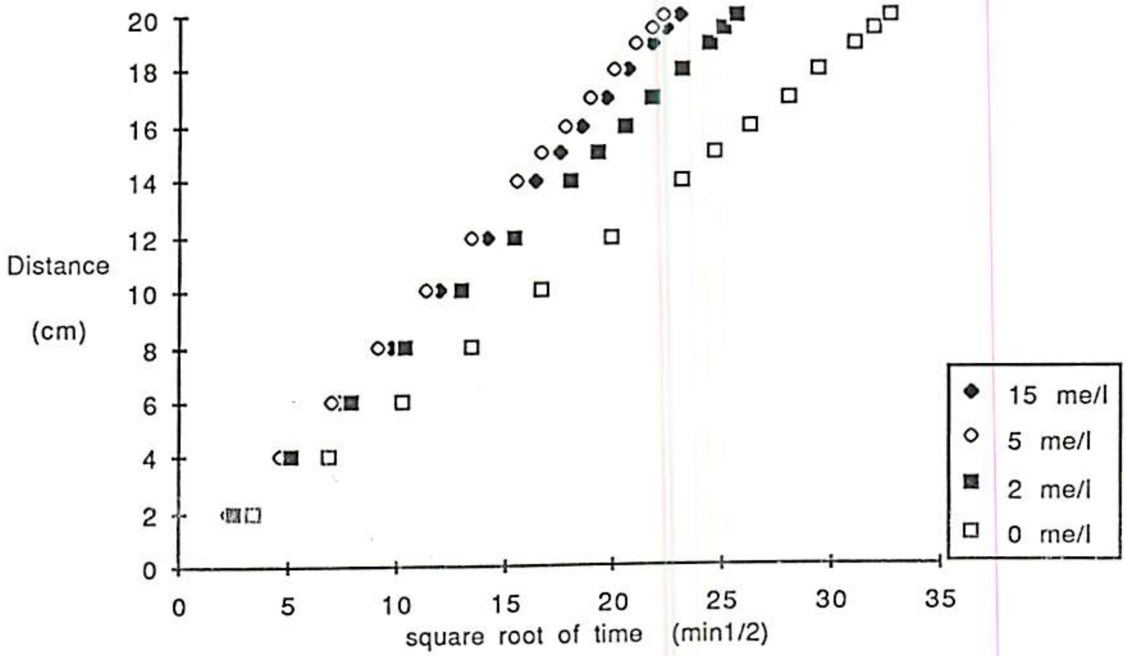


Figure 3: Distance versus square root of time for soil columns treated with solution of SAR 5

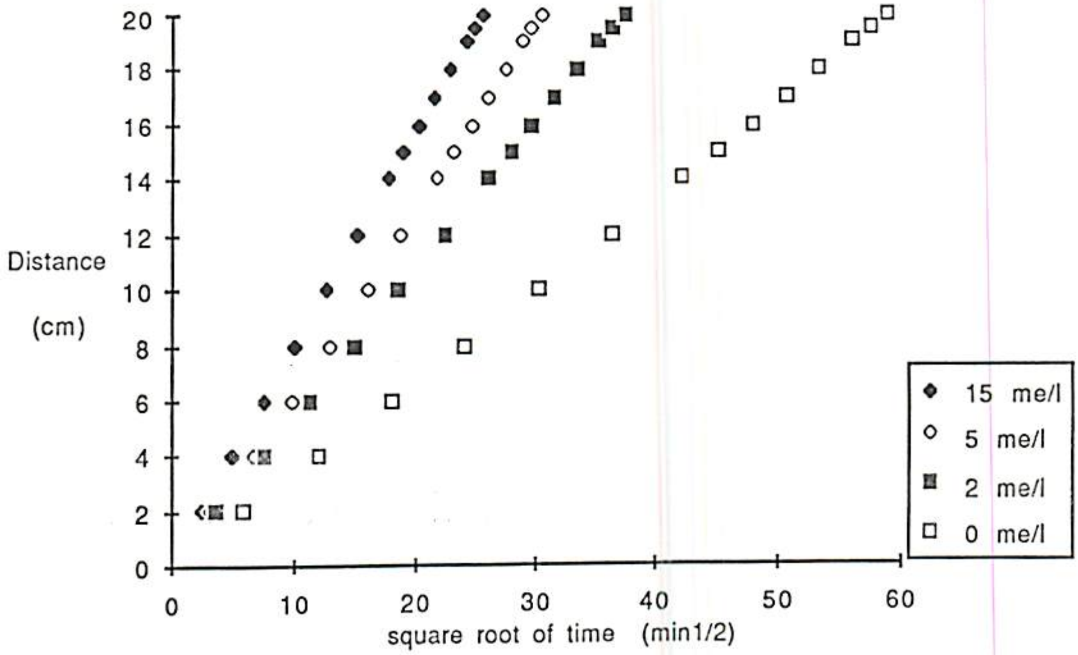


Figure 4: Distance versus square root of time for soil columns treated with SAR 15

