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INFLUENCE OF ELECTROLYTE CONCENTRATION, SODIUM ADSORPTION RATIO AND CATION COMBINATIONS ON RELATIVE SATURATED HYDRAULIC CONDUCTIVITY OF SALINE SOIL

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Soil hydraulic conductivity (*K*) is an important parameter in the transport of water and salts in the soils. This study was performed to determine the influence of water quality parameters flowing through the soil on the relative saturated hydraulic conductivity (*rKs*) of salt affected soil. Its aim was to examine the effect of electrolyte concentration at different SAR (sodium adsorption ratio) values of Na–Ca and Na–Mg leaching solutions on changes in *rKs* of saline soil. The experiments were conducted under laboratory conditions in packed soil columns with saline soil from the Jatov locality, Slovakia. The leaching solutions at SAR values of 5, 10, 20, 30, 40 and at the concentrations of Na–Ca and Na– Mg binary electrolytes of 20, 40, 60, 100 and 120 mmol l^{-1} were used. The concentration and composition of the water flowing through the soil showed a significant influence on relative saturated hydraulic conductivity of the soil used in the experiments. The results of the measurements indicated a decrease in *rKs* by gradually decreasing the electrolyte concentration and with increasing SAR values of the percolating electrolytes of both cationic pair Na–Ca and Na–Mg. The laboratory experiments also showed that the values of *rKs* of the soil measured with Na–Ca solutions were higher than those measured with Na–Mg solutions.

KEY WORDS: electrolyte concentration, sodium adsorption ratio, calcium, sodium and magnesium cation, relative saturated hydraulic conductivity, saline soil

Introduction

Soil salinity and sodicity are serious environmental hazards that can limit agricultural production and cause destructive soil degradation. These problems are especially high in arid and semiarid areas, where the poor quality water is often used for irrigation. The substances dissolved in irrigation water in different ways affect the soil properties (physical, chemical, microbiological), the growth and development of plants. The degree of their influence depends on salts concentration, method of irrigation, amount of irrigation water and on irrigated land (Richards (ed.), 1954; Ayers and Westcot, 1985).

The adverse effect of poor quality irrigation water on the physical properties of the soil is associated with the accumulation of dispersive cations such as sodium and potassium in the soil solution, which affect soil physical properties. The high concentration of Na^+ in irrigation water can result in chemical instability of the soil, degradation of soil structure, clogging of pores, infiltration problems and reduction of the soil hydraulic conductivity (*K*), due to exchange and equilibrium processes between the soil soluble and solid phases (Rhoades et al., 1992). Ca^{2+} and Mg^{2+} cations can reduce the negative effect of Na^+ on the soil structure. Generally, the beneficial cation effects on soil stability and hydraulic properties relate to the type of exchangeable cations in the following order $Ca^{2+} > Mg^{2+} > K^+ > Na^+$ (Rengasamy and Marchuk, 2011; Quirk and Schofield, 1955). Due to the dominance of sodium salts in many sources of irrigation water, sodium-related parameters such as exchangeable sodium percentage (ESP) of soils and sodium adsorption ratio (SAR) of irrigation water have been commonly used to study the effects of sodium in irrigation water on soil structural stability (Rengasamy, 2018; Shainberg and Letey, 1984; Shainberg and Shalheved, 1984). SAR of the irrigation water is used as a measure of the risk of sodicity/alkalinity of irrigation water. According to Richards (ed.), (1954) and Rhoades et al., (1992), at SAR values higher than 6 to 9, irrigation water can be expected to cause problems in soils containing clay-type swellable minerals.

