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Hydraulic conductivity of Molisolls irrigated with sodic-bicarbonated waters in Santa Fe (Argentine)

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ABSTRACT

Irrigation waters with high sodicity and low salinity levels may deteriorate soil physical properties, consequently affecting the water movement in the soil. The objectives of this study were: (i) to evaluate the effect of supplemental irrigation with waters that have a residual sodium carbonate (RSC) [Richards, L.A. (Ed.), 1954. Diagnóstico y rehabilitación de suelos salinos y sódicos. Manual de Agricultura, vol. 60. Limusa, México] greater than 1.25 $mmol_c\,L^{-1}$ on the hydraulic conductivity (K) of Hapludolls and Argiudolls located in Santa Fe State (Argentina) and (ii) to identify the possible causes of K alteration. Irrigated and non-irrigated plots were selected to evaluate soil bulk density, water dispersed clay content, and K in two depth intervals: 0–7 and 15–25 cm. K was measured with tension infiltrometers at three tension values: 0, 0.15, and 0.3 kPa. Increases in ESP in both depths from 1 to 10 caused a 10% to 79% decrease in K in the irrigated relative to non-irrigated treatments. Changes in K were associated with increased clay dispersion suggesting that this factor results in failure of the structure, resulting in increased blockage of soil pores. Between 51% and 62% of the total clay was dispersed in water in irrigated treatments, and 36–44% in non-irrigated treatments. Results emphasize the importance of preventing soil dispersion. This process induces degradation of big pores, especially those with equivalent radii greater than 1000 μm, which is essential for quick water flow. The conductivity of these pores was decreased from 48% to 79% in irrigated relative to non-irrigated treatment. A field method is proposed to determine when reclamation practices should begin.

1. Introduction

Waters containing residual sodium carbonate (RSC) greater than 1.25 $mmol_c\,L^{-1}$ are marginal for irrigation purposes (Richards, 1954), and generally produce degradation of physical and chemical properties of the soil (Andriulo et al., 1998; Buckland et al., 2002; Pilatti et al., 2004, 2006). As a result, soil water and air movement are affected. The effect of irrigating soils with waters of poor quality has been broadly studied, and it is known that hydraulic conductivity (K) is negatively affected by soil sodication (Shainberg and Letey, 1984; Sumner, 1993; Levy, 1999). Although an exchangeable sodium percentage (ESP) value of 15 is acceptable as a critical threshold to define Na-affected soils, nowadays researchers agree that lower ESP values may cause adverse effects if the soil solution has low electrolyte concentrations (So and Aylmore, 1993; Crescimanno et al., 1995). Furthermore, the critical level of the relationship sodium adsorption ratio: water electric conductivity (SAR/EC_w) associated with K deterioration seems to depend on several factors such as, soil type, clay mineralogy, texture, pH, oxide content, silt, and CO_2 concentration (Shainberg et al., 2001).

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Irrigation waters with high SAR and low EC_w increase the exchangeable sodium percentage and dilute salt concentration in soil solution (Richards, 1954; Sumner, 1993; Wienhold and Trooien, 1995). Moreover, with high concentration of bicarbonate ion, there is a tendency for calcium to precipitate as carbonate and the relative proportion of sodium is increased (Richards, 1954). These processes trigger the mechanisms responsible for conductive pore deterioration, therefore, causing the reduction of *K*. The most common mechanisms are: (i) destruction of soil aggregates by dispersion and slaking and (ii) clay swelling (Frenkel et al., 1978; Pupisky and Shainberg, 1979; Gupta and Abrol, 1990; Wienhold and Trooien, 1998). The first one is an irreversible process and can generate waterproof strata in the soil. The second process is reversible through the addition of electrolytes or bivalent cations (Shainberg and Letey, 1984; Oster, 1994; Melkamu et al., 1997); however, McNeal and Coleman (1966) reported that reversibility was limited.

It was demonstrated that *K* is a very sensitive indicator to detect changes in soil porosity caused by ESP increment (Keren and Ben-Hur, 2003). Nevertheless, most of the information was generated under laboratory conditions using soil columns repacked with aggregates of different sizes, which may not faithfully represent the field conditions due to the formation of cracks and channels that originate patterns of preferential flow (Shainberg and Letey, 1984). To overcome this problem, Menneer et al. (2001) have proposed field studies to be carried out using tension-infiltrometers to evaluate the effects of irrigation with sodium-contaminated wastewaters. This instrument is being broadly used to determine soil hydraulic properties *in situ*, i.e. to detect changes in porous space, and to study the preferential flow throughout soil macropores (Watson and Luxmoore, 1986; Ankeny et al., 1990; Haddadj and Gascuel-Odoux, 1998; Cameira et al., 2003).