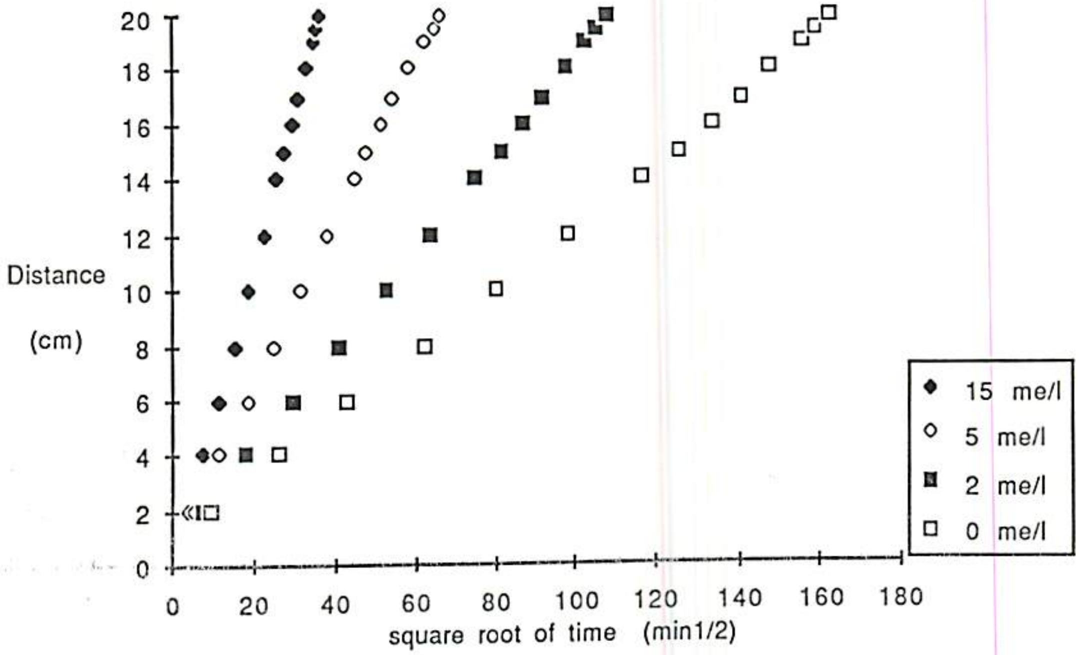


Figure 5: Distance residuals on soil columns wetted with 15 me/l

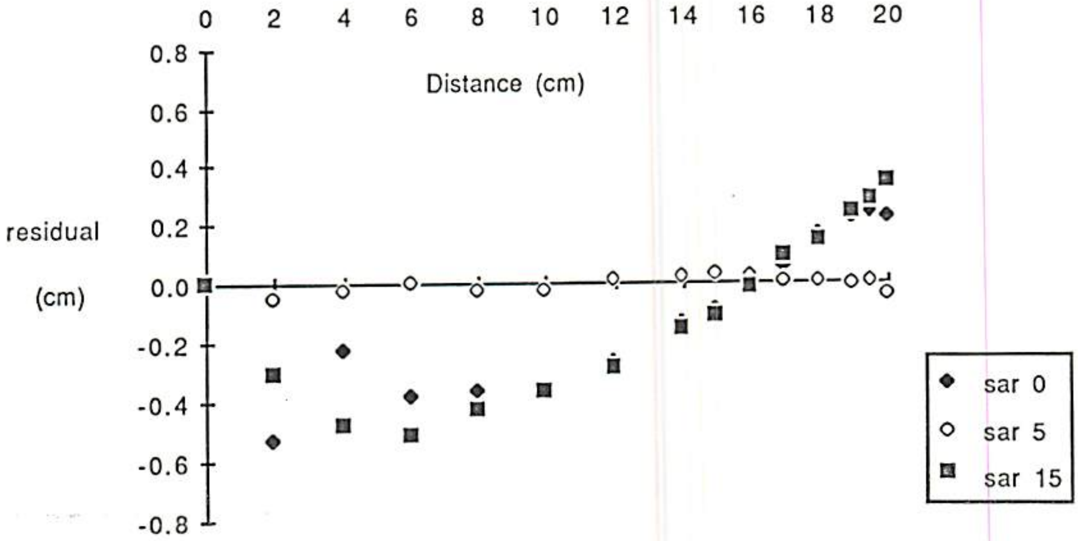


Figure 6: Distance residuals on soil columns wetted with 5 me/l

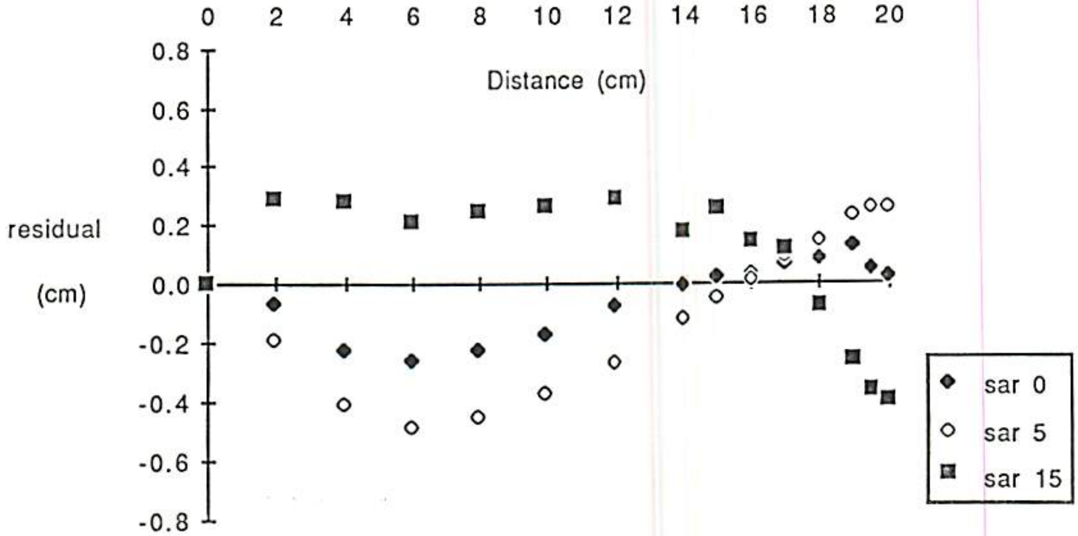


Figure 7: Distance residuals on soil columns wetted with 2 me/l

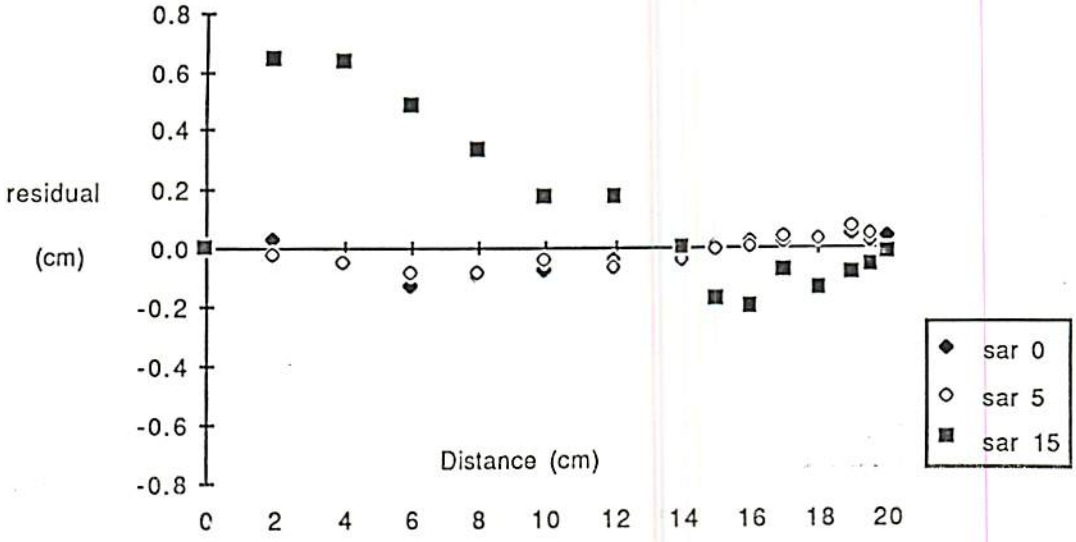


Figure 8: Distance residuals on soil columns wetted with distilled water

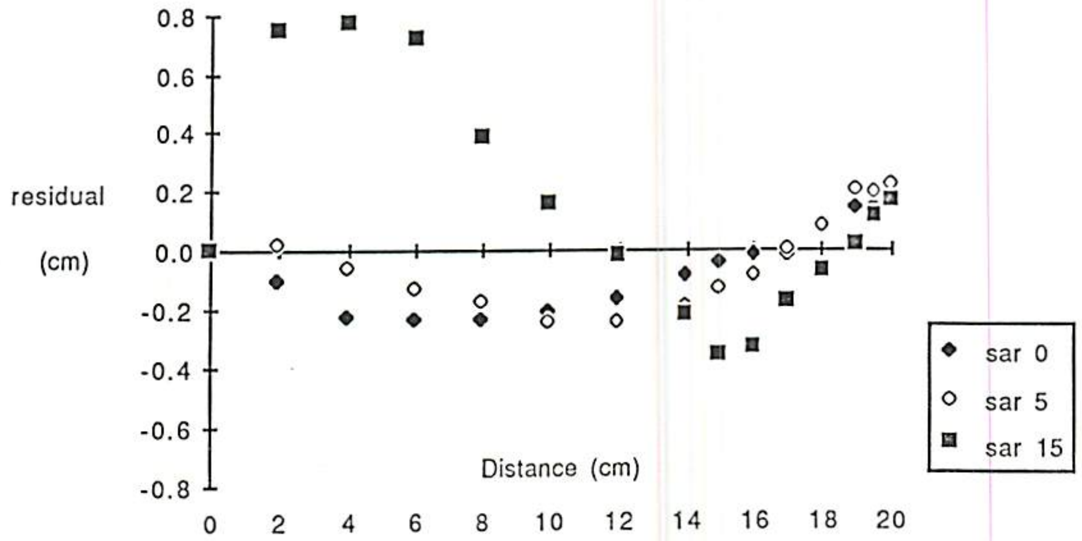


Figure 9: λ versus θ for soil columns wetted with 15 me/l

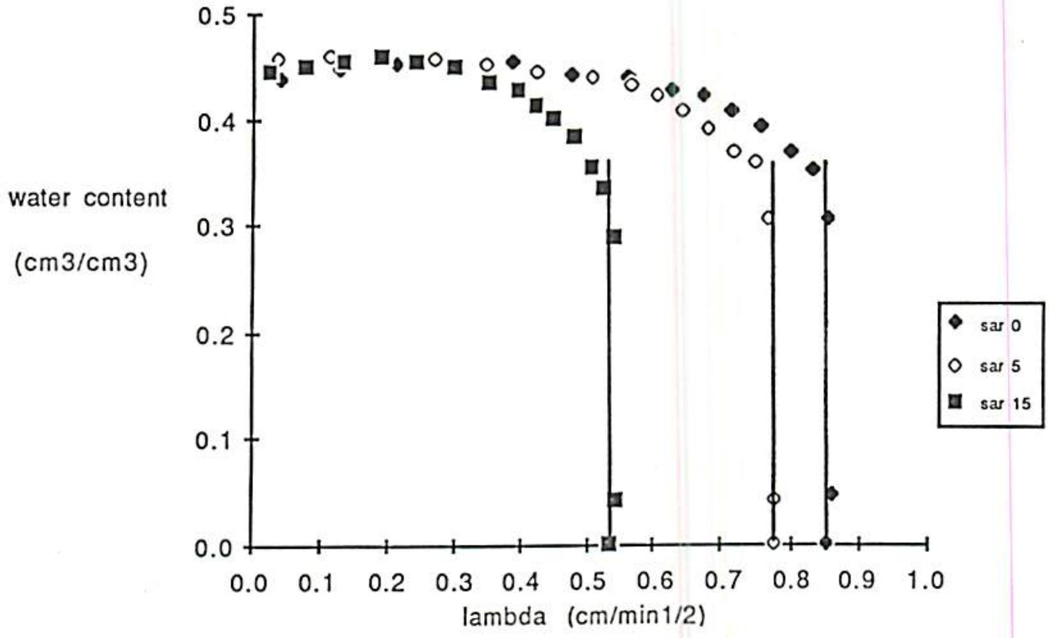


Figure 10: λ versus θ for soil columns wetted with 5 me/l

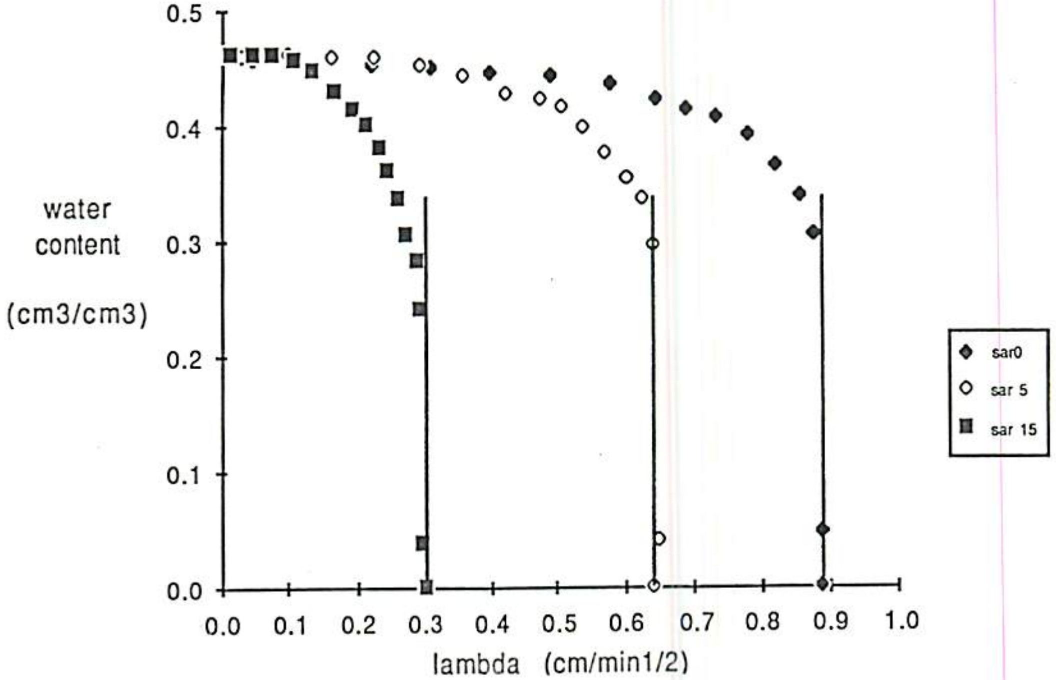


Figure 11: λ versus θ for soil columns wetted with 2 me/l

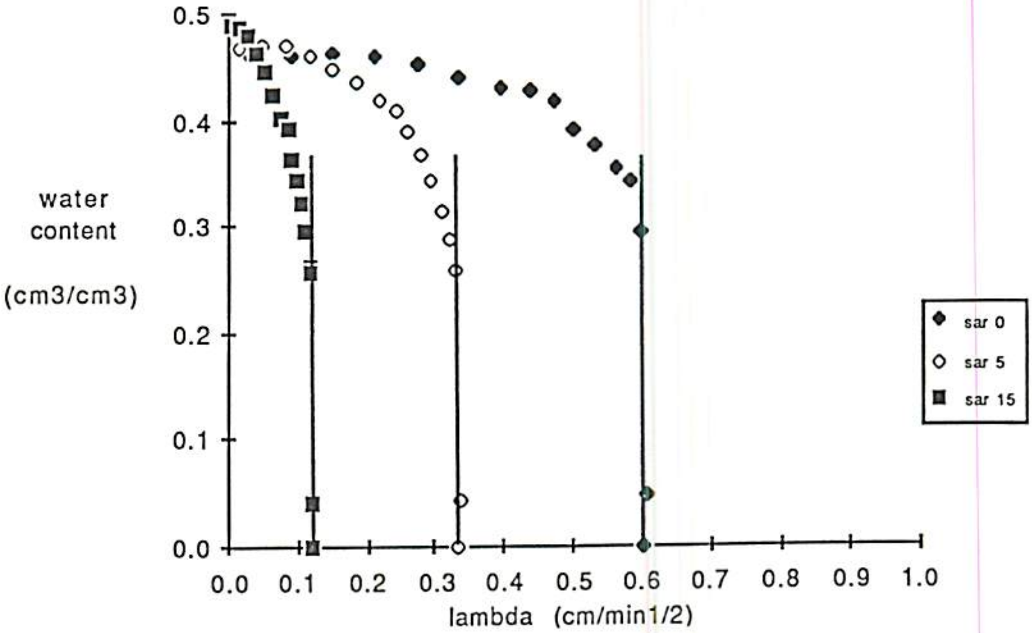


Figure 12: λ versus θ for soil columns wetted with distilled water

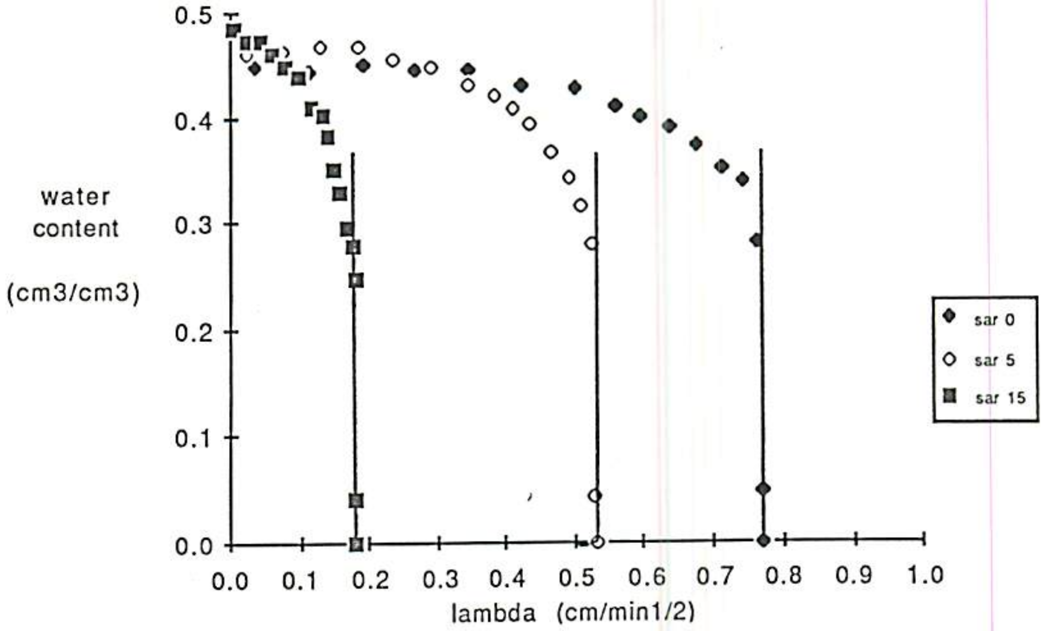


