

Hydraulic conductivity in response to exchangeable sodium percentage and solution salt concentration

Jefferson Luiz de Aguiar Paes², Hugo Alberto Ruiz³, Raphael Bragança Alves Fernandes⁴,
Maria Betânia Galvão dos Santos Freire⁵, Maria de Fatima Cavalcanti Barros⁶, Genelício Crusóe Rocha⁷

<http://dx.doi.org/10.1590/0034-737X201461050015>

ABSTRACT

Hydraulic conductivity is determined in laboratory assays to estimate the flow of water in saturated soils. However, the results of this analysis, when using distilled or deionized water, may not correspond to field conditions in soils with high concentrations of soluble salts. This study therefore set out to determine the hydraulic conductivity in laboratory conditions using solutions of different electrical conductivities in six soils representative of the State of Pernambuco, with the exchangeable sodium percentage adjusted in the range of 5-30%. The results showed an increase in hydraulic conductivity with both decreasing exchangeable sodium percentage and increasing electrical conductivity in the solution. The response to the treatments was more pronounced in soils with higher proportion of more active clays. Determination of hydraulic conductivity in laboratory is routinely performed with deionized or distilled water. However, in salt affected soils, these determinations should be carried out using solutions of electrical conductivity different from 0 dS m⁻¹, with values close to those determined in the saturation extracts.

Key words: saline soils, saline-sodic soils, exchangeable-sodium-percentage, soil solution electrical conductivity.

RESUMO

Condutividade hidráulica em resposta à saturação por sódio e concentração salina da solução

Para estimar o movimento de água no solo, determina-se, em laboratório, a condutividade hidráulica em meio saturado. Porém, os resultados dessa análise, ao se utilizar água destilada ou deionizada, podem não corresponder às condições de campo em solos que apresentem concentrações elevadas de sais solúveis. Por essa razão, determinou-se, em laboratório, utilizando-se soluções de trabalho de diferentes condutividades elétricas, a condutividade hidráulica de seis solos representativos do Estado de Pernambuco, com percentagem de saturação de sódio ajustada no intervalo de 5 a 30%. Os resultados evidenciaram que houve incremento nos valores de condutividade hidráulica, diretamente relacionado com a diminuição da percentagem de saturação de sódio e com o aumento da condutividade

Received: 04/25/2013; Approved: 02/26/2014.

¹ Part of the first author Master's Dissertation.

² Agronomist, Master of Science. Instituto Federal de Roraima, *Campus* Novo paraíso, BR-174, Km 512, Vila Novo Paraíso, s/n, 69360-000, Caracará, Roraima, Brasil. jefferson.paes@ifrr.edu.br (corresponding author).

³ Biochemist, Doctor of Science. Departamento de Solos, Universidade Federal de Viçosa, *Campus* Viçosa, Avenida Peter Henry Rolfs, s/n, 36570-000, Viçosa, Minas Gerais, Brasil. hruiz@ufv.br

⁴ Agronomist, Doctor of Science. Departamento de Solos, Universidade Federal de Viçosa, *Campus* Viçosa, Avenida Peter Henry Rolfs, s/n, 36570-000, Viçosa, Minas Gerais, Brasil. raphael@ufv.br

⁵ Agronomist, Doctor of Science. Departamento de Solos, Universidade Federal Rural de Pernambuco, *Campus* Recife, Avenida Dom Manoel de Medeiros, s/n, Dois Irmãos, 52171-030, Recife, Pernambuco, Brasil. betania@depa.ufrpe.br

⁶ Agronomist, Doctor of Science. Departamento de Solos, Universidade Federal Rural de Pernambuco, *Campus* Recife, Avenida Dom Manoel de Medeiros, s/n, Dois Irmãos, 52171-030, Recife, Pernambuco, Brasil. fatima@depa.ufrpe.br

⁷ Agronomist, Doctor of Science. Departamento de Solos, Universidade Federal de Viçosa, *Campus* Viçosa, Avenida Peter Henry Rolfs, s/n, 36570-000, Viçosa, Minas Gerais, Brasil. genelicio.rocha@ufv.br

elétrica na solução de trabalho. A resposta aos tratamentos foi mais acentuada nos solos com maiores proporções de argilas mais ativas. As determinações de condutividade hidráulica são realizadas com água deionizada ou destilada. No entanto, para solos afetados por sais, conclui-se que as análises deveriam ser realizadas com soluções com condutividades elétricas diferentes de 0 dS m^{-1} , utilizando-se valores próximos aos do extrato da pasta de saturação.