Hydraulic conductivity is a key parameter for research involving water and salts movement in the soil and can be affected by pore size and distribution of soil particles, mineralogical composition and concentration and composition of the water flowing through the soil. The studies by Jayawardane et al., (2011); Chinchmalatpure et al., (2014); Menezes et al., (2014); Suarez et al., (1984); Rengasamy and Marchuk (2011),

indicated the combined effect of percolating water quality and soil properties on saturated hydraulic conductivity (*Ks*). In soils with different structure, the changes in *Ks* in leaching with solutions of different concentration and ion composition were observed. They found out, that *Ks* was significantly affected by SAR, different concentrations and ratios of exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), pH and total electrolyte concentration of soil solution, ESP as well as by the cations and anions of the soils. Hydraulic conductivity of the soil is strongly dependent on soil structure, which can be degraded during wetting and leaching. The results of studies by Frenkel et al., (1978); Shainberg et al., (1981) and Ben-Hur et al., (2009) showed that plugging of pores by dispersed clay particles is a major cause of reduced Ks for surface soils irrigated with sodic waters. Shainberg et al., (1981) examined the changes in *Ks* and clay dispersivity as a function of concentration and SAR of percolating solutions. They found, that both the *Ks* and clay dispersivity of the soil mixture were very sensitive to the level of exchangeable Na^{+} and to the salt concentration of percolating solution.
The aim of this study was to determine how the sodium adsorption ratio and the different concentration of Na–Ca and Na–Mg leaching electrolytes affect the relative saturated hydraulic conductivity of saline soil from Jatov locality – Slovakia.

Material and methods

The laboratory experiments were performed on disturbed saline soil samples from the Jatov locality (48°7′58″ N latitude 18°01′41″ E longitude) from the topsoil horizon (0–30 cm). The Jatov locality is located on the Danube plain, in the middle of southwestern Slovakia and is one of the driest and warmest areas in Slovakia. The annual average air temperature is 9°C–10°C and the average annual rainfall are 500–600 mm. The physical and chemical characteristics of soil sample used for the experiments are given in Table 1 and Table 2. These parameters were determined by using the standard methods according to Hraško et al., (1962); Richards (ed.), (1954); Gupta et al., (1985); Sotáková, (1988); Valla et al., (1983). Soil chemical parameters were obtained by analysis of saturated soil extract (Table 1) and by analysis of soil water extract (1:5) (Table 2).
The soil was air dried, crushed and passed through a 2 mm sieve. This was then mixed thoroughly and the subsamples were used to fill the plexiglass soil columns (4 cm diameter and 20 cm long) to a bulk density of 1.3 g cm^{3}. The soil column was placed in a vertical position. Its outlet end was closed with a perforated plexiglass plate and a filter paper (to prevent the escape of soil particles) and a plexiglass plug with valves. The column was wetted slowly from bottom of the column with solution at the highest electrolyte concentration and the highest SAR value.
To study the effect of electrolyte concentration at different SAR values and at different cation combinations of Na–Ca and Na–Mg in percolating binary electrolytes on *rKs* of the soil, 60 combined electrolytes were prepared. The desired levels of concentrations and SAR of the experimental solutions were obtained by mixing the chemical compounds $NaCl+CaCl_2.2H_2O$ in the first case and by mixing the $NaCl+MgCl_2.6H_2O$ chemical compounds in the second case. The leaching solutions with SAR values of 5, 10, 20, 30 and 40 were prepared in concentrations of 20, 40, 60, 100 and 120 mmol l^{-1} of both Na–Ca and Na–Mg solutions. The SAR values for Na–Ca cationic pair were calculated by using the equation (1) and the SAR values for Na–Mg cationic pair were calculated by using the equation (2) (Richards (ed.), 1954):

$$SAR = Na^{+}/(\sqrt{(Ca^{2+}/2)}) \qquad (1)$$

where
SAR – sodium adsorption ratio [-],
Na^{+}, Ca^{2+} – the cation concentration [mmol l^{-1}].

$$SAR = Na^{+}/(\sqrt{(Mg^{2+}/2)}) \qquad (2)$$

where
SAR – sodium adsorption ratio [-],
Na^{+}, Mg^{2+} – the cation concentration [mmol l^{-1}].

