Effect of water quality on soil structure and infiltration under furrow irrigation.

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Abstract

The quality of irrigation water has the potential to significantly affect soil structural properties, infiltration and irrigation application efficiency. While the effect of electrolyte concentration (as indicated by the electrical conductivity EC) and sodium adsorption ratio (SAR) have been studied under laboratory conditions, the effect on soil profile structural properties and irrigation performance have not been widely investigated under field conditions. In this paper, water with three different levels of sodium (SAR = 0.9, 10 & 30) was applied as alternative treatments to a clay loam soil. The application of 238-261 mm of medium to high SAR water was found to reduce aggregate stability, increase the bulk density of both the surface crust and underlying soil, and reduce the total depth of infiltration and final infiltration rate. Where low SAR water was used, there was no significant ($P<0.05$) difference in final infiltration rate after the first four irrigations. However, where moderate and high SAR water was applied after the first four irrigations with the low EC-SAR water, the final infiltration rate was found to decrease on each of the successive irrigation events. For the moderate and high SAR treatments, this suggests that a steady-state equilibrium had not been reached within that part of the soil profile impeding infiltration. It is proposed that the initial reduction in infiltration is related to the physical processes of slaking leading to the development of an apedal, hardsetting surface soil layer. Similarly, it is proposed that the subsequent increase in bulk density and decline in infiltration where moderate and high EC-SAR water is applied is due to an increase in clay tactoid swelling reducing the size of the conducting micro-pores, dispersion blocking pores, and/or an increase in the thickness of the apedal surface layer. The reduction in infiltration associated with the use of high SAR irrigation water was found to reduce the performance of the irrigations with the application efficiency of the final irrigation decreasing from 40% where the low SAR water was used, to 21% where the high SAR water was applied. The implications for surface irrigating with water containing high sodium levels are discussed.

Introduction

The performance of surface (eg furrow, border) irrigation is closely related to the infiltration function of the soil (Walker and Skogerboe, 1987). However, the infiltration function has been found to vary throughout the season by a factor of up to four (Elliott *et al*., 1983) with differences in infiltration attributed to surface sealing, variations in the soil moisture content prior to irrigation, and the effect of mulch on flow retardation (Raine *et al.*, 1998). These variations in infiltration, both spatial and temporal, represent a major physical constraint to achieving high irrigation application efficiencies (Shafique and Skogerboe, 1983).

Under field conditions, irrigated soils are exposed to sequential periods of rapid wetting followed by drying. Soils which are subjected to these wetting and drying cycles have been found to exhibit low aggregate stability (Caron *et al.*, 1992; Rasiah *et al*., 1992) resulting in the release of colloidal material and the collapse of soil pores (Levy and Miller, 1997). However, the quality of the irrigation water applied will also affect the soil chemical properties which influence soil dispersion and aggregate breakdown, surface sealing and crust formation, and changes in the infiltration function (Shainberg and Letey, 1984).

Surface irrigation with water from shallow wells is utilised on approximately 40% of irrigated land in Iran. The quality of the well water is variable with some areas using water with high sodium and total electrolyte concentrations. However, the impact of the water quality on the soil structure, infiltration function and irrigation performance is not always recognised and the quality of the water used for irrigation is not always reported. Hence, few workers have been able to distinguish the physio-chemical impacts associated with the quality of the water applied (eg. dispersion) from the physical impacts associated with wetting and consolidation (ie slumping, hydraulic sealing). Similarly, much of the research investigating the effect of water quality on soil structure and soil-water movement has been conducted under laboratory conditions using disturbed or repacked soil cores and conditions which do not accurately represent field conditions (Shainberg and Letey, 1984) and are not able to be used to evaluate impacts on irrigation performance. Hence, the objective of the work reported in this paper was to evaluate the effect of irrigation water quality on the soil structural properties and irrigation performance measured under field conditions.

Materials and Methods

This work was conducted on the Tehran University farm in Karaj, Iran. The soil at the trial site has a uniform clay loam texture (dominated by illite and chlorite) overlying a semi-permeable hardpan at 60 cm. The site had been fallowed for more than three years prior to the implementation of the trial. The trial work consisted of setting up 27 irrigated furrows (top width ~ 0.25 m; base width ~ 0.1 m) with a spacing of 0.75 m, length of 30 m and a slope of 0.01%. The beds were planted with maize and divided into 9 plots, each consisting of three neighbouring furrows. The outer furrows in each plot were used as guard rows and all measurements were taken on the centre furrow.

The soil properties were obtained prior to (Table 1), and after (Tables 2 & 3), the treatments had been applied. Soil samples were obtained using a 50 mm diameter core from the 0-30 cm and 30-60 cm depths in each treatment and replicate. Samples below 60 cm were not obtained as the hardpan layer at 60 cm restricts water movement and root growth below this depth. The pH and electrical conductivity (EC_{se}) were measured on a saturation extract. Sodium cations were measured by flame photometry (Rich, 1965) and the other major cations and anions were measured using titration techniques (Chapman, 1965; Allison and Moodie, 1965; Stout and Johnson, 1965). The particle sizes were measured using the hydrometer method (Gee and Bauder, 1986).