Palavras-chave: solos salinos, solos salino-sódicos, percentagem de sódio trocável, condutividade elétrica da solução do solo, extrato da pasta de saturação.

INTRODUCTION

In semiarid regions, salinization can negatively affect soil physical properties. One of the critical processes for soil structure is clay dispersion, which is often aggravated by the excess exchangeable sodium expressed by the exchangeable sodium percentage (ESP) (Spera *et al.*, 2008; Paes *et al.*, 2013).

In salt-affected soils, the solution salt concentration, usually expressed as electrical conductivity (EC), is very important for the phenomena of flocculation and dispersion because the action performed on the diffuse double layer (Gillman, 1974).

The soil hydraulic conductivity can be determined in the field or laboratory. The laboratory measurements are generally carried out using constant head permeameters. Klute & Dirksen (1986) emphasized that these analyzes provide approximate results and are recommended when the methodologies for evaluation in the field are impractical.

However, the results obtained in laboratory for salt-affected soils may differ greatly from those in the field.

The soil hydraulic conductivity can be underestimated in the lab mainly due to the dilution of the salt concentration in the soil solution, when distilled or deionized water as percolating solution.

Therefore, the use of percolating solution with EC similar to the saturated soil paste extract could enhance the accuracy of hydraulic conductivity analyses in laboratory. This possible inaccuracy in current determinations of soil hydraulic conductivity may mistakenly indicate the need for irrigation using water with higher EC and/or chemical amendments to preserve soil structure, which tends to increase salinization and raise production costs.

The objective of this study was therefore to determine the soil saturated hydraulic conductivity using solutions of different EC in six representative soils of the State of Pernambuco, with exchangeable sodium percentage (ESP) adjusted in the range 5-30%.

MATERIAL AND METHODS

The study was carried out in the Department of Soil Science, Universidade Federal de Viçosa, Viçosa, Minas Gerais, located in the geographic coordinates $20^{\circ} 45' \text{ S}$ e $42^{\circ} 51' \text{ O}$.

Soil samples were collected from one horizon of six representative soil profiles of the State of Pernambuco classified (Embrapa, 2006) as: Fluvisol - RY ($07^{\circ} 52' 21'' \text{ S}$ and $36^{\circ} 57' 49'' \text{ W}$); Haplic Luvisol - TX ($07^{\circ} 52' 29'' \text{ S}$ and $35^{\circ} 27' 01'' \text{ W}$); Albaqualf - SX ($08^{\circ} 21' 28'' \text{ S}$ and $36^{\circ} 10' 20'' \text{ W}$); Chromic Luvisol - TC ($08^{\circ} 30' 10'' \text{ S}$ and $39^{\circ} 19' 39'' \text{ W}$); Vertisol - VX ($07^{\circ} 37' 44'' \text{ S}$ and $40^{\circ} 03' 14'' \text{ W}$) and Argiluvic Chernosol - MT ($07^{\circ} 44' 32'' \text{ S}$ and $35^{\circ} 14' 04'' \text{ W}$). To avoid interference of organic matter, the samples were preferably collected in the B horizon, except for RY which, for not having this horizon, had the samples collected from A horizon.

The samples were air-dried, crushed, and passed through a 2-mm mesh sieve to obtain air-dry fine earth (ADFE). Part of these samples was separated for the assay and the other part was used for particle size analysis and chemical characterization of the soil studied (Tables 1, 2).

The treatments were arranged in a $6 \times 3 \times 3$ factorial design, as follows: six soil samples, three exchangeable sodium percentages (ESP): 5; 15 and 30% and three electrical conductivities (EC) of the percolating solution: 0.0; 0.6 and 1.2 dS m^{-1} . The experiment was arranged in a randomized block design with five replicates.

First, to achieve the ESP values, the Na:Ca ratio on the cation exchange complex of the soils was adjusted using constant head permeameters (Ferreira, 1999). The permeameters were made with PVC columns, diameter of approximately 5 cm and 14 cm long, bottom lid adapted with drainage system and lined with filter paper.