Figure 13: Measured and calculated water content profiles in soil columns treated with SAR 0 and wetted with 15 me/l.

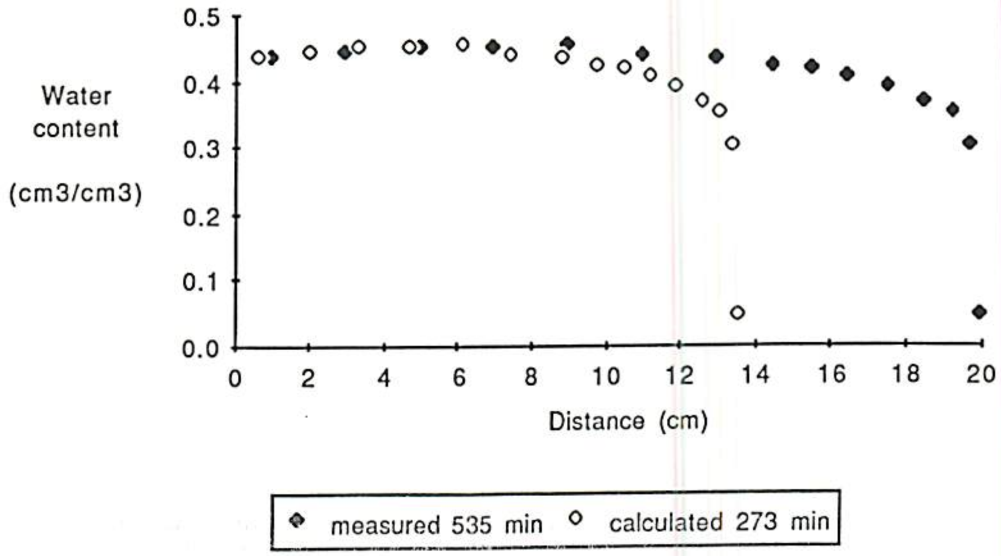


Figure 14: Measured and calculated water content profiles in soil columns treated with SAR 0 and wetted with 5 me/l.

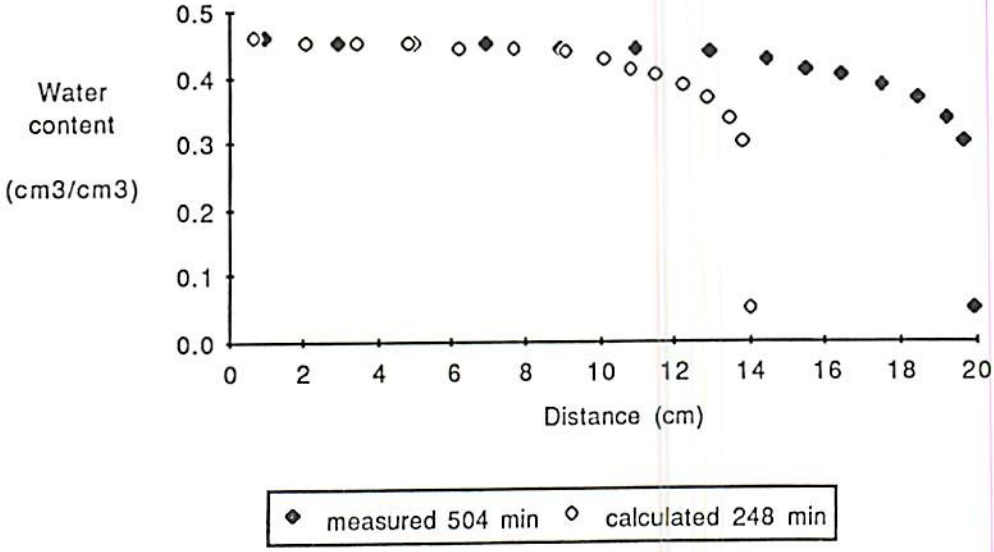


Figure 15: Measured and calculated water content profiles in soil columns treated with SAR 0 and wetted with 2 me/l.

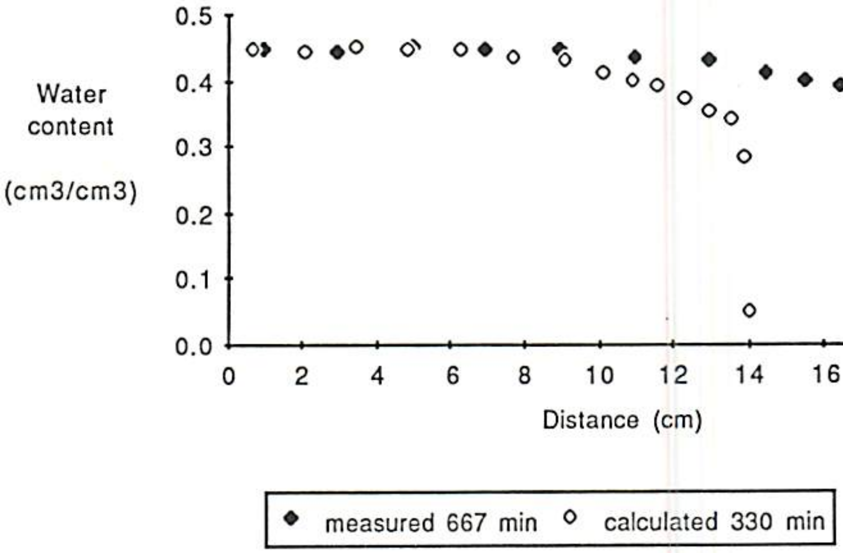


Figure 16: Measured and calculated water content profiles in soil columns treated with SAR 0 and wetted with distilled water.

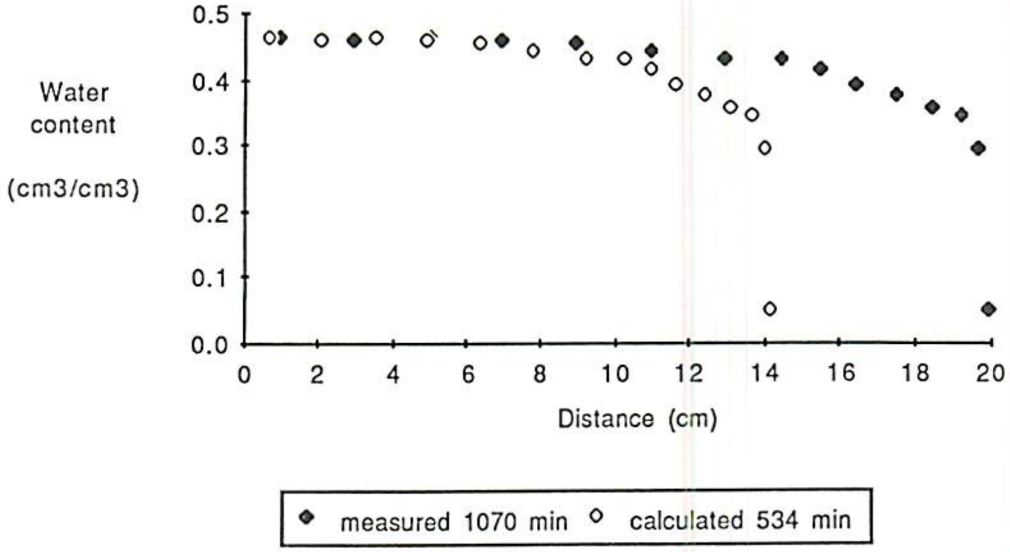


Figure 17: Measured and calculated water content profiles in soil columns treated with SAR 5 and wetted with 15 me/l.

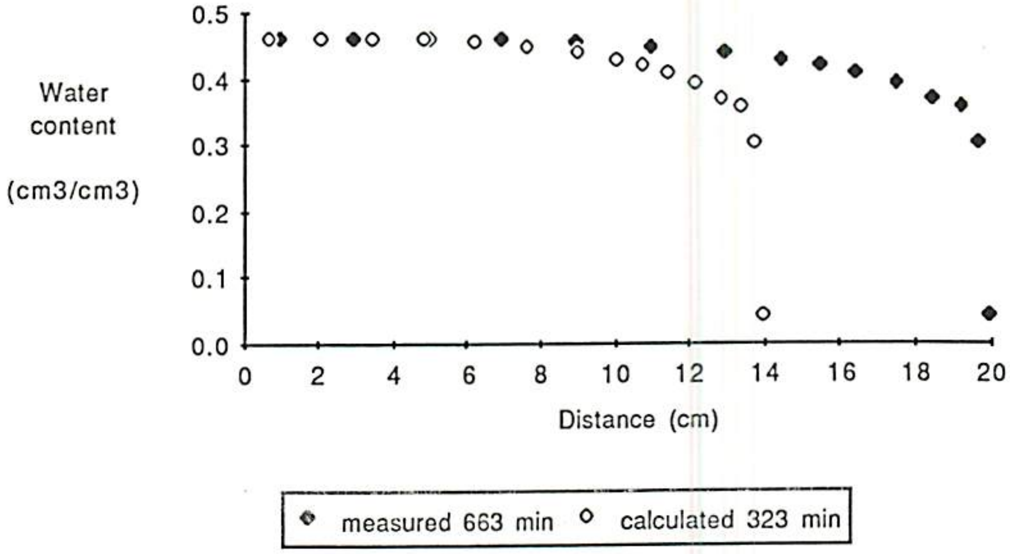


Figure 18: Measured and calculated water content profiles in soil columns treated with SAR 5 and wetted with 5 me/l.