The risks and consequences of applying irrigating waters that have RSC onto soils of the Pampean region of Argentina have been acknowledged for a long time. Arens (1969) indicated that few years are necessary to make a good soil turn into a sodic soil in this region. Cerana (1980) has found similar results for soils of the State of Córdoba (Argentina) and proposed an ESP value of 5% being more appropriate than 15% as the level to be used to classify the soil as sodic.

In the Pampean region of Argentina, the surface irrigated with waters that have RSC is increasing, and experimental evidence of soil deterioration has already been shown by Andriulo et al. (1998). Pilatti et al. (2004) found that supplemental irrigation with waters containing RSC greater than 1.25 $mmol_c\ L^{-1}$ and low saline concentration have caused sodication in Molisolls of Santa Fe. It is necessary, however, to identify the physical properties that have deteriorated the most in order to understand what has caused soil degradation. Sensitive indicators are needed to promote sustainable management (Steinberg, 1999). Therefore, the objectives of this research were: (i) to evaluate *in situ* the effect of supplemental irrigation with waters containing a residual sodium carbonate on the hydraulic conductivity of A horizon of Hapludolls and Argiudolls in Santa Fe State (Argentina), and ii) to identify the possible causes for the degradation of hydraulic conductivity.

2. Materials and method

The field experiments were located in the south central portion of Santa Fe State (Argentina), near the towns of Hughes, Llambi Campbell, and Marcelino Escalada, where the climate is mesothermic subhumid-humid (C2B′3ra′, Thornthwaite (1948)) and annual isohyets vary from 800 to 1000 mm.

Sampling sites (Table 1) were selected based on the soil characteristics (Pilatti et al., 2004). The soils sampled were Hapludolls and Argiudolls (INTA, 1983, 1992) with different particle size distribution (Table 2), and all under no-till cropping system for more than 4 years. At each place, before seeding the summer crop and the first irrigation, one non-irrigated area (NI) and one irrigated area (I) were chosen to carry out the evaluations. The irrigated areas experienced sodication due to the application of 100–350 mm $year^{-1}$ of irrigation waters, with an RSC greater than 1.25 $mmol_c\ L^{-1}$ (Table 3). This process took place without increasing soil salinity. Irrigation of discontinuous supplemental type was performed with a center pivots. At the field experiment located near Hughes, two irrigated areas that differed in irrigation duration (30 and 3 years) were also evaluated. The 30-year irrigated area was named I_{30} and the 3-year irrigated area was named I_3. Complementary, one natural A horizon located near Llambi Campbell was also studied to improve the interpretation results obtained nearby.

Chemical characteristics of the groundwater used for irrigation are shown in Table 3. Water electrical conductivity (EC_w) was analyzed according to Richards (1954), Ca^{2+} and Mg^{2+} by titration, Na^+ by flame photometry, and HCO_3^- and CO_3^{2-} according to Jackson (1982). The residual sodium carbonate (RSC) was calculated as $[(CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})]$

Table 1 – Localization and soils of the studied cases

Town	Soil classification	Treatment
Hughes	Typic Hapludoll, Santa Isabel serie	(1) Non-irrigated (NI) (2) Three years irrigated (I_3) (3) Thirty years irrigated (I_{30})
Llambi Campbell	Acuic Argiudoll, Humboldt serie	(1) Non-irrigated (NI) (2) Irrigated (I)
Marcelino Escalada	Acuic Argiudoll, Angeloni serie	(1) Non-irrigated (NI) (2) Irrigated (I)

Table 2 – Particle size distribution (%) of the study soils

Town	Soil fraction	Non-irrigated		Irrigated			
		A_p	A	A_p		A	
				I_3	I_{30}	I_3	I_{30}
Hughes	Sand, >50 μm	42.9	34.7	36.4	38.6	37.2	39.4
	Silt, 2–50 μm	38.9	43.0	45.6	41.6	38.9	39.1
	Clay, <2 μm	18.1	22.3	18.0	19.8	24.0	21.6
Llambi Campbell	Sand, >50 μm	9.4	10.3	10.4		9.8	
	Silt, 2–50 μm	71.1	67.0	69.4		64.1	
	Clay, <2 μm	19.5	22.7	20.1		26.1	
Marcelino Escalada	Sand, >50 μm	7.9	7.3	9.2		8.5	
	Silt, 2–50 μm	68.2	59.7	71.1		64.4	
	Clay, <2 μm	23.8	33.0	19.7		27.1	

A_p, 0–7 cm depth; A, 15–25 cm depth; I_3, 3 years irrigated; I_{30}, 30 years irrigated.