All solutions were prepared at an equilibrated pH values of 8. The ratio of the cation concentrations of c_{Na+}/c_{Ca2+} and c_{Na+}/c_{Mg2+} in all Na–Ca and Na–Mg leaching solutions which were used in the experiments, are given in Table 3 and Table 4.
The soil column was initially saturated with Na–Ca salt solution at the highest electrolyte concentration and SAR 40 by capillary tension from the bottom of the column. Subsequently, the same solution was applied to the top

Table 1. Physicochemical characteristics of soil sample (Jatov)

Grain size distribution [%]					Org. C	pH	EC	CEC	ESP	SAR
0.001 [mm]	0.001–0.01 [mm]	0.01–0.05 [mm]	0.05–0.25 [mm]	0.25–2.0 [mm]	[%]	[-]	[mS m^{-1}]	[mmol kg^{-1}]	[-]	[-]
23.7	15.4	32.7	25.4	2.8	1.25	8.5	273	434	12.9	32

CEC – cation exchange capacity
ESP – exchange sodium percentage
EC – specific electrical conductivity
SAR – sodium adsorption ratio

of the column to measure the saturated hydraulic conductivity at a constant hydraulic head of 2.0 cm. When the Ks of the soil column of the effluent had stabilized, the sequentially lower concentration solution with the same SAR was applied. This process continued with the solutions with gradually lower concentrations until the final solution with the lowest concentration. The experiment was then repeated sequentially with Na–Ca solutions at SAR values of 30, 20, 10 and 5 using the experimental procedure described above for the electrolyte at SAR 40. For any given SAR, the same soil column was used to measure Ks at progressively lower electrolyte concentrations using the same approach as in the related studies (Jayawardane et al., 2011; Aram et al., 2019). The leachate solutions were collected from each column at time intervals to calculate Ks. After reaching hydraulic equilibrium, as indicated by the output rate, the saturated hydraulic conductivity was calculated (Klute and Dirkson, 1986). For each binary electrolyte, the equilibrium hydraulic conductivity value was taken as the hydraulic conductivity measured at the end of each leaching cycle when the flow rate reached approximately steady state. The values of Ks were calculated at sequential time intervals (t) using Darcy's law (3):

$$Ks = VL/AHt \tag{3}$$

where
V – volume of solution at steady state [cm^3],
L – length of the soil column [cm],
A – cross-sectional area of the soil column [cm^2],
H – hydraulic head difference [cm],
t – time interval [h].

The saturated hydraulic conductivity of the soil column obtained by using the greatest electrolyte concentration and the corresponding SAR value was taken as the initial hydraulic conductivity Ks_0. Subsequently, the columns were gradually leached with solutions of the same SAR, but with a reduced electrolyte concentration. The obtained hydraulic conductivity was marked as Ks_i.

Table 2. Chemical composition of soil water extract (1:5)

Na^+ [mmol kg^{-1}]	K^+ [mmol kg^{-1}]	Ca^{2+} [mmol kg^{-1}]	Mg^{2+} [mmol kg^{-1}]	SO_4^{2-} [mmol kg^{-1}]	Cl^- [mmol kg^{-1}]	HCO_3^- [mmol kg^{-1}]
23.5	0.89	0.79	0.32	1.25	0.79	24.4

Table 3. The ratio of the cation concentrations in Na–Ca binary electrolyte

c [mmol l^{-1}]	c_{Na+}/c_{Ca2+}				
	SAR 5	**SAR 10**	**SAR 20**	**SAR 30**	**SAR 40**
20	0.67	1.88	6.29	13.40	23.81
40	0.42	1.10	3.35	7.02	12.02
60	0.33	0.82	2.39	4.83	8.19
80	0.28	0.67	1.87	3.72	6.25
100	0.24	0.57	1.56	3.24	5.10
120	0.21	0.50	1.35	2.62	4.33

c – the concentration of Na–Ca binary electrolyte
c_{Na+}/c_{Ca2+} – the ratio of cation concentrations in the Na–Ca electrolyte