Each soil sample (ADFE) was carefully placed in the permeameter, using a glass rod to homogenize the soil distribution and avoid the formation of layers of different

densities, to a height of 9 cm. A glass wool disk was placed at the top of the column to avoid disturbances at the surface by the solutions.

The sodium adsorption ratio (SAR) of the NaCl + CaCl₂ solutions needed to achieve the exchangeable sodium percentages (ESP) were previously determined using Eq. (1) (Pereira *et al.*, 1982):

$$ESP = \frac{100 (-0.0135 + 0.0212 RAS)}{1 + (-0.0135 + 0.0212 RAS)} \quad (1)$$

The solutions used for adjusting the Na:Ca ratio (saturating solutions) were prepared to reach a final concentration of 50 mmol_c L⁻¹, using NaCl and CaCl₂, Eq. (2):

$$[Na^+] + [Ca^{2+}] = 50 \text{ mmol}_c \text{ L}^{-1} \quad (2)$$

This relatively high concentration allows a quick adjustment on the exchange complex. Thus, the [Na⁺] and [Ca²⁺] values were calculated by Eq. (3):

$$SAR = \frac{[Na^{2+}]}{\sqrt{[Ca^{2+}]/2}} \quad (3)$$

To carry out saturation in ascending order, the columns were placed in trays containing the saturating

solution, according to the treatment, to a height corresponding to two thirds of the height of the soil sample (6 cm), reducing to the maximum the air in the soil pore space. The saturation occurred for a period of 48 h (Freire *et al.*, 2003a).

The saturating solution was then applied, using constant head permeameters to reach the equilibrium, which was determined by the equal reading of the electrical conductivity between the effluent and the influent solutions.

After reaching the equilibrium of the different SAR values, using the NaCl + CaCl₂ solutions, the samples were removed from the permeameters, air-dried, crushed, and passed through a 2-mm mesh sieve to obtain ADFE. Subsequently, part of the sample was separated for the analysis and the other part was washed with isopropyl alcohol to remove the soluble salts and determination of ESP effectively achieved with the passage of the solutions (Table 3).

The ESP values observed were different from those expected. The differences observed were due to use of estimation by the equation established by Pereira *et al.* (1982), which was derived from to an average of all soils studied by these authors.

Before the determination of the hydraulic conductivity, the concentrated solutions (EC ≈ 5.0 dS m⁻¹)

Table 1. Particle size composition of soil samples

Characteristic	RY	TX	SX	TC	VX	MT
Coarse sand (g kg ⁻¹)	360	159	415	333	303	165
Fine sand (g kg ⁻¹)	216	388	112	190	203	100
Silt (g kg ⁻¹)	211	213	70	144	156	237
Clay (g kg ⁻¹)	213	240	403	333	338	498

RY = Fluvisol; TX = Haplic Luvisol; SX = Albaqualf; TC = Chromic Luvisol; VX = Vertisol; MT = Argiluvic Chernosol.

Table 2. Chemical characterization of soil samples

Characteristic	RY	TX	SX	TC	VX	MT
pH in water (1:2,5)	6.69	7.14	6.20	6.26	6.85	4.94
pH in KCl (1:2,5)	6.06	4.60	4.54	4.09	5.37	4.65
Δ pH	-0.63	-2.54	-1.66	-2.17	-1.48	-0.29
Ca ²⁺ (cmol _c kg ⁻¹)	8.31	11.98	0.88	6.95	5.67	4.00
Mg ²⁺ (cmol _c kg ⁻¹)	4.45	7.60	4.80	4.64	0.90	1.37
K ⁺ (cmol _c kg ⁻¹)	0.69	0.08	0.27	0.18	0.74	0.07
Na ⁺ (cmol _c kg ⁻¹)	1.37	0.35	1.00	0.25	0.03	0.17
Sum of bases (cmol _c kg ⁻¹)	14.83	20.00	6.94	12.02	7.34	5.62
(H+Al) (cmol _c kg ⁻¹)	0.00	0.60	4.40	0.00	2.40	2.90
CEC total (cmol _c kg ⁻¹)	14.83	20.00	11.34	12.02	9.74	8.52
CEC of clay fraction (cmol _c kg ⁻¹)	69.62	85.83	28.14	36.10	28.82	17.11
Exchangeable sodium percentage	9.30	1.80	14.40	2.10	0.40	3.00
Electrical conductivity 1:1 (dS m ⁻¹)	5.65	2.82	0.40	0.25	0.24	0.30
Organic C (g kg ⁻¹)	8.60	6.30	4.00	6.70	2.80	9.20
Remaining P (mg L ⁻¹)	48.08	40.59	45.52	41.26	41.02	10.93