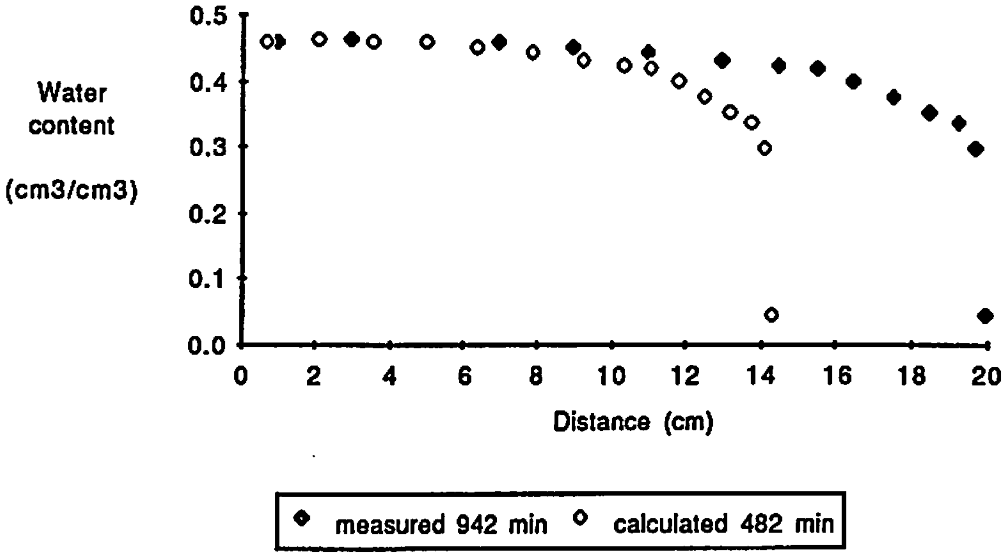


Figure 19: Measured and calculated water content profiles in soil columns treated with SAR 5 and wetted with 2 me/l.

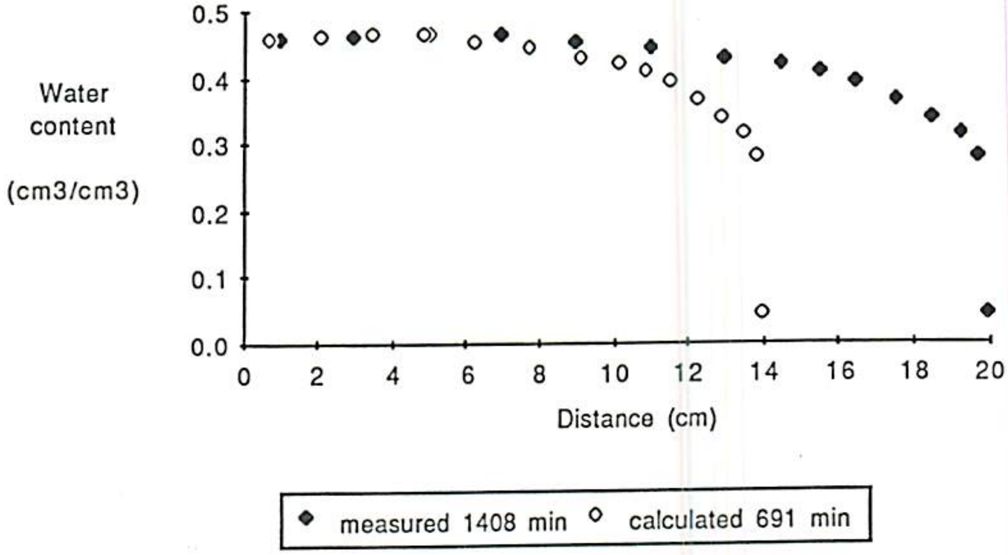


Figure 20: Measured and calculated water content profiles in soil columns treated with SAR 5 and wetted with distilled water.

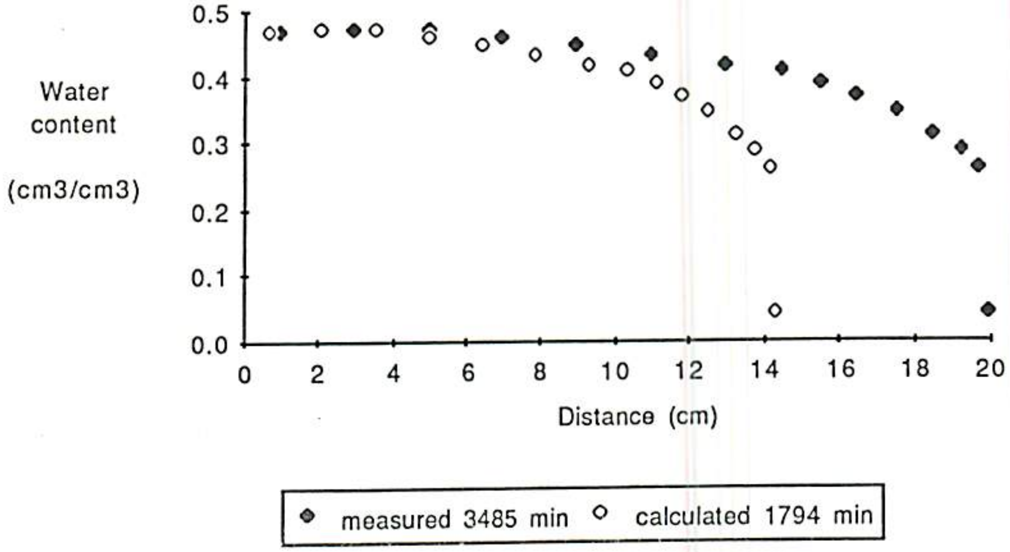


Figure 21: Measured and calculated water content profiles in soil columns treated with SAR 15 and wetted with 15 me/l.

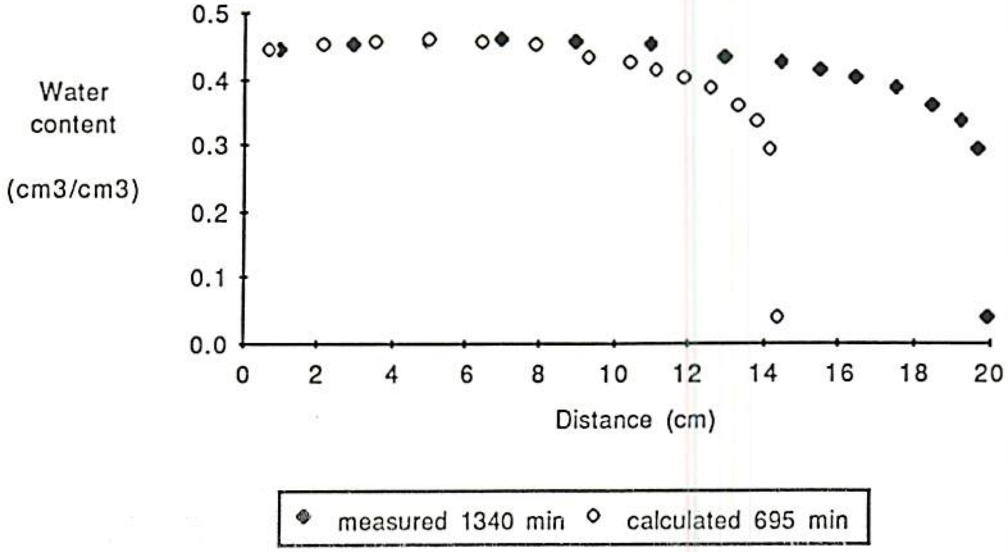


Figure 22: Measured and calculated water content profiles in soil columns treated with SAR 15 and wetted with 5 me/l.

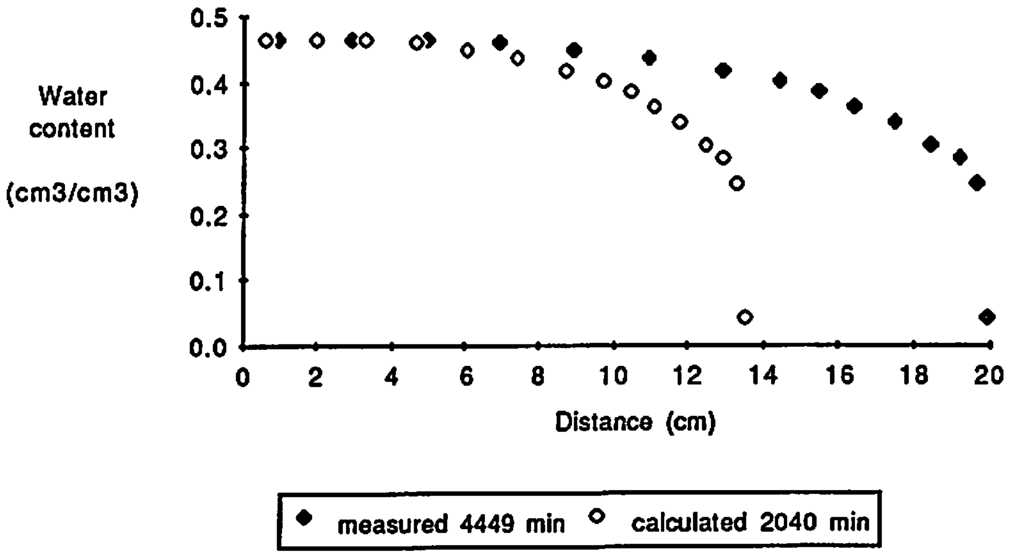


Figure 23: Measured and calculated water content profiles in soil columns treated with SAR 15 and wetted with 2 me/l.

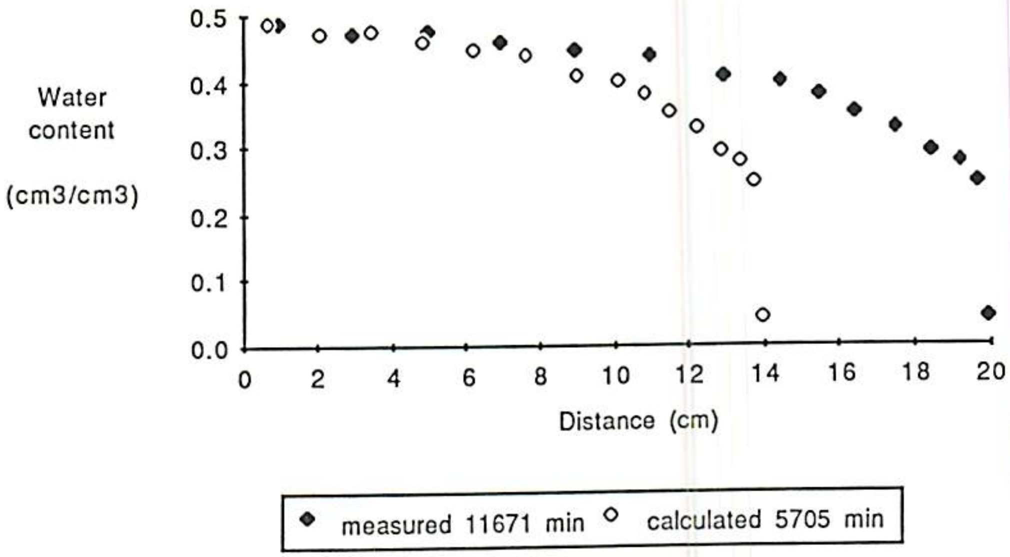


Figure 24: Measured and calculated water content profiles in soil columns treated with SAR 15 and wetted with distilled water.