[Insert Table 1 about here]

Irrigation water was applied to all plots at the same time on twelve occasions during the season. No rainfall was received at the site during the trial. The first four irrigations on all plots involved the use of local groundwater (EC = 0.6 dS m^{-1}; SAR = 0.9) to ensure that the maize crop was established. Subsequent irrigations involved the application of three different water quality treatments (with three replications) randomly allocated to the plots. The low salt, low sodicity (low EC-SAR) treatment continued to use the groundwater while the other two treatments involved modifying the groundwater. Sodium chloride solutions were injected at a controlled rate into the irrigation supply pipeline to produce a moderate EC-SAR treatment (EC = 2 dS m^{-1}; SAR = 10) and a high EC-SAR treatment (EC = 6 dS m^{-1}; SAR = 30). Irrigations were applied when the soil moisture deficit reached 50% of the plant available water content (field capacity = 21.9%; wilting point = 9.8%) as measured using a neutron moisture meter on two of the low EC-SAR treatment plots. In all cases, water was applied to the furrows at a constant flow rate for a period (>200 mins) long enough to achieve a steady state infiltration rate. The rate of inflow to each furrow for each irrigation event ranged from 1.6 to 2.4 L s^{-1}.

Kostiakov-Lewis infiltration functions in the form: $I = kt^a + f_o t$ where I is the cumulative infiltration, a and k are fitted parameters, f_o is the final infiltration rate, and t is the infiltration opportunity time, were calculated for each irrigation using the irrigation advance data and the two-point method (Elliott and Walker, 1982). The final, or basic, infiltration rate was calculated as the difference between the furrow inflow and outflow rates (Walker and Skogerboe, 1987) measured after the outflow had reached a steady state. The furrow outflow was measured using a Washington State College (WSC) flume (Chamberlain, 1952).

The effect of irrigation water quality was assessed by measuring the soil chemical and physical properties after the final irrigation event. The development of a surface seal was identified by measuring the density of the seal formed by the irrigation and the change in bulk density within the profile. To measure the surface seal density, two samples of the seal layer (0-5 cm) were removed as clods from each treatment and oven-dried at 100°C for two days. The clods were then coated in paraffin and volume displacement used to determine their densities (Blake and Hartge, 1986). Bulk density measurements were undertaken using a core (diameter = 5 cm) inserted to a depth of 5 cm prior to the first irrigation and following the final irrigation. The bulk density at the end of the season was measured on the soil immediately below the apedal surface layer (ie. ~5-10 cm). In both cases, the soil material from the core was oven-dried as above before being weighed and the bulk density calculated using the method of Blake and Hartge (1986).

Changes in the aggregate stability of the surface soil was assessed using a wet sieve method (Kemper and Rosenau, 1986). Surface soil samples were collected both before the first irrigation and after the last irrigation and crushed to pass through a 4.6 mm sieve. A 50 g soil sample was put on the top mesh of a sieve nest (2.00, 1.00, 0.50, 0.212, 0.106 and 0.075 mm mesh size) and immersed in distilled water. The sieves were then oscillated through a vertical distance of 1 cm at a rate of 30 rpm for a period of 10 mins. After sieving, the soil material on each sieve was collected, dried at 100°C for two days and weighed. The results are presented as the mean weight diameter (MWD) calculated according to Youker and McGuinness (1956).

Analyses of variance (ANOVA) were conducted prior to the calculation of least significance differences (LSD) for the soil chemical and physical data. The LSD analyses were calculated using the data from the two soil layers exposed to each of the three water treatments (ie. six treatment effects). This was conducted to enable comparisons between treatments for each soil layer as well as between the soil layers within each treatment. Paired *t*-tests were conducted on the infiltration data. Unless otherwise stated, 3 replicates of each treatment were used in the statistical tests.

Results and Discussion

Effect on soil chemical and physical properties

The application of the water quality treatments produced significant ($P<0.01$) differences in both the soil chemical (Table 2) and physical (Table 3) properties. In each case, the EC_{se} of the surface soil at the end of the irrigation season was similar to the EC of the applied water (Table 2). However, the EC_{se} of the subsoil was significantly ($P<0.01$) higher than the EC_{se} of the surface soil suggesting that leaching of this layer was inadequate to achieve equilibrium with the applied water.

[Insert Tables 2 & 3 about here]

For the moderate and high EC-SAR water treatments, sodium concentrations were significantly ($P<0.01$) higher, and the calcium and magnesium levels significantly ($P<0.01$) lower, in the soil surface layer compared with the subsoil (Table 2). Hence, there were significant differences in the SAR measured at the end of the season with the surface soil SAR being significantly higher than that of the subsoil for the moderate and high EC-SAR treatments. This is consistent with the elevated sodium levels in the applied water displacing calcium and magnesium ions from the exchange in the surface layers enabling increased leaching of these cations deeper into the profile. There was no significant ($P<0.01$) difference in any of the chemical properties of the surface and subsoil layers after the application of the low EC-SAR water.

The repeated application of irrigation water was visually found to produce an apedal surface layer approximately 5 cm thick. This layer exhibited characteristic signs of hardsetting behaviour associated with soils of similar texture (Mullins *et al*., 1990) including a collapse of some or all of the aggregated structure with wetting and a hardening without restructuring during drying. No significant ($P<0.01$) difference was found in the formation, thickness or block size of the apedal layer among the water quality treatments. However, the process