RY = Fluvisol; TX = Haplic Luvisol; SX = Albaqualf; TC = Chromic Luvisol; VX = Vertisol; MT = Argiluvic Chernosol.

were diluted with deionized water to reach the working values of 0.6 and 1.2 dS m⁻¹. The treatment 0 dS m⁻¹ was carried out only with deionized water. In this article, the use of the term “working solution” is based on the consideration that distilled or deionized water can be considered as infinitely diluted solutions.

The procedures for determining the hydraulic conductivity followed the routine of Soil Physics Laboratory, Department of Soil Science-UFV, adapted from EMBRAPA (2011), since the hydraulic conductivity was determined in samples of ADFE.

To facilitate the visualization of changes in hydraulic conductivity with the treatments, we determined the relative hydraulic conductivity (Freire *et al.*, 2003a) by assigning the unit to the maximum mean hydraulic conductivity of each soil.

Means of hydraulic conductivity and relative hydraulic conductivity were analyzed statistically. The analysis of variance grouped the soils, after testing the homogeneity of variances. The eight degrees of freedom for ESP of the soil and EC of the working solution were analyzed by orthogonal contrasts. In the presentation of the results, we used mean contrasts calculated by dividing the numerical value of the contrasts by the sum of the modules of the coefficients divided by two (Alvarez & Alvarez, 2006). However, in the discussion of these results, we indicated statistical difference for contrasts significant at 5% and the term “trend” for contrasts significant between 5 and 20%.

RESULTS AND DISCUSSION

The means of saturated hydraulic conductivity and relative hydraulic conductivity are shown in Tables 4 and 5.

The analysis of variance showed no homogeneity of variances in hydraulic conductivity for all soils studied and thus it was not possible to carry out the test of comparison of means. The non-homogeneity of variances can be attributed to the disparity of hydraulic conductivity values of some soils.

However, the standardization by calculating the relative hydraulic conductivity, produced homogeneity of variances between the soils and allowed the comparison of means by the Scott-Knott test ($p < 0.05$) (Table 6).

There was greater mean relative hydraulic conductivity for the Argiluvic Chernosol. This result can be explained, at least partially, by the higher degree of weathering of this soil compared to the others in this study, with significant amount of iron oxides in the clay fraction (Freire *et al.*, 2003b). The sample collection of the Argiluvic Chernosol was performed in the “Zona da

Mata” region of Pernambuco, with higher rainfall rates than the northeastern semi-arid region, where the other soils were collected. It also has ΔpH closer to zero (Table 2). These characteristics are important for charge balance and, consequently, for particle flocculation.

Of the remaining five soils with higher proportion of active clay, i.e., clay CEC > 27 cmol_c kg⁻¹ (Table 2), the Albaqualf showed the highest relative hydraulic conductivity (Table 6). This result can be attributed, at least partially, to a greater proportion of coarse sand (Table 1), which, according to Santos & Ribeiro (2000), contributes to increase in macroporosity and, consequently, increase in hydraulic conductivity.

The remaining four soils, Haplic Luvisol, Fluvisol, Vertisol and Chromic Luvisol, showed no statistically significant differences in the relative hydraulic conductivity (Table 6). This lack of difference can be attributed to similarities in their particle size distribution (Table 1), remaining P values, ΔpH (Table 2) and the mineralogical composition of the clay fraction (Freire *et al.*, 2003b; Cunha, 2010), with predominance of highly active clay minerals (Table 2).

Because of the disparity observed in ESP values after adjustment (Table 3), we used in the discussion, the pre-established values of 5, 10 and 15%. When comparing results of hydraulic conductivity and relative hydraulic conductivity in response to treatments, we used the orthogonal contrasts in Table 7. As described in the section Material and Methods, the term “trend” will be used for significant differences in the range of 5 to 20%.