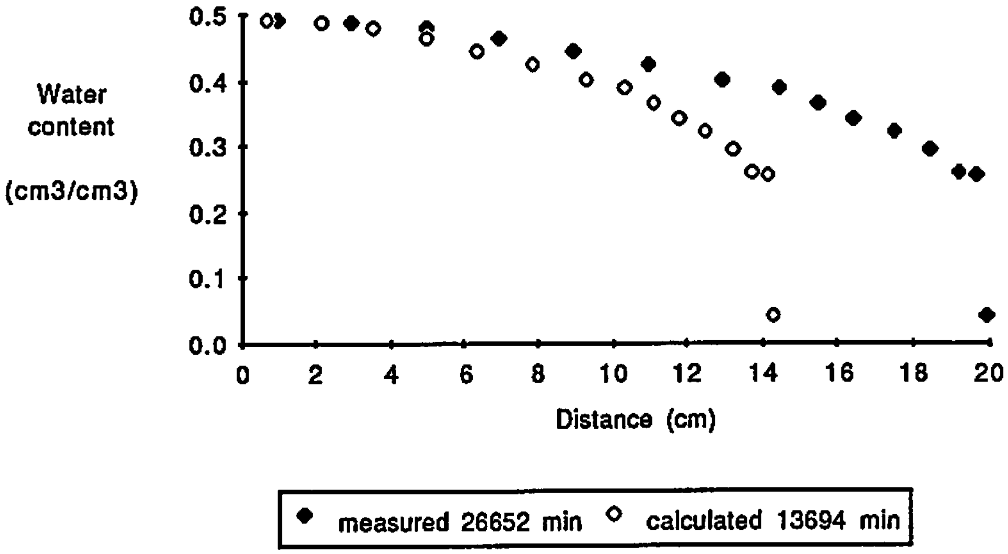


Figure 25: Soil-water diffusivity in soil columns treated with SAR 0.

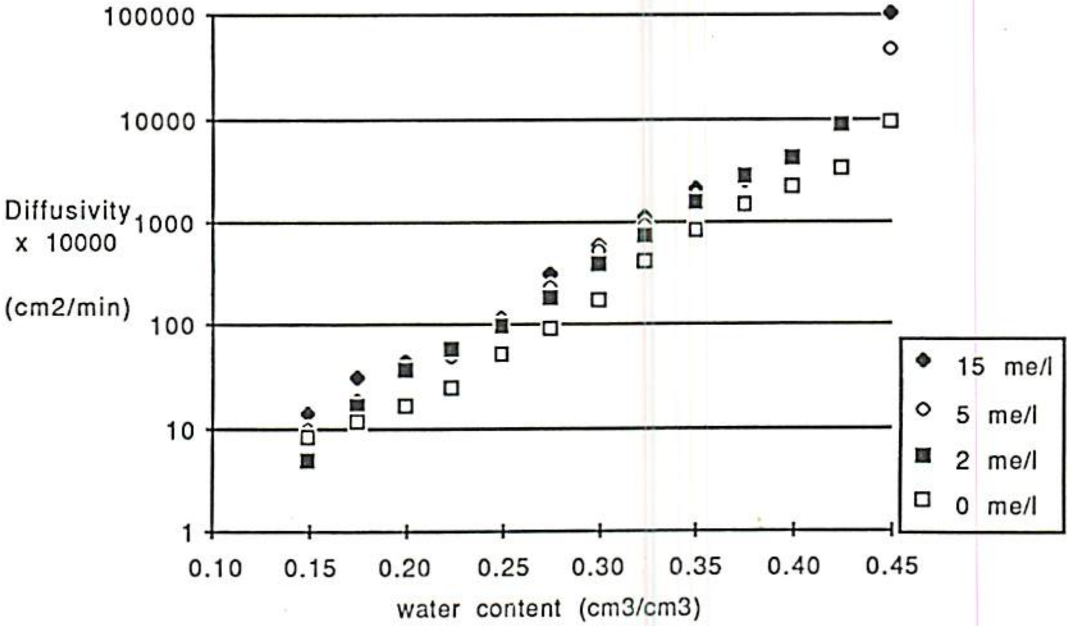


Figure 26: Soil-water diffusivity in soil columns treated with SAR 5.

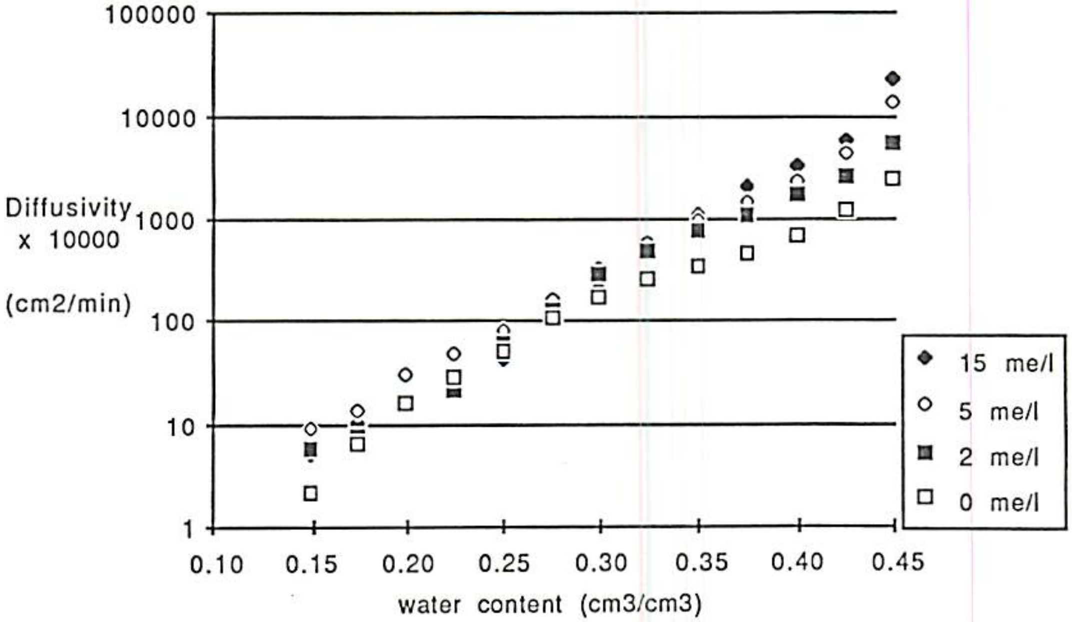


Figure 27: Soil-water diffusivity in soil columns treated with SAR 15.

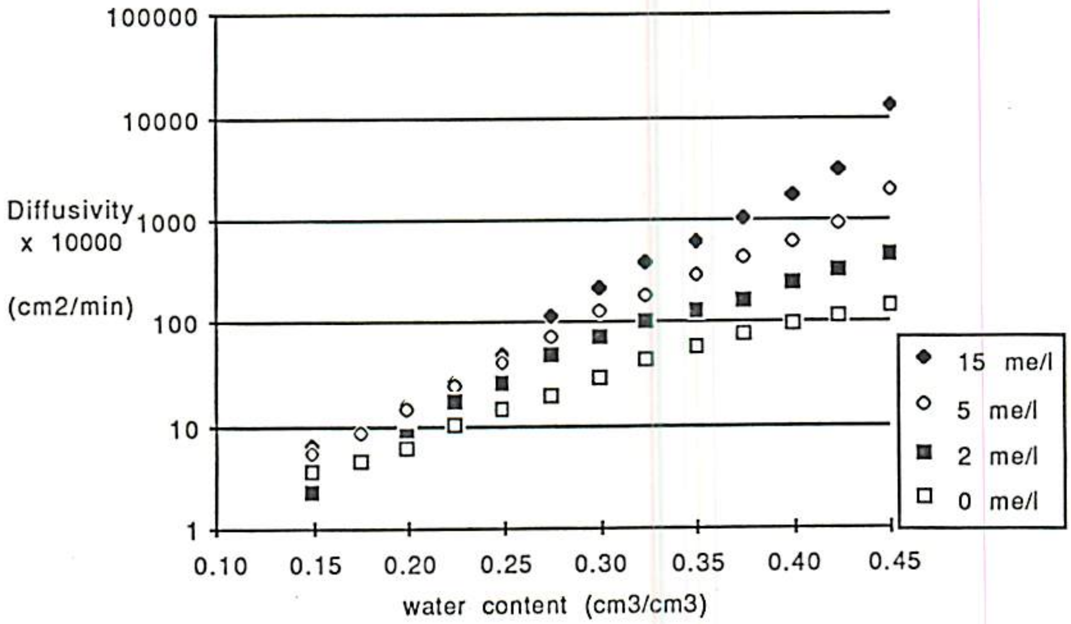


Figure 28: Total soluble salt concentration in soil columns treated with SAR 0, 5 or 15 and wetted with solution of 15 me/l.

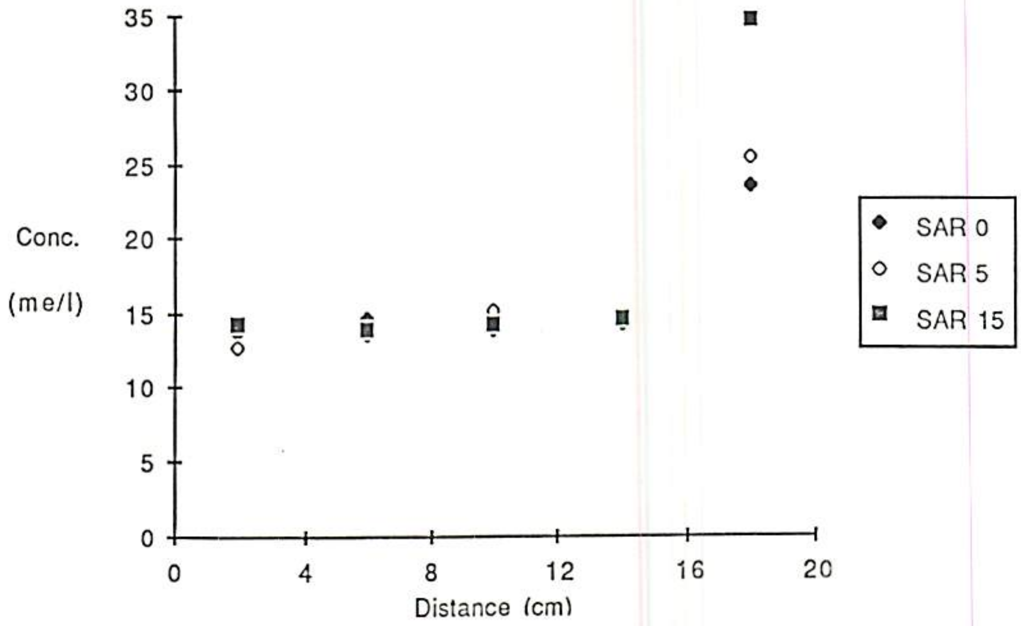


Figure 29: Total soluble salt concentrtation in soil columns treated with SAR 0, 5 or 15 and wetted with solution of 5 me/l.