Table 4. The ratio of the cation concentrations in Na–Mg binary electrolyte

c [mmol l^{-1}]	$c_{Na+}/_{Mg2+}$				
	SAR 5	**SAR 10**	**SAR 20**	**SAR 30**	**SAR 40**
20	1.11	3.12	10.37	22.11	39.29
40	0.69	1.81	5.53	11.57	19.83
60	0.54	1.36	3.94	7.97	13.52
80	0.45	1.10	3.08	6.15	10.32
100	0.40	0.94	2.58	5.35	8.41
120	0.35	0.84	2.24	4.33	7.14

c – the concentration of Na–Mg binary electrolyte
c_{Na+}/c_{Mg2+} – the ratio of cation concentrations in the Na–Mg electrolyte

The changes in hydraulic conductivity between treatments were represented as a relative saturated hydraulic conductivity (*rKs*) to provide a hydraulic conductivity reduction from the initial Ks_0. The values of soil *rKs* was calculated according to the equation (4):

$$rKs = Ks_i / Ks_0 \quad (4)$$

where
rKs – relative saturated hydraulic conductivity of the soil [-],
Ks_0 – initial saturated hydraulic conductivity of the soil [cm h^{-1}],
Ks_i – saturated hydraulic conductivity of the soil leached by the following solution i [cm h^{-1}].

Using the methodology described above for Na–Ca solutions, the experiments to measure the soil Ks were then repeated with Na–Mg solutions, substituting calcium chloride for magnesium chloride in preparing the leaching solutions with the corresponding SAR value. At the end of each experiment, the soil *rKs* values were calculated for all leaching electrolyte concentrations with corresponding SAR values for both solutions Na–Ca and Na–Mg.

Results and discussion

By laboratory experiments on a disturbed soil sample from the surface layer (0–30 cm) of the soil from the Jatov locality a changes in relative saturated hydraulic conductivity of the soil leached with Na–Ca and Na–Mg solutions with different concentrations and different SAR were observed. The measured results showed that the concentration, SAR and cation combinations of the electrolyte flowing through the studied saline soil have a significant effect on *rKs* of the soil. The values of *rKs* increased with increasing electrolyte concentration at all SAR for both cationic pair Na–Ca and Na–Mg. With increasing SAR of percolating electrolyte, the values of soil *rKs* decreased. A graphical representation of the dependence of soil *rKs* on the concentration and SAR of both leaching solutions Na–Ca and Na–Mg is shown in Fig. 1 and Fig. 2.
When comparing the *rKs* values determined in leaching with Na–Ca solutions at SAR value of 5 and at a concentrations of 20, 40, 60, 80, 100 mmol l^{-1}, with the rKs values determined in leaching with Na–Ca solutions at SAR 10, 20, 30, 40 and at a corresponding concentrations, a reduction in *rKs* of the soil was found. The highest reduction in *rKs*, up to 67.3%, was found when the leaching solution at a concentration of 40 mmol l^{-1} and SAR 40 was used. Percentage reduction in *rKs* values determined in leaching with Na–Ca solutions at SAR 10, 20, 30, 40, compared to *rKs* values determined in leaching with SAR 5 solutions is shown in Table 5.
The course of soil *rKs* dependence on electrolyte concentration and SAR for Na–Mg cationic pair was similar as in the first case when Na–Ca solutions were