The significances of the contrasts, in relation to the results of the hydraulic conductivity and relative hydraulic conductivity, are similar. This similarity occurs because the calculation of the relative hydraulic conductivity is the result of the ratio between the hydraulic conductivity and a constant, corresponding to the maximum mean value of hydraulic conductivity for each soil.

The contrasts C1 and C2 evaluated the response of the soils to sodium saturation. There were differences for the Fluvisol, Haplic Luvisol, Albaqualf, Chromic Luvisol and Vertisol when comparing ESP at 5, 15 and 30%, with reduction in hydraulic conductivity and relative hydraulic conductivity with increasing exchangeable sodium content (Table 7).

The soils mentioned above showed a marked content of clay minerals type 2:1, such as illite and smectite (Freire *et al.*, 2003b; Cunha, 2010). According to McNeal & Coleman (1966), soils with predominant highly active minerals are more susceptible to the dispersive effect caused by sodium, which may favor clay dispersion, clogging of pores and the consequent reduction of hydraulic conductivity.

The Argiluvic Chernosol showed no response to the different proportions of exchangeable sodium (Table 7), indicating that its physical properties, related to the water flow, remained preserved, even for a high ESP. This result, as already mentioned, is probably linked to the mineralogical composition and the degree of weathering of the soil, with a strong presence of hematite in the clay fraction (Freire *et al.*, 2003b).

The contrasts C3 to C8 (Table 7) compare the EC of the working solutions for each soil and ESP; the odd numbers relate 1.2 dS m⁻¹ with 0 and 0.6 dS m⁻¹, and the even numbers relate 0.6 dS m⁻¹ with 0 dS m⁻¹. In general, there is an increase in hydraulic conductivity and, hence, in the relative hydraulic conductivity with increasing EC.

The analysis of the individual behavior of each soil in relation to the different working solutions, based on

the significances of the contrasts C3 to C8 (Table 7), showed for the Fluvisol that, regardless of ESP values (5, 15 and 30%), differences occurred only when comparing the working solution with the highest salt concentration (EC = 1.2 dS m⁻¹) with solutions of lower EC values (0 and 0.6 dS m⁻¹).

The Fluvisol showed no significant differences in the comparison between the percolating solutions of lower salt concentration (0 vs. 0.6 dS m⁻¹), suggesting that, when affected by sodicity problems (ESP > 5%), a value considered as critical by McIntyre (1979), it would be necessary to use irrigation water with EC greater or equal to 1.2 dS m⁻¹. This procedure, in field conditions, will probably preserve the structure of the soil and, hence, increase the hydraulic conductivity, decreasing the risk of reduction in permeability.

Table 3. Exchangeable sodium percentage (ESP) determined in soil samples after equilibration with NaCl and CaCl₂ solutions

Soil	ESP		
	5	15	30
		(%)	
Fluvisol	9.4	17.8	36.0
Haplic Luvisol	6.8	18.7	34.0
Albaqualf	7.8	20.0	35.8
Chromic Luvisol	5.6	20.5	31.6
Vertisol	8.3	22.0	34.2
Argiluvic Chernosol	6.0	16.9	28.6

Table 4. Saturated hydraulic conductivity (K₀), considering exchangeable sodium percentage (ESP) and electrical conductivity (EC) of the solution

Soil	PST (%)			
	CE	5	15	30
	dS m ⁻¹	K ₀ (cm h ⁻¹)		
Fluvisol	0	0.6750	0.1130	0.0970
	0.6	0.6449	0.2350	0.1150
	1.2	0.7865	0.4213	0.2500
Haplic Luvisol	0	1.1865	0.2660	0.0528
	0.6	0.9557	0.8596	0.3775
	1.2	1.5004	0.9374	0.4482
Albaqualf	0	0.3805	0.1853	0.0572
	0.6	0.6088	0.3672	0.2106
	1.2	0.6282	0.7140	0.4684
Chromic Luvisol	0	0.0798	0.0000	0.0000
	0.6	0.1750	0.0769	0.0474
	1.2	0.2115	0.1018	0.0483
Vertisol	0	0.3158	0.1551	0.0860
	0.6	0.6960	0.2916	0.1131
	1.2	0.7560	0.4333	0.1363
Argiluvic Chernosol	0	1.3519	1.3989	1.3273
	0.6	1.5720	1.6678	1.7939
	1.2	1.9039	1.6749	1.3244

Table 7 shows that the Haplic Luvisol responded in a similar way as the Fluvisol to the treatment with the lowest ESP, adjusted to 5%. For the other ESPs, there was a marked increase in hydraulic conductivity with the increase in salt concentration.