(Eaton, 1950), and adjusted sodium adsorption ratio (SAR°) was determined based on the Ayers and Westcot (1985) methodology. Ca^{2+}, Mg^{2+}, CO_3^{2-}, and HCO_3^- are the concentrations of these elements in $mmol_c\,L^{-1}$; Ca° is the corrected Ca^{2+} value obtained from (HCO_3^-/Ca^{2+}) and EC_w:

$$SAR^{\circ} = \frac{Na^{+}}{\sqrt{(Ca^{\circ} + Mg^{2+})/2}}$$

The hydraulic conductivity (*K*) was measured with tension-infiltrometers (Perroux and White, 1988) at tensions (τ) of 0 kPa (K_0), 0.15 kPa ($K_{0.15}$), and 0.3 kPa ($K_{0.3}$) following the procedures used by Ankeny et al. (1991). The descending sequence of tensions was adopted because an ascending sequence may cause hysteresis (Jarvis and Messing, 1995). Measurements were done in non-irrigated and irrigated treatments in A_p and *A* horizons at two depths (A_p: 0–7 cm; *A*: 15–25 cm), and six repetitions for each tension were carried out.

Before placing the tension-infiltrometer on the soil, a surface of about 60 cm of diameter was cleaned and leveled without altering soil structure. Then, a thin layer of fine sand was applied on the soil surface, covering an identical area to that of the infiltrometer disk (120 mm diameter). In order to ensure an appropriate hydraulic contact between the disk and the soil, the tension-infiltrometer was slightly pressed on the sand. After wetting the sand (30 s), measurements were done in 15–30 s intervals. Each test was concluded when at least five serial readings presented similar results. This moment was considered a steady state. The readings were used to carry out the calculations of *K* according to Ankeny et al. (1991). The time to reach the steady state was approximately 1 h at high values of tension, and it decreased at low values of tension. Four liters of water, equal to that used for irrigating the soil, were used to perform each determination.

According to the capillary theory, tensions of 0.3 and 0.15 kPa were applied consecutively to exclude pores of equivalent radius greater than 500 and 1000 μm, respectively, from the process transport. The percentage of water flow (%flow) that occurred through macropores of equivalent radii greater than 1000 μm, and the decrease of the water conduction capacity of these pores ($\%D_{flow}$) in the irrigated treatments were determined with the following equations:

$$\%\text{flow} = \left[100 - \left(\frac{K_{0.15}}{K_0}\right)\right] \times 100 \quad (1)$$

$$\%D_{flow} = \left[100 - \left(\frac{K_{0I} - K_{0.15I}}{K_{0NI} - K_{0.15NI}}\right)\right] \times 100 \quad (2)$$

where K_{0I} and $K_{0.15I}$, K_{0NI} and $K_{0.15NI}$ are the K_0 and $K_{0.15}$ in the irrigated and non-irrigated treatments, respectively.

The percentage of decrease of K_0 ($\%D_{K_0}$) was calculated with the following equation:

$$\%D_{K_0} = \left[1 - \left(\frac{K_{0I}}{K_{0NI}}\right)\right] \times 100 \quad (3)$$

The *K* data were log-normally distributed according to the Shapiro–Wilks-test ($W > 0.9$). Consequently, log-transformed data were used for statistical analysis of the data.

Simultaneously with the *K* measurements, undisturbed soil samples (5 cm × 5 cm cores) were collected to determine bulk density (ρ_b) (Blake and Hartge, 1986). Six soil cores were sampled at each treatment. Soil samples (Pilatti and de

Table 3 – Composition of irrigation waters

Town	pH	EC_w ($dS\,m^{-1}$)	Na^+ ($mmol_c\,L^{-1}$)	Ca^{2+} ($mmol_c\,L^{-1}$)	Mg^{2+} ($mmol_c\,L^{-1}$)	CO_3^{2-} ($mmol_c\,L^{-1}$)	HCO_3^- ($mmol_c\,L^{-1}$)	SAR° ($(mmol_c\,L^{-1})^{0.5}$)	RSC ($mmol_c\,L^{-1}$)
Hughes	7.2	1.7	19.4	0.5	0.7	–	15	28.5	13.8
Llambi Campbell	8.3	0.9	6.6	1.3	0.8	–	4.4	7.0	2.3
Marcelino Escalada	7.7	1.3	12.5	0.5	0.3	–	9.2	23.2	8.4

EC_w, water electrical conductivity; SAR°, adjusted sodium adsorption ratio; RSC, residual sodium carbonate.