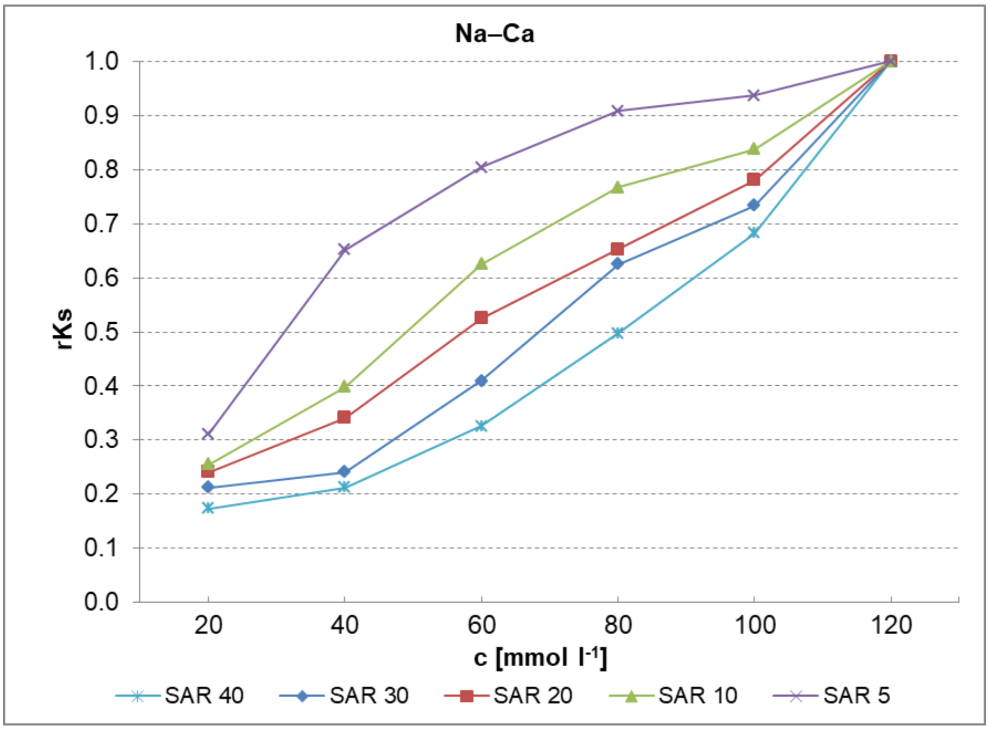

Fig. 1. The relative saturated hydraulic conductivity (rKs) of the soil versus concentration of Na–Ca binary electrolyte at a sodium adsorption ratio (SAR) of 5, 10 20, 30 and 40.

used in leaching (Fig. 2). The soil *rKs* increased with increasing electrolyte concentration at all SAR values. With increasing of SAR of percolating electrolyte, the values of *rKs* decreased. Percentage reduction in *rKs* values determined in leaching with Na–Mg solutions at SAR 10, 20, 30, 40 compared to *rKs* values determined in leaching with solution at SAR 5 at a corresponding concentrations, is shown in Table 6. The highest percentage reduction in *rKs*, up to 66.8%, was found in leaching with Na–Mg solution at a concentration of 40 mmol l^{-1} and SAR 40.

When comparing the results of soil *rKs* measurements, when the binary electrolyte NaCl + $CaCl_2.2H_2O$ in the first case, and the binary electrolyte NaCl + $MgCl_2.6H_2O$ in the second case, were used in leaching, a decrease in soil *rKs* values was found for Na–Mg cationic pair compared to Na–Ca cationic pair. Percentage reduction in *rKs* values by using Na–Mg electrolytes for leaching at a concentration of 20–100 mmol l^{-1} and at SAR of 5, 10, 20, 30 and 40, compared to Na–Ca leaching electrolytes at the same concentrations and SAR is shown in Table 7. The lowest reduction in *rKs* values of 1.67% was found in leaching with electrolyte with a concentration of 100 mmol l^{-1} and SAR 10. The highest reduction in *rKs* values of 32.75% was found when the electrolyte with a concentration of 20 mmol l^{-1} and SAR 40 was used in leaching.