The Albaqualf responded to the increases in EC (Table 7). For all ESP values, there were significant differences or trends in the comparison of solutions with different EC values (0, 0.6, and 1.2 dS m⁻¹) (C3-C8), showing increases in hydraulic conductivity and relative hydraulic conductivity with increasing salt concentration in the working solutions.

The Chromic Luvisol behaved in a similar way as the Albaqualf, considering the significance of the contrasts. However, at ESP of 30%, no differences were observed when comparing the solutions of low electrical conductivity (0 and 0.6 dS m⁻¹) with the solution with EC = 1.2 dS m⁻¹ (C7); whereas there was difference with the use of solutions with lower salt concentrations (0.6 vs 0 dS m⁻¹, C8).

This result suggests that, since there was complete pore obstruction, leading to null values of hydraulic conductivity when using only deionized water (Table 4), the solutions with EC at 1.2 dS m⁻¹ allowed better soil water flow. However, these EC values (0.6 and 1.2 dS m⁻¹) were not high enough to prevent the soil remain with values considered critical for hydraulic conductivity, that is, with hydraulic conductivity <0.1 cm h⁻¹ (McIntyre, 1979) (Table 4).

The Vertisol showed responses to increases in solution salt concentrations up to ESP of 15%. There was no difference between the solutions (C7 and C8) by adjusting the soil to ESP equal to 30%.

From the foregoing, therefore, the EC range of working solutions used in this study corresponds to moderate or no risk of salinization caused by irrigation water (Ayers & Westcott, 1994). However, the ESP adjusted to 30% is more than twice the limit established by Richards (1954), which characterizes the soil as sodic.

This fact suggests that high EC values, higher than those indicated as moderate risk of salinity, should be maintained, at least in this soil, in order to increase the ionic strength of the solution, minimizing the dispersive effect of sodium at high ESP values.

Table 6. General means of relative saturated hydraulic conductivity of soils under study compared by the Scott-Knott test

Soil	Relative hydraulic conductivity ^{1/}
Argiluvic Chernosol	0.8180 A
Albaqualf	0.5640 B
Haplic Luvisol	0.4880 C
Fluvisol	0.4710 C
Vertisol	0.4390 C
Chromic Luvisol	0.3890 C

^{1/} Different letters indicate statistically significant differences at 0.05 by the Scott-Knott test.

Table 5. Saturated relative hydraulic conductivity (K_{OR}), considering the exchangeable sodium percentage (ESP) and electrical conductivity of the solution (EC)

Soil	CE dS m ⁻¹	ESP (%)		
		5	15	30
		K_{OR}		
Fluvisol	0	0.8580	0.1430	0.1230
	0.6	0.8200	0.2980	0.1460
	1.2	1	0.5360	0.3180
Haplic Luvisol	0	0.7910	0.1770	0.0350
	0.6	0.6370	0.5730	0.2520
	1.2	1	0.6250	0.2990
Albaqualf	0	0.4390	0.214	0.0660
	0.6	0.7020	0.423	0.2430
	1.2	0.7240	1	0.5400
Chromic Luvisol	0	0.3770	0.000	0.0000
	0.6	0.8280	0.3640	0.2240
	1.2	1	0.4810	0.2280
Vertisol	0	0.4090	0.2010	0.1140
	0.6	0.9210	0.3770	0.1460
	1.2	1	0.5610	0.1760
Argiluvic Chernosol	0	0.7100	0.7350	0.6970
	0.6	0.8260	0.8760	0.9420
	1.2	1	0.8800	0.6960

Table 7. Mean orthogonal contrasts (C) of saturated hydraulic conductivity and relative saturated hydraulic conductivity of soils under study, considering the exchangeable sodium percentage (ESP) and soil electrical conductivity (EC) of the working solution^{1/}