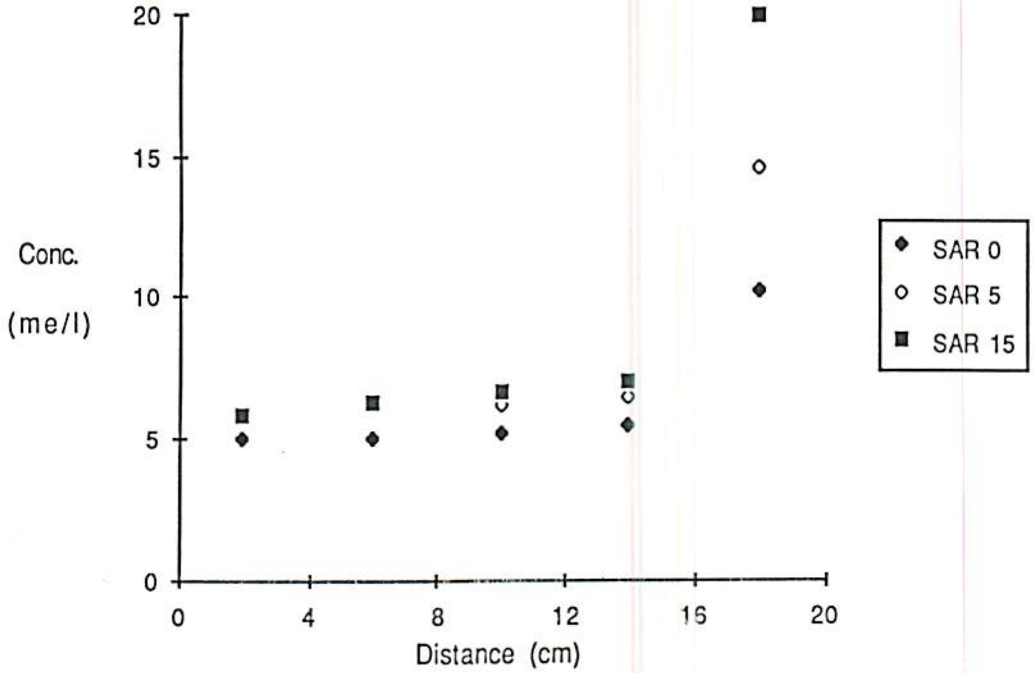


Figure 30: Total soluble salt concentration in soil columns treated with SAR 0, 5 or 15 and wetted with solution of 2 me/l.

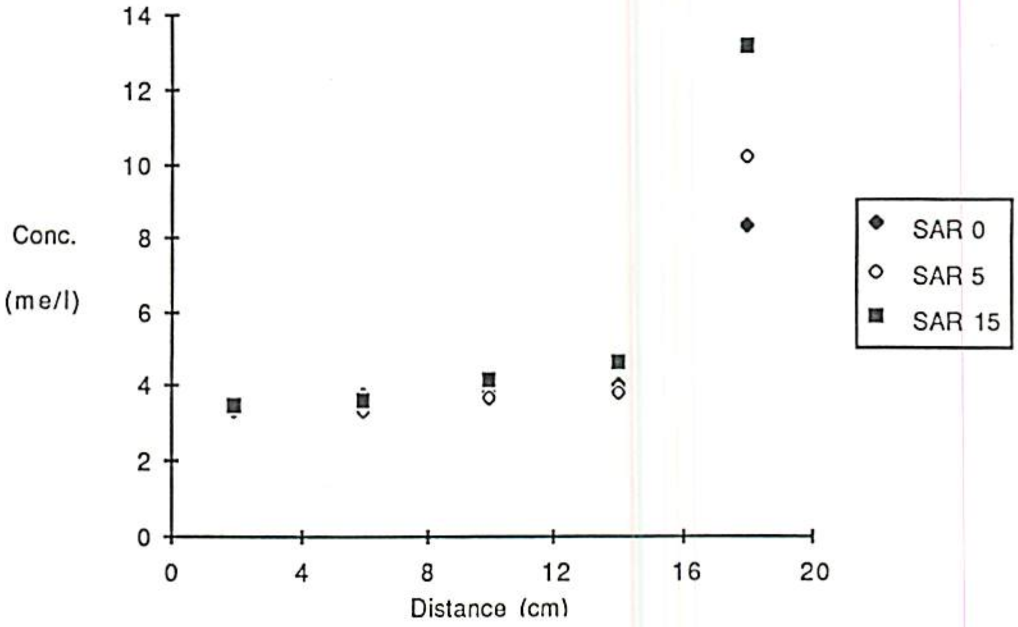


Figure 31: Total soluble salt concentration in soil columns treated with SAR 0, 5 or 15 and wetted with distilled water.

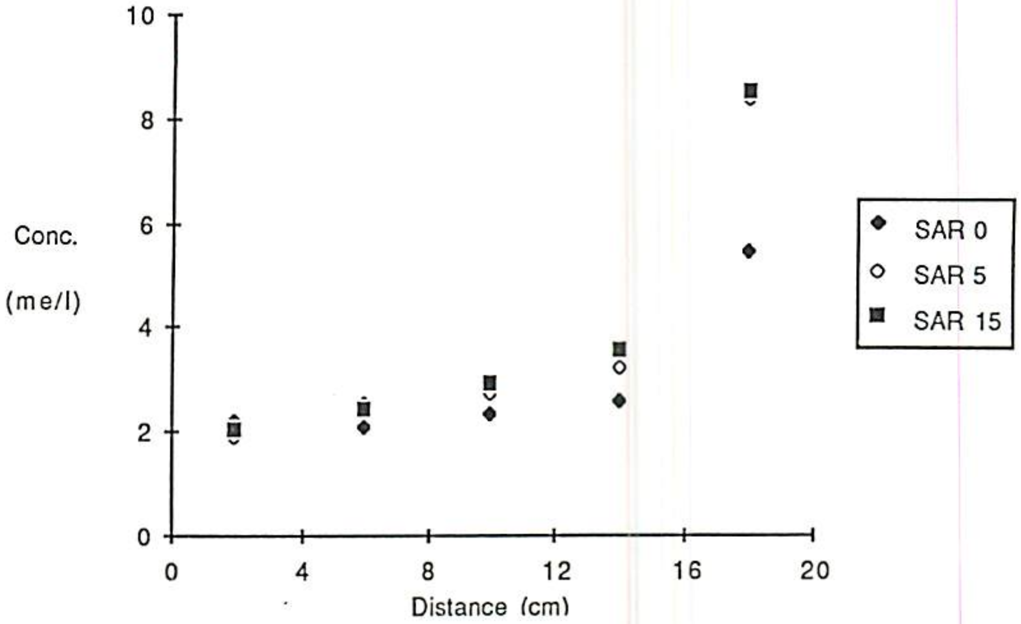


Figure 32: Soluble Na concentration after infiltration in soil columns treated with SAR 0.

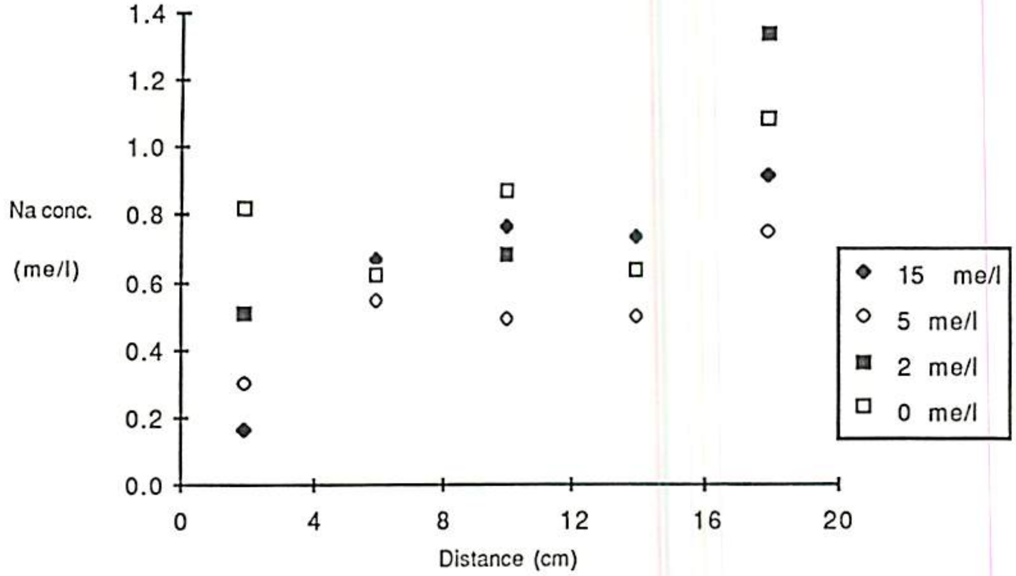


Figure 33: Soluble Na concentration after infiltration in soil columns treated with SAR 5.

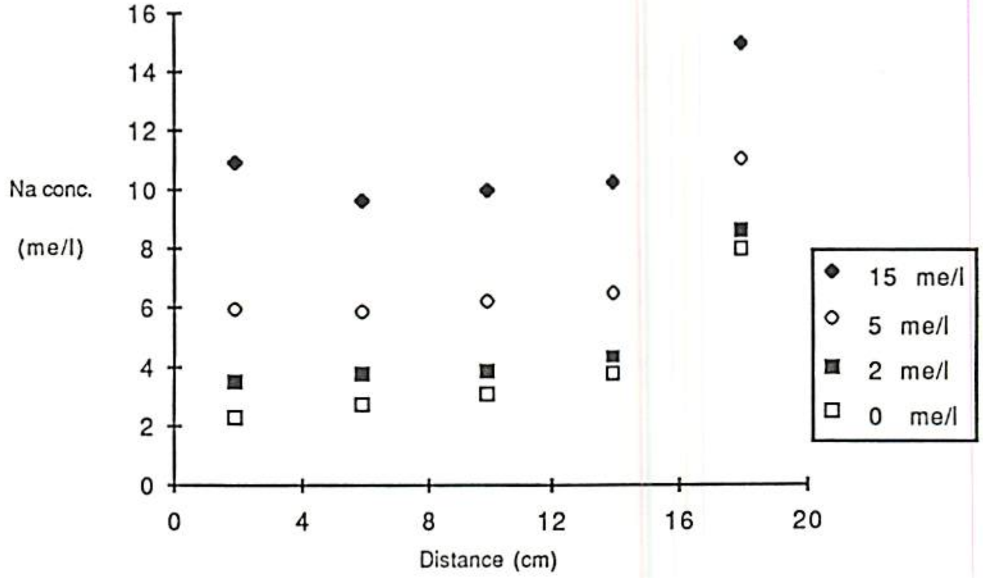


Figure 34: Soluble Na concentration after infiltration in soil columns treated with SAR 15.