Orellana, 1994) were also taken at the same places to measure the water-dispersed clay content (Cl_d). This involved the particle dispersion with distilled water, shaking for 17 h, and the determination of the suspended particle content with the densimeter method (Gee and Bauder, 1986). The dispersion index (DI) was equal to Cl_d divided by the amount of total clay in 100 g of soil. The electrical conductivity of the saturation paste extracts (EC_e) was also measured (Richards, 1954). Cation exchangeable capacity (CEC) was determined after extraction with ammonium acetate, pH 7. Exchangeable sodium (Exch. Na^+) was analyzed by flame photometry, and soil organic carbon (OC) according to the Walkley–Black method (Jackson, 1982). Exchangeable sodium percentage (ESP) was calculated as [(Exch. Na^+/CEC) $\times$ 100]. Then, the EC_e and ESP were used to calculate the sodicity index [SI = EC_e/ESP] (Hulugalle and Finlay, 2003).

The mean values of the variables ρ_b, DI, OC, Exch. Na^+, EC_e, CEC and ESP were analyzed for the treatments NI and I using the *t*-test ($\alpha = 5\%$). The statistical analyses were conducted with SAS (1991).

3. Results and discussion

The irrigation waters can induce soil physical deterioration according to their sodium adsorption ratio (SAR), electrical conductivity (EC_w), and residual sodium carbonate (RSC) (Table 3) (Richards, 1954; Ayers and Westcot, 1985; Levy, 1999; Pilatti et al., 2006). Levels of alkalinization and sodication are shown in Table 4. Irrigation caused a significant increase in Exch. Na^+ content (between 1.7 and 17 times), and ESP (between two and nine times) in irrigated relative to non-irrigated treatment in both depths, but EC_e did not increase. Similar results were found by Pilatti et al. (2004), who studied 25 cases spread out the Pampean Molisolls of Argentina.

The values of *K* for each studied place are shown in Fig. 1. There was an important decrease of *K* in the irrigated treatments at all analyzed tensions, but especially at the tension of 0 kPa.

At the field experiment located near Hughes in the A_p soil horizon, K_0, $K_{0.15}$, and $K_{0.3}$ were greater in the non-irrigated than in the I_3 and I_{30} treatments (Fig. 1a and b), indicating the occurrence of soil structure deterioration. The worst condition was observed for I_{30}. As a result, this treatment had the greater quantity of Exch. Na^+, which has negatively affected *K*. In the *A* depth of I_{30}, irrigation has caused a decrease of *K* at all evaluated tensions. In this case, significant differences on the soil bulk density values (Table 5) between non-irrigated and I_{30} treatment were observed. However, *K* only decreased at the τ of 0.15 and 0.3 kPa in I_3 treatment. These results indicate that, to some extent, pores of equivalent radii smaller than 1000 μm were affected. The dispersion index (DI) was greater in the irrigated than in the non-irrigated treatments (Table 6), which suggests that this soil fraction may be responsible for the pores filling.

In the soil located near Llambi Campbell (Fig. 1c and d), there were no significant differences of *K* between non-irrigated and irrigated treatments in the A_p, possibly because this layer had already been physically degraded before being irrigated (Ghiberto et al., 2002). This fact was verified by comparing the measured *K* values of the non-irrigated and irrigated treatments with those obtained for this soil in its natural condition (Fig. 1c). In the *A* depth, *K* decreased significantly at all tensions for irrigated treatment (Fig. 1d). Differences in soil bulk density were not detected (Table 5) between treatments, while DI was greater in irrigated than non-irrigated treatments (Table 6).

The hydraulic conductivity decreased significantly in the irrigated treatment, at all tensions and both depths (A_p and *A*) in the soil located near Marcelino Escalada (Fig. 1e and f). The high mean value of *K* in non-irrigated may be attributed to the presence of preferential water flow. This shows the sensitivity of the tension-infiltrometer in the measurements of *K*. In this case, A_p densification was observed (Table 5), and DI was significantly greater in irrigated than in non-irrigated treatments for both depths (Table 6).

The overall results show that irrigation with RSC waters greater than 1.25 $mmol_c\,L^{-1}$ has strongly deteriorated the hydraulic conductivity in both A_p and *A* depths, with percentages of decrease of K_0 ($\%D_{K_0}$) greater than 25% (Table 7).