ESP %	EC dS m ⁻¹	C1	C2	C3	C4	C5	C6	C7	C8	CV %
5	0	2	0	-1	-1	0	0	0	0	
	0.6	2	0	-1	1	0	0	0	0	
	1.2	2	0	2	0	0	0	0	0	
15	0	-1	1	0	0	-1	-1	0	0	
	0.6	-1	1	0	0	-1	1	0	0	
	1.2	-1	1	0	0	2	0	0	0	
30	0	-1	-1	0	0	0	0	-1	-1	
	0.6	-1	-1	0	0	0	0	-1	1	
	1.2	-1	-1	0	0	0	0	2	0	
Saturated hydraulic conductivity (cm h⁻¹)										
Fluvisol		0.497*	0.102#	0.127#	-0.030	0.247*	0.122	0.144#	0.018	43
Haplic Luvisol		0.724*	0.395*	0.429*	-0.231	0.375#	0.594*	0.233#	0.325#	28
Albaqualf		0.205*	0.177*	0.134#	0.228*	0.437*	0.182#	0.335*	0.153#	43
Chromic Luvisol		0.110*	0.028#	0.084*	0.095*	0.063*	0.077*	0.025	0.047#	51
Vertisol		0.386*	0.181*	0.250*	0.380*	0.210*	0.137#	0.037	0.027	43
Argiluvic Chernosol		0.078	0.099	0.442*	0.220	0.141	0.269#	-0.236#	0.467*	28
Relative saturated hydraulic conductivity										
Fluvisol		0.632*	0.130#	0.161#	-0.038	0.314*	0.155	0.183#	0.022	41
Haplic Luvisol		0.483*	0.263*	0.286*	-0.154	0.250*	0.396*	0.155#	0.216#	41
Albaqualf		0.288*	0.248*	0.187#	0.320*	0.613*	0.255#	0.469*	0.215#	41
Chromic Luvisol		0.519*	0.131#	0.397*	0.450*	0.299*	0.364*	0.116	0.224#	41
Vertisol		0.511*	0.240*	0.331*	0.503*	0.278*	0.181#	0.048	0.035	41
Argiluvic Chernosol		0.041	0.052	0.232*	0.116	0.074	0.141	-0.124	0.245#	41

^{1/} C1: ESP 5% vs 15 and 30%. C2: ESP 15% vs 30%. C3: EC 1.2 dS m⁻¹ vs 0 and 0.6 dS m⁻¹ d/ESP 5%. C4: EC 0.6 dS m⁻¹ vs 0 dS m⁻¹ d/ESP 5%. C5: EC 1.2 dS m⁻¹ vs 0 and 0.6 dS m⁻¹ d/ESP 15%. C6: EC 0.6 dS m⁻¹ vs 0 dS m⁻¹ d/ESP 15%. C7: EC 1.2 dS m⁻¹ vs 0 and 0.6 dS m⁻¹ d/ESP 30%. C8: EC 0.6 dS m⁻¹ vs 0 dS m⁻¹ d/ESP 30%.

*e #: Significant at 0.05 and 0.2 by the F test.

The Argiluvic Chernosol showed no marked responses to EC increase in the percolating solutions, at lower ESP values (Table 7). However, there is a trend of reduced hydraulic conductivity in C8, due to the high proportion of exchangeable sodium and the use of deionized water in the working solution. It is noteworthy that the relative hydraulic conductivity of this soil was the highest, considering the six soils studied (Table 6), which indicates less variation of hydraulic conductivity with the treatments.

As discussed before, the weather conditions, with a predominance of constant rain and high rainfall rates in the “Zona da Mata” region of Pernambuco, where this soil was collected, and the possible presence of stable microaggregates were probably the main reason for the less interference of sodium and EC of the working solution in the hydraulic conductivity.

It appears, therefore, that for less weathered soils with a predominance of high activity clay and with salinity problems, a more time consuming but appropriate analysis should take into account the EC of the saturation extract and the proportion of Na in the cation exchange complex.

In order to simplify the analysis, the EC of the saturation extract could be replaced by the EC of the extract 1:1 and double this value to use it in the working solution (EC_{ST}). The exchangeable cation values would be used to calculate the $Na/(Ca + Mg + K)$ ratio, and this ratio would indicate the proportions for the preparation of the $NaCl + CaCl_2$ solutions, expressed as $mmol_c L^{-1}$, which would be adjusted to the CE_{ST} used to determine the hydraulic conductivity.