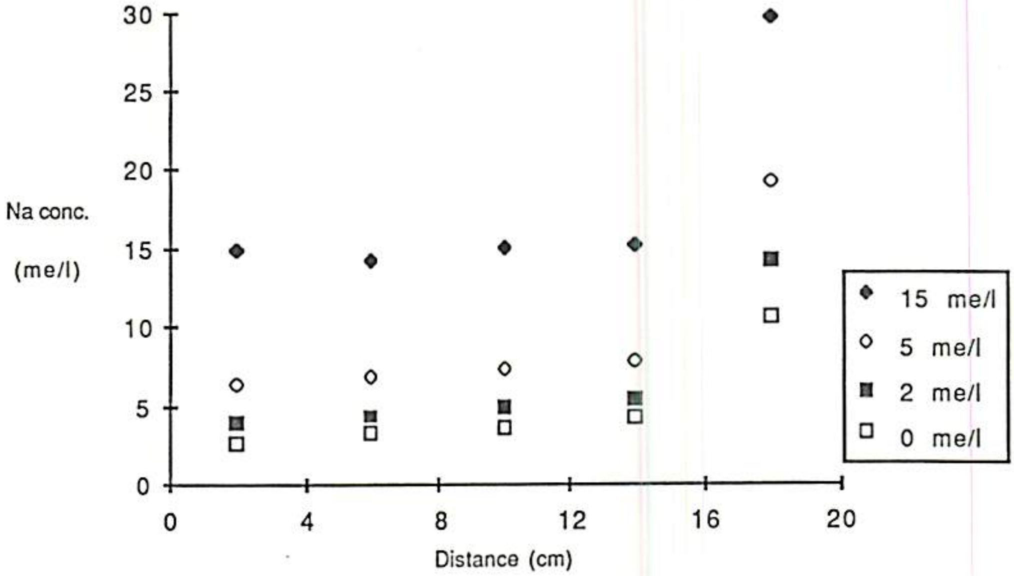


Figure 35: Soluble Ca concentration after infiltration in soil columns treated with SAR 0.

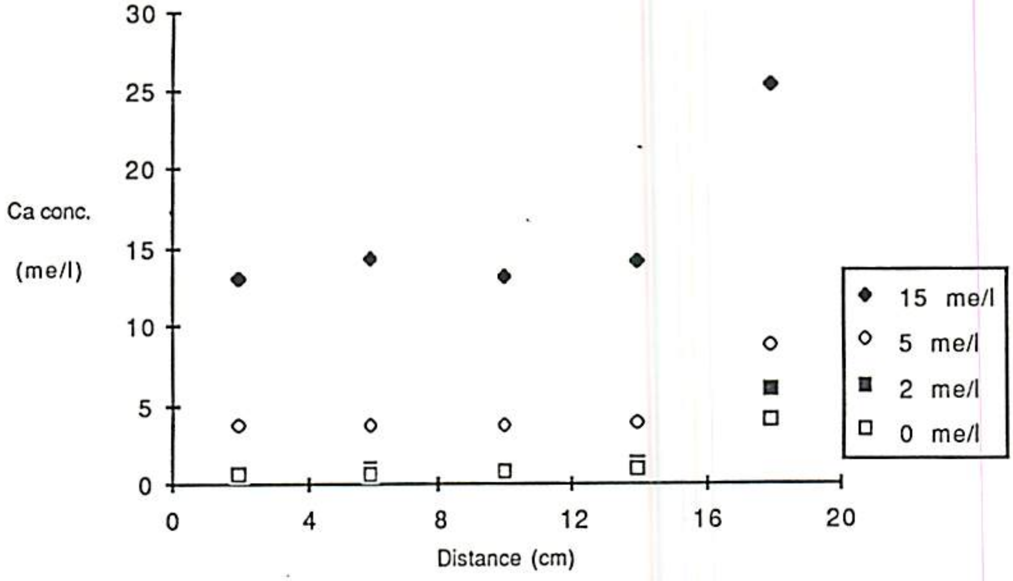


Figure 36: Soluble Ca concentration after infiltration in soil columns treated with SAR 5.

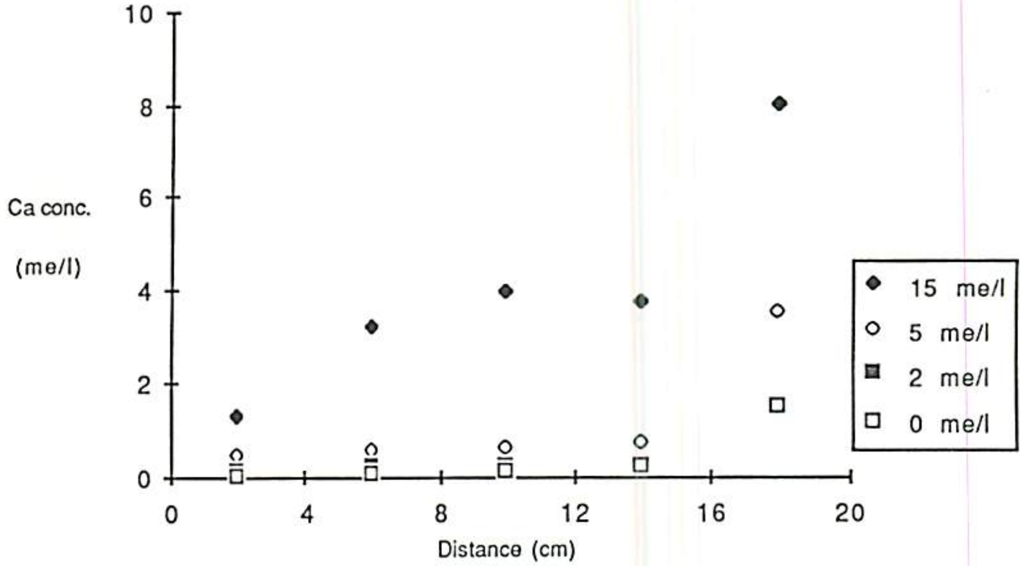


Figure 37: Soluble Ca concentration after infiltration in soil columns treated with SAR 15.

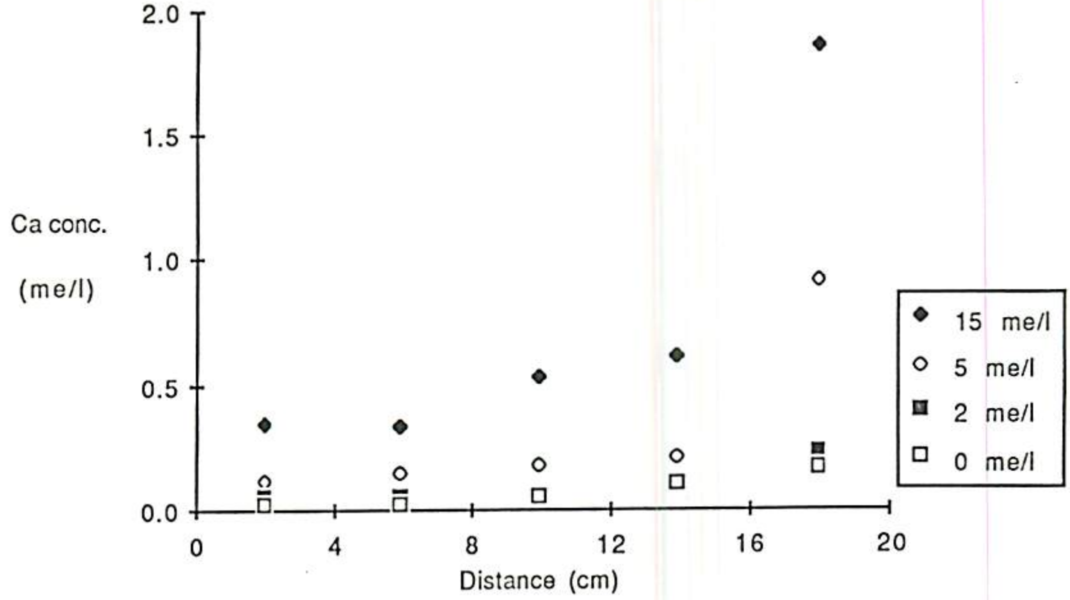


Figure 38: Na balance (measured - added) after infiltration in soil columns treated with SAR 5.

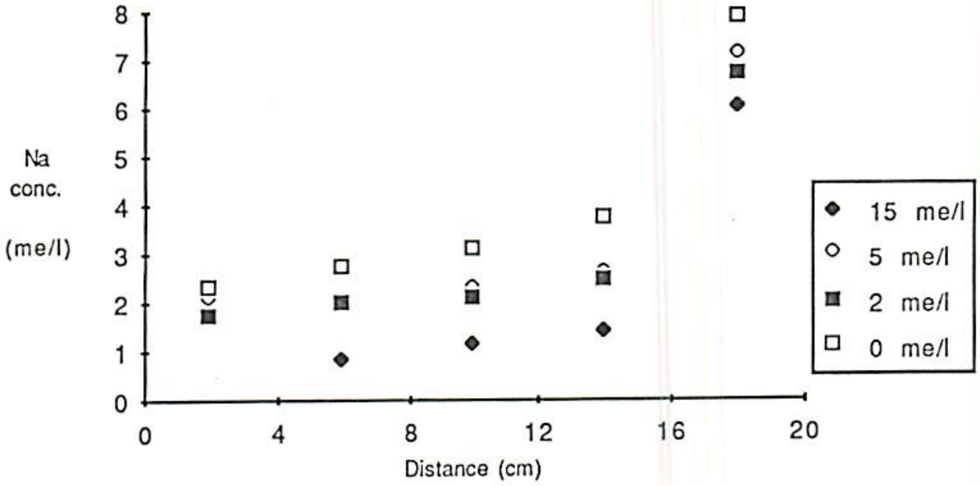


Figure 39: Na balance (measured - added) after infiltration in soil columns treated with SAR 15.

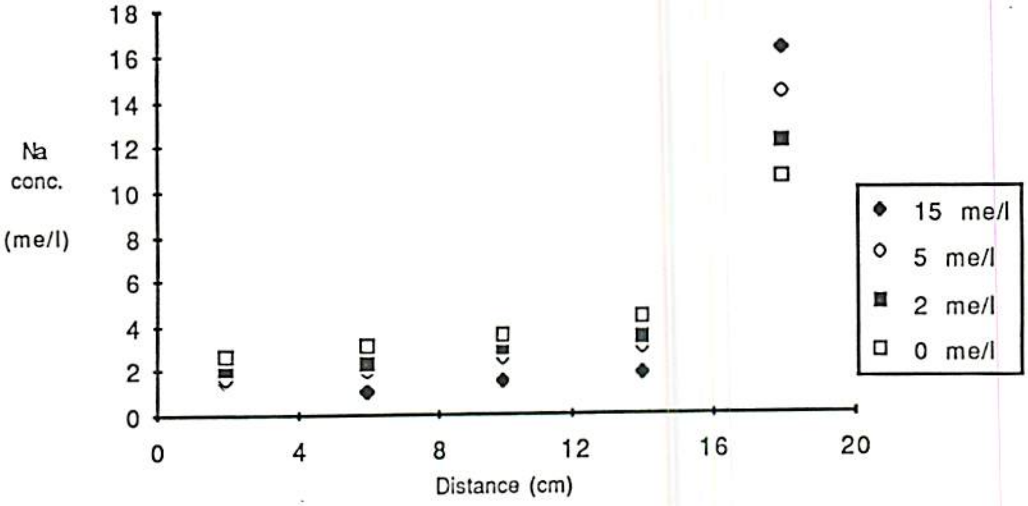


Figure 40: Ca balance (measured - added) after infiltration in soil columns treated with SAR 0.