Quirk and Schofield (1955) have indicated that the critical limit of sodium in the exchangeable complex, starting from which soil structure is damaged, takes place when *K* decreases

Table 4 – Organic carbon (OC), electrical conductivity of the saturation paste extracts (EC_e), cation exchangeable capacity (CEC), exchangeable sodium content (Exch. Na^+) and exchangeable sodium percentage (ESP) for each place and depth

Treatment	OC (%)		EC_e ($dS\,m^{-1}$)		CEC ($cmol_c\,kg^{-1}$)		Exch. Na^+ ($cmol_c\,kg^{-1}$)		ESP ($cmol_c\,kg^{-1}$)	
	A_p	A	A_p	A	A_p	A	A_p	A	A_p	A
NI-Hughes	1.9 a	1.1 a	0.9 a	0.9 a	20.1 a	21.4 a	0.1 a	0.6 a	1 a	2 a
I_3-Hughes	1.8 a	0.8 a	0.7 a	0.9 a	19.2 a	20.2 a	1.2 b	1.0 b	6 b	4 a
I_{30}-Hughes	2.0 a	1.4 b	0.7 a	0.7 a	20.1 a	21.8 a	1.7 b	2.0 b	9 b	9 b
NI-Llambi Campbell	1.2 a	1.1 a	0.6 a	0.6 a	14.2 a	14.9 a	0.4 a	0.3 a	3 a	2 a
I-Llambi Campbell	1.2 a	1.1 a	0.7 a	0.9 a	13.3 a	15.5 a	1.2 b	1.6 b	9 b	10 b
NI-Marcelino Escalada	1.5 a	0.7 a	0.7 a	0.7 a	14.6 a	15 a	0.1 a	0.3 a	1 a	2 a
I-Marcelino Escalada	1.5 a	0.6 a	0.8 a	0.6 a	14.6 a	17.1 a	1.1 b	0.8 b	8 b	5 b

A_p, 0–7 cm depth; *A*, 15–25 cm depth; NI, non-irrigated; I, irrigated; I_3, 3 years irrigated; I_{30}, 30 years irrigated. Mean values followed for the same letters in each column are not significantly different ($P < 0.05$).

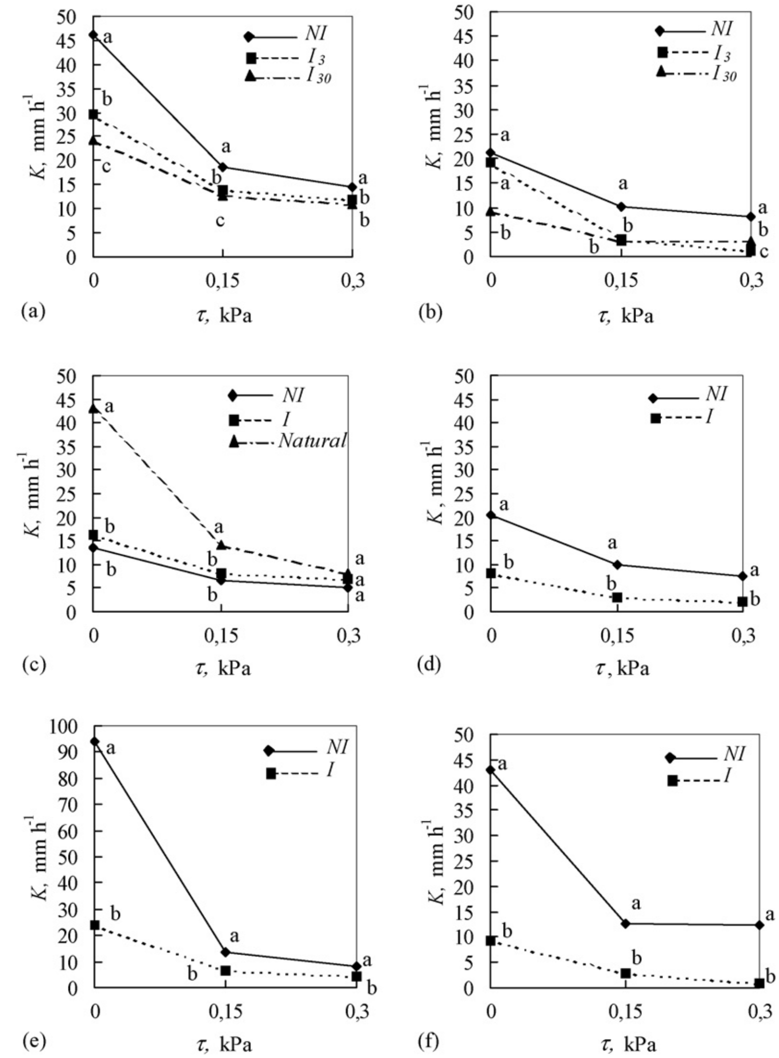

Fig. 1 – Hydraulic conductivity (*K*) vs. the applied tension (*τ*) for the non-irrigated and irrigated treatments located in: (a) Hughes, A_p depth; (b) Hughes, *A* depth; (c) Llambi Campbell, A_p depth; (d) Llambi Campbell, *A* depth; (e) Marcelino Escalada, A_p depth; (f) Marcelino Escalada, *A* depth. Different letters in each tension indicates significant differences ($P < 0.05$) between treatments.