The measurements showed that *rKs* of the soil increased with increasing of the concentration of both solutions Na–Ca and Na–Mg at all SAR values (5, 10, 20, 30 and 40) and decreased with increasing of SAR. These results are confirmed by several previous works by Jayawardane

Table 5. Percentage reduction in *rKs* values for Na–Ca electrolytes

c [mmol l^{-1}]	Reduction in *rKs* [%]			
	SAR 10	SAR 20	SAR 30	SAR 40
20	18.2	22.7	31.7	45.1
40	38.9	47.6	63.0	67.3
60	22.2	34.7	48.7	59.3
80	15.5	28.0	30.8	43.7
100	10.5	16.6	21.6	27.3

rKs – relative saturated hydraulic conductivity
c – the concentration of Na–Ca binary electrolyte

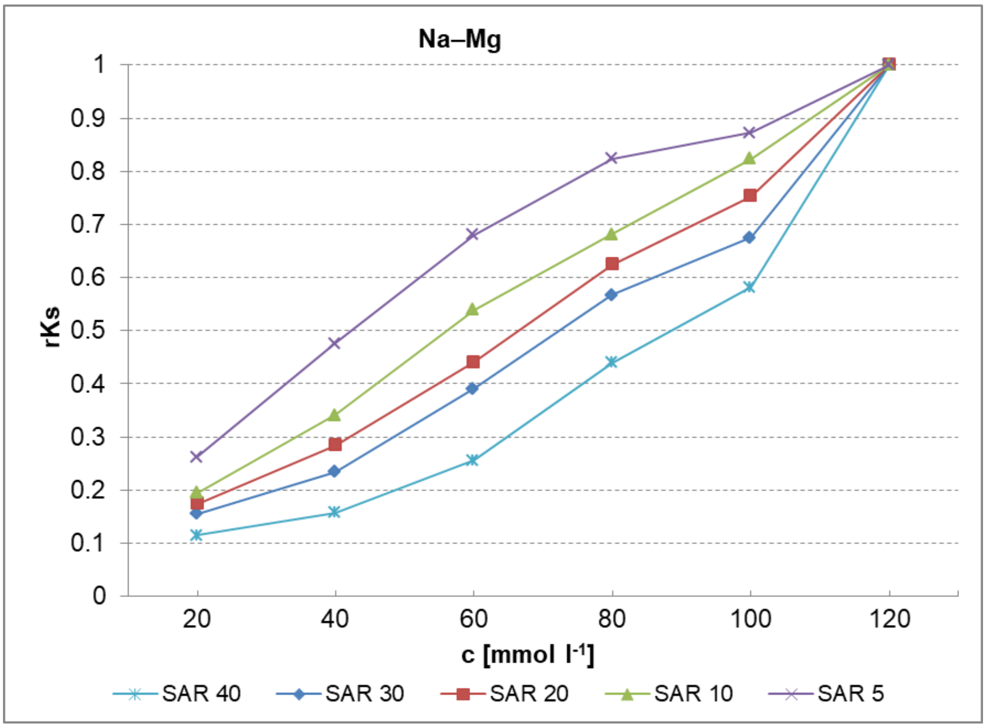

Fig. 2. The relative saturated hydraulic conductivity (rKs) of the soil versus concentration of Na–Mg binary electrolyte at a sodium adsorption ratio (SAR) of 5, 10 20, 30 and 40.

Table 6. **Percentage reduction in *rKs* values for Na–Mg electrolytes**

c [mg l^{-1}]	Reduction in *rKs* [%]			
	SAR 10	SAR 20	SAR 30	SAR 40
20	25.8	33.8	40.6	56.2
40	28.3	40.3	50.8	66.8
60	20.8	35.3	42.5	62.4
80	17.21	24.1	31.1	48.9
100	5.6	13.7	22.6	33.3

rKs – relative saturated hydraulic conductivity
c – the concentration of Na–Mg binary electrolyte

Table 7. **Percentage reduction in *rKs* values by using Na–Mg electrolytes compared to Na–Ca electrolytes**

c [mmol l^{-1}]	Reduction in *rKs* [%]				
	SAR 5	SAR 10	SAR 20	SAR 30	SAR 40
20	15.71	23.53	27.80	26.76	32.75
40	26.99	14.32	16.72	2.90	25.82
60	15.30	13.76	16.19	5.10	21.71
80	9.25	11.08	4.29	9.55	13.89
100	6.83	1.67	3.59	8.04	14.54

rKs – relative saturated hydraulic conductivity
c – the concentration of Na–Ca resp. Na–Mg binary electrolyte

et al., (2011); Chinchmalatpure et al., (2014); Menezes et al., (2014); Dikinya et al., (2007). The reduction in *rKs* was related to the ratio of the cation concentrations of c_{Na+}/c_{Ca2+} and c_{Na+}/c_{Mg2+} in all Na–Ca and Na–Mg leaching solutions used at the experiments (Table 3 and Table 4). The higher was this ratio, the higher was the reduction in soil *rKs*. The reduction in the Ks may be attributed to swelling and dispersion of the soil clays caused by Na^+ ions. At an electrolyte concentration of 20 mmol l^{-1} and SAR 40, the most unfavorable ratio of c_{Na+}/c_{Ca2+} and c_{Na+}/c_{Mg2+} in the electrolytes was found. With increasing electrolyte concentration, this ratio decreased, the adverse effect of sodium on the soil structure was reduced, as a result of which the *rKs* of the soil increased. At higher concentrations, the Ca^{2+} and Mg^{2+} cations can counteract the dispersive nature of Na^+ and thus reduce the dispersive effects on the soil structure. With increasing SAR of the electrolyte, the ratio of c_{Na+}/c_{Ca2+} and c_{Na+}/c_{Mg2+} in the leaching electrolytes increased, the adverse effect of sodium on the soil structure increased, causing a decrease in *rKs* of the soil. Laboratory experiments also showed that *rKs* measured with Na–Ca solutions were higher than those measured with Na–Mg solutions. The effect of magnesium is different from that of calcium because they have different affinities for adsorption on the exchange complex. The flocculation effect of Ca^{2+} is higher than that of Mg^{2+} which is not as efficient in flocculating clay as Ca^{2+} and under specific conditions can have a dispersive effect. Na–Mg soils were found to give rise to more dispersed clay and lower hydraulic conductivity than Na–Ca soils (Rengasamy and Marchuk, 2011; Rengasamy et al., 2016; Shainberg and Letey, 1984).

The concentration, SAR and combination of cations of the electrolyte flowing through the soil greatly affect its permeability. When selecting water for irrigation, it is therefore important to monitor not only its total ion concentration but also the ratio of the exchangeable cations (Na^+, K^+, Mg^{2+} and Ca^{2+}), which significantly affect the structure of the soil and thus its hydraulic conductivity.

Conclusion

The changes in the relative saturated hydraulic conductivity of saline soil as a function of concentration, SAR and cation combinations of percolation solutions were measured. The results obtained from laboratory experiments indicated an increase in soil *rKs* with decreasing SAR values and with increasing concentration of both leaching solutions Na–Ca and Na–Mg. The greatest impact on *rKs* of the soil has sodium, the excessive amount of which causes dispersion of clay soil particles and thus reduces its permeability. At higher concentrations of leaching solutions, the Ca^{2+} and Mg^{2+} cations have the effect of reducing the dispersive effects of sodium. Results also revealed that *rKs* of the soil measured with Na–Ca solutions was higher than those measured with Na–Mg solutions. Mg^{2+} cations have a different affinity for adsorption on the exchange

complex than Ca^{2+} and are not as effective at clay flocculation as Ca^{2+}.
In further experiments aimed at studying the effect of concentration and SAR of leaching solutions on *Ks* of saline soil, it will be appropriate to use more soil types with different clay content and different ESP of the soil.

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