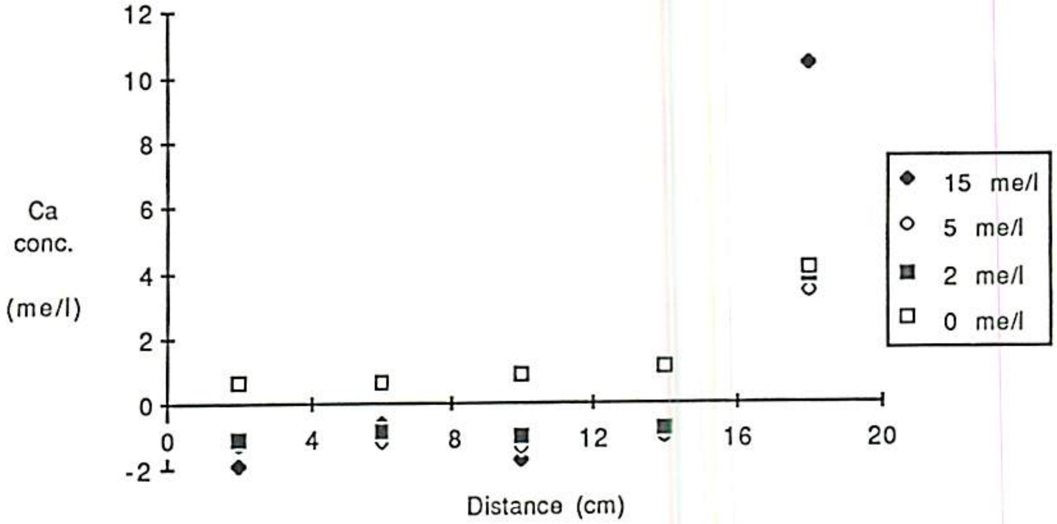


Figure 41: Ca balance (measured - added) after infiltration in soil columns treated with SAR 5.

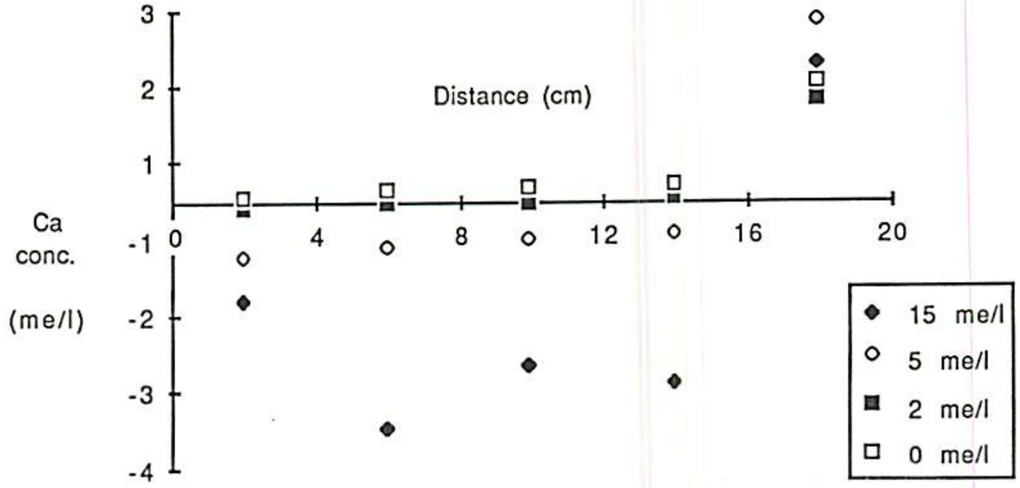


Figure 42: Ca balance (measured - added) after infiltration in soil columns treated with SAR 15.

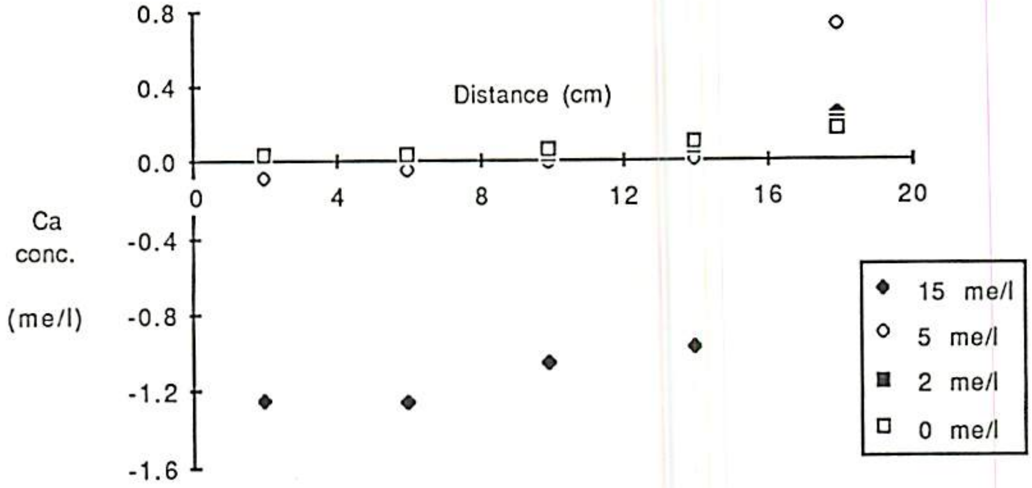
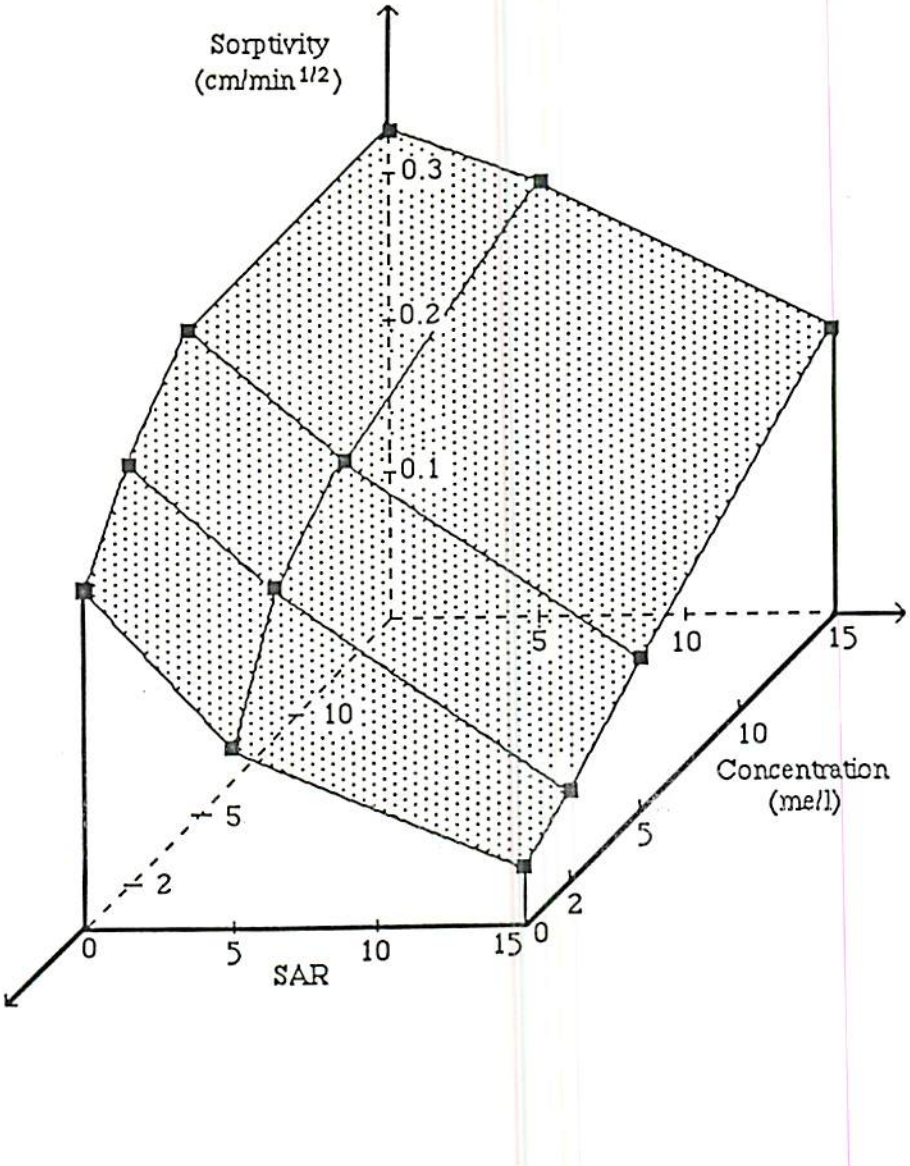


Figure 43: Sorptivity values of soil columns studied.



CONCLUSIONS

Soil-water diffusivity values in salt affected soils were determined by Bruce and Klute's method for irrigation waters of different compositions and concentrations. Observed changes in soil-water diffusivity were caused by sodium content in the soil profile or soil solution of low concentration. These changes, more pronounced at larger water content, were observed even in soils with low sodium content when low concentrated solutions were used to wet the soil. Therefore, irrigation waters with low salt concentration are expected to cause infiltration problems if insufficient salt is released by the soil. For example, rainwaters having salt concentration below 0.3 me/l (Hem, 1970), can, although in low magnitude, affect soil hydraulic properties.

Soil-water sorptivity can be severely affected by large sodium contents or low concentration of soil solution. Significant reductions were observed for soil columns treated with solutions with SAR 5 or 15 and wetted with solution concentrations lower than 15 me/l, while for Ca-saturated soils the changes were significant only when the soil solution concentration was lower than 5 me/l.

Use of Bruce and Klute's method can generate reliable and reproducible estimates of salt effects on soil-water diffusivity. Total validity of obtained values is questionable if the boundary conditions and assumptions involved in the method are significantly affected by changes in soil structure. No experimental procedures have yet been reported, however even for laboratory conditions, in which the method's theory was completely satisfied. For example, slight increases in temperature as a result of heat of wetting when water is adsorbed onto unsaturated soils are not accounted for by this method (Nielsen et al., 1972).

According to results obtained in the present work, precautions should be observed for long time infiltration studies used to determine soil-water diffusivity by Bruce and Klute's method. The method does not account for the participation of vapor movement in the soil-water diffusivity.

The choice of vacuum extraction to leach a soil sample for laboratory studies might not be successful. The unequal distribution of soil-water pressure through the soil sample, commonly imparted by those low suction extractors, results in non-uniform leaching with the sample bottom being leached more than the top. The measurement of effluent concentration for checking the leaching procedure in the present work was not very efficient since the collected solution did not represent the soil solution. In addition to intermittent applications of the leaching solution as proposed by Miller et al. (1965), the use of a porous plate attached to the bottom of the soil sample is suggested to assure an equal soil-water pressure distribution throughout the soil sample.

At field conditions, the use of sprinkler irrigation to impart more frequent wetting fronts in the unsaturated soil profile seems to be an effective way to leach salt affected soils. Irrigation practices that tend to keep the soil near saturation for long periods of time are not indicated for these soils.

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