Table 5 – Soil bulk density ($Mg\ m^{-3}$) for each place and depth

Town	Horizon	Non-irrigated	Irrigated
Hughes	A_p	1.288 a	(I_3) 1.306 a
	A	1.374 a	(I_3) 1.377 a
Hughes	A_p	1.288 a	(I_{30}) 1.326 a
	A	1.374 a	(I_{30}) 1.411 b
Llambi Campbell	A_p	1.343 a	1.376 a
	A	1.296 a	1.360 a
Marcelino Escalada	A_p	1.210 a	1.324 b
	A	1.369 a	1.370 a

A_p, 0–7 cm depth; *A*, 15–25 cm depth; I_3, 3 years irrigated; I_{30}, 30 years irrigated. Mean values followed for the same letters in each line are not significantly different ($P < 0.05$).

Table 6 – Dispersion index (DI) for each treatment and depth

Treatment	A_p	A
NI-Hughes	37.3 a	35.9 a
I_3-Hughes	59.9 b	50.9 b
I_{30}-Hughes	56.3 b	57.3 b
NI-Llambi Campbell	41.7 a	37.3 a
I-Llambi Campbell	54.3 b	50.0 b
NI-Marcelino Escalada	37.9 a	43.7 a
I-Marcelino Escalada	58.5 b	61.8 b

A_p, 0–7 cm depth; *A*, 15–25 cm depth; DI, amount of dispersed clay in water (Cl_d) divided by the amount of total clay in 100 g soil. Mean values followed for the same letters in each place and depth are not significantly different ($P < 0.05$).

Table 7 – Percentage of decrease of K_0 ($\%D_{K_0}$) for each place and depth

Town	A_p	A
Hughes	(I_3) 35	(I_3) 10
Hughes	(I_{30}) 46	(I_{30}) 56
Llambi Campbell	63	79
Marcelino Escalada	74	60

A_p, 0–7 cm depth; A, 15–25 cm depth; I_3, 3 years irrigated; I_{30}, 30 years irrigated. $\%D_{K_0} = [1 - (K_{0I}/K_{0NI})] \times 100$.

Table 9 – Decrease of the water conduction capacity ($\%D_{flow}$) of pores >1000 μm in the irrigated treatments

Town	A_p	A
Hughes	(I_3) 43	–
Hughes	(I_{30}) 57	(I_{30}) 44
Llambi Campbell	71	79
Marcelino Escalada	78	53

A_p, 0–7 cm depth; A, 15–25 cm depth; I_3, 3 years irrigated; I_{30}, 30 years irrigated. $\%D_{flow} = [100 - ((K_{0I} - K_{0.15I})/(K_{0NI} - K_{0.15NI})) \times 100]$.

between 10% and 15%, but McNeal and Coleman (1966) have accepted a value of 25% of K reduction. It should be kept in mind that the limits indicated by the authors mentioned above were determined from repacked laboratory columns, and may not reflect what happens in the field (Shainberg and Letey, 1984; Sumner, 1993). In order to obtain a valid relationship for field conditions, ESP values (Table 4) and the $\%D_{K_0}$ (Table 7) were used to obtain Eq. (4). The $\%D_{K_0}$ was considered to equal zero for the non-irrigated treatments and the natural condition in Llambi Campbell:

$$\%D_{K_0} = 8.68 \times \text{ESP} - 13.75 \quad (r^2 = 0.84; P < 0.001) \tag{4}$$

This equation shows that the 25% of K decrease accepted here as critical limit, is reached with an ESP value of 4.5. These results agree with those (5%) mentioned by McIntyre (1979) for Australian soils. However, it is well known that the critical limit is not a fixed value but rather presents a variation, depending on Exch. Na^+ and EC_e. In addition, this critical limit is controlled by other soil factors, such as mineralogy, texture and organic matter (Rengsamy and Olsson, 1991; Sumner, 1993; Halliwell et al., 2001). These factors may cause the differences in the critical limit; i.e. the determined critical limit of about 5% for Australian soils and 15% proposed by USDA (Richards, 1954).

Lebron et al. (2002) found that as the ESP increases, the size of soil aggregates decreases, following a potential relationship where the inflection point occurs in the ESP range of 5–15%. This range is shown in literature as the critical limit at which clay tactoids are dispersed. On the other hand, Crescimanno et al. (1995) concluded that ESP values of 2–5% might also cause adverse effects on soil structure if low electrolyte concentrations are present in the soil solution. The breakdown of soil aggregates results in collapse of big pores, reduction of pore size, and increase of pore tortuosity, which directly induce K reduction. These kinds of events may be the cause for the observed decrease of K and are in agreement with the findings of Pilatti et al. (2006) who, in the same circumstances, found that the destruction of soil aggregates by slaking and dispersion were for the main cause of the decrease of water infiltration.

In the present study, water flow (%flow) occurred through macropores of equivalent radii greater than 1000 μm, and varied between 52% and 85% in almost all cases (Eq. (1) and Table 8). Similar results were found by Watson and Luxmoore (1986), Wilson and Luxmoore (1988), and Dunn and Phillips (1991). Therefore, it is expected that plugging of bigger pores would cause greater reduction of K, because of its potential relationship with the diameter of the soil pores. Results of the present study seem to confirm these expectations. The water conduction capacity of pores >1000 μm decreased between 48% and 79% in the irrigated treatments, except in the A depth of the less irrigated treatment of Hughes (Eq. (2) and Table 9).

One of the possible reasons for the K reduction was the pores obstruction caused by organic colloids and disperses mineral particles, as was also mentioned by Kosmas and Moustakas (1990). Keren and Ben-Hur (2003), based on laboratory experiments, hypothesized that abrupt flow of deionized water through repacked soil samples generates a steep concentration gradient between soil solutions outside (diluted) and inside (more concentrated) the aggregates. Afterwards, the water movement inward the aggregates, due to the concentration gradient, could provide additional energy to induce particle dispersion. Similar processes have possibly occurred under field conditions in the irrigated treatments, during the non-irrigated season, due to the dilution effect of the rain. The passage of rainwater through soil dilutes salt concentration of the soil solution but has little effect on the quantity of sodium in the exchange complex, which is less variable seasonally (Wienhold and Trooien, 1995). Thus, favorable conditions for the particles dispersion are produced (Sumner, 1993; Andriulo et al., 1998).

The dispersion index (DI) was greater (Table 6) in irrigated than in non-irrigated treatments, probably due to the effect of Exch. Na^+ combined with low EC_e. DI increased as sodicity index (SI) decreased (Fig. 2). The decrease of SI was caused by the increase of ESP, while EC_e remained constant (Table 4). For

Table 8 – Percentage of the water flow (%flow) occurred through macropores of equivalent radii greater than 1000 μm

Town	Non-irrigated, A_p	Irrigated, A_p	Non-irrigated, A	Irrigated, A
Hughes	59	(I_3) 53	52	(I_3) 82
Hughes	59	(I_{30}) 48	52	(I_{30}) 67
Llambi Campbell	32	60	71	70
Marcelino Escalada	85	73	52	62

A_p, 0–7 cm depth; A, 15–25 cm depth; I_3, 3 years irrigated; I_{30}, 30 years irrigated. $\%flow = [100 - (K_{0.15}/K_0) \times 100]$.

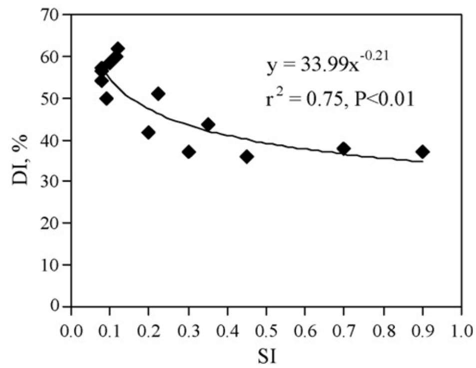

Fig. 2 – Relationship between sodicity index (SI) and dispersion index (DI) in irrigated and non-irrigated treatments.

an ESP value of 4.5, EC_e values smaller than 0.9 could cause soil dispersion. The SI was smaller than 0.2 in irrigated treatments, which seems to confirm the dispersive effect of sodium. On the other hand, the $\%D_{K_0}$ was directly related to the increase of DI in both depths (Fig. 3), which is in agreement with the result of Evangelou (1994). The critical 25% of D_{K_0} was achieved with a DI of 47.5% (Fig. 3). Moreover, in irrigated treatments DI was always greater than this value (Table 7).

The best correlation of $\%D_{K_0}$ with DI in the A_p depth may be attributed to its greater susceptibility to soil dispersion because of the additional energy inputs that it receives from the direct impact of the rain-drop or irrigation water (Levy, 1999). Thus, the necessary EC_e to prevent both soil mechanical and spontaneous dispersion in the A_p should always be higher than that required to prevent just soil spontaneous dispersion in the *A* depth (Rengsamy and Olsson, 1991).

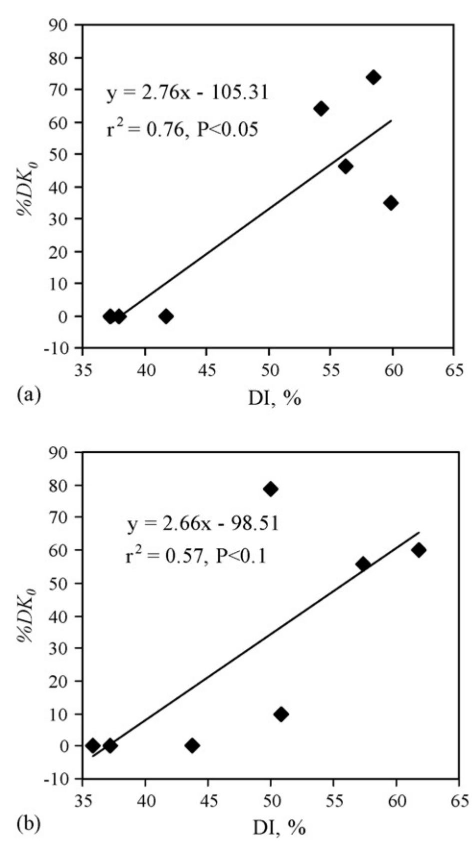

Fig. 3 – Relationship between dispersion index (DI) and percentage of decrease of K_0 [$\%D_{K_0} = (1 - (K_{0I}/K_{0NI})) \times 100$] in (a) A_p depth and (b) *A* depth.

Another factor that may have contributed to the occurrence of clay dispersion at lower values of ESP is the predominance of illites in the studied soils (Stephan et al., 1977; Cosentino and Pecorari, 2002). This type of clay mineral may remain dispersed in solutions of high electrical conductivity because the irregular shape, size, and morphology of the particles prevent strong cohesion (Churchman et al., 1993). These characteristics, in loamy and clayed soils, make the dispersed material move short distances leading to pores blockage without causing macroscopic movement of particles (Shainberg and Letey, 1984; Levy, 1999). The presence of platy structures were observed at naked eyes in the irrigated treatment in the *A* horizon of Llambi Campbell soil. These platy structures could have been formed through the mechanism mentioned above. Lebron et al. (2002) reported that *K* was significantly related to the pore size, aggregate size, and ESP, but neither soil bulk density nor the shapes of the pores have affected *K*.

The results indicate that only in two cases the decrease of *K* was associated with an increase of soil bulk density, and coincidently with a high DI (Tables 5 and 6). It seems that, in most cases, the verified increase of Exch. Na^+ was enough to affect somehow the soil porosity that made *K* decrease. However, it was insufficient to cause soil densification. This fact suggests that by measuring *K* with tension-infiltrometer it is possible to detect the "initial stage" of the soil physical degradation process, which is very important to avoid further soil deterioration.

Since the used methodology was sensitive to identify the adverse effects of waters with high-moderated residual sodium carbonate on soil structure, it is suggested that a good practice would be to maintain a small "control" area without irrigation, near the irrigated area. This area should be used to periodically monitor ESP, EC_e, and *K* should be measured with tension-infiltrometers. The measurements should be carried out from the beginning of the irrigation practice, and periodically afterwards. This, in turn, will allow irrigation to be interrupted as soon as the critical level of ESP and EC_e, or $\%D_{K_0}$ is detected. Immediately recovery practices, as those mentioned by Gupta and Abrol (1990), Jayawardane and Chan (1994) and Oster et al. (1999), should be performed in order to maintain the quality of the soils. However, one has to keep in mind that this study was carried out with soils and waters of singular characteristics. Consequently, more research has to be developed to confirm the utility of the proposed methodology for other soil types and water conditions, especially to determine critical ESP-EC_e values related to the $\%D_{K_0}$.

4. Conclusions

Supplemental irrigation with waters with high-moderated RSC made soil hydraulic conductivity decrease but at values of

ESP not always considered as critical as the ones in literature. Changes in the hydraulic conductivity were associated with soil particles dispersion and with the degradation of bigger pores. The hydraulic conductivity measured with tension-infiltrometer in the field, in conjunction with the ESP and EC_e, were sensitive indicators for detecting early soil physical degradation. These indicators could be used to prevent soil deterioration, and therefore, to contribute to the sustainable management of the soils.

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