CONCLUSIONS

The increase in the exchangeable sodium percentage and decrease in the electrical conductivity of working solution are directly related to the reduction in the saturated hydraulic conductivity.

The response to the variation in the exchangeable sodium percentage and the variation in the electrical conductivity of the percolation solution was more pronounced in soils with higher proportions of active clays.

Measurements of saturated hydraulic conductivity in salt-affected soils must be carried out with solutions of electrical conductivity different from $0 dS m^{-1}$, using values close to those of the saturated soil part extract.

REFERENCES

Alvarez V VH & Alvarez GAM (2006) Comparação de médias ou teste de hipóteses? Viçosa, SBCS/UFV. 42p. (Boletim Informativo, 31).
Ayers RS & Westcot DW (1994) Water quality for agriculture. 3ªed. Roma, FAO. 174p.

Cunha JC (2010) Comparação de dispersantes químicos na análise granulométrica de solos do estado de Pernambuco. Dissertação de Mestrado. Viçosa, Universidade Federal de Viçosa. 67p.
Embrapa – Empresa Brasileira de Pesquisa Agropecuária (2006) Sistema Brasileiro de Classificação de Solos. 2ªed. Rio de Janeiro, Embrapa-SPI. 306p.
Embrapa - Empresa Brasileira de Pesquisa Agropecuária (2011) Manual de métodos de análise de solo. 2ªed. Rio de Janeiro, Ministério da Agricultura e do Abastecimento. 230p.
Ferreira PA (1999) Drenagem de terras agrícolas. Viçosa, Universidade Federal de Viçosa. 187p.
Freire MBGS, Ruiz HA, Ribeiro MR, Ferreira PA, Alvarez VVH & Freire FJ (2003a) Condutividade hidráulica de solos de Pernambuco em resposta à condutividade elétrica e RAS da água de irrigação. Revista Brasileira de Engenharia Agrícola e Ambiental, 7:45-52.
Freire MBGS, Ruiz HA, Ribeiro MR, Ferreira, PA, Alvarez VVH & Freire FJ (2003b) Estimativa do risco de sodificação de solos de Pernambuco pelo uso de águas salinas. Revista Brasileira de Engenharia Agrícola e Ambiental, 7:227-232.
Gillman GP (1974) The influence of net charge on water dispersible clay and sorbed sulphate. Australian Journal of Soil Research, 12:173-176.
Klute A & Dirksen C (1986) Hydraulic conductivity and diffusivity: laboratory methods. In: Klute, A. (eds.) Methods of soil analysis: Part 1. Physical and mineralogical methods. Madison, American Society of Agronomy - Soil Science Society of America. p.687-732.
Mcneal BL & Coleman NT (1966) Effect of solution composition on soil hydraulic conductivity. Soil Science Society of America, 30:308-312.
Mcintyre DS (1979) Exchangeable sodium, subplasticity and hydraulic conductivity of some Australian soils. Australian Journal of Soil Research, 17:115-120.
Paes JLA, Ruiz HA, Fernandes RBA, Freire MBGS, Barros MFC & Rocha GC (2013) Dispersão de argilas em solos afetados por sais. Revista Brasileira de Engenharia Agrícola e Ambiental, 17:1135-1142.
Pereira FAM, Medina BF, Gheyi HR & Etchevers JD (1982) Solos afetados por sais no Nordeste. II. Correlação entre sódio solúvel e intercambiável. Revista Brasileira de Ciência do Solo, 6:167-170.
Richards LA (1954) Diagnosis and improvement of saline and alkali soils. Washington, USDA. 160p. (Agriculture Handbook, 60).
Santos EEF & Ribeiro MR (2000) Influência da irrigação e do cultivo nas propriedades de um latossolo e um argilossolo da região dosubmédio São Francisco: atributos morfológicos e físicos. Revista Brasileira de Ciência do Solo, 24:875-884.
Spera ST, Denardin JE, Escosteguy PAV, Santos HP & Figueroa EA (2008) Dispersão de argila em microagregados de solo incubado com calcário. Revista Brasileira de Ciência do Solo, 32:2613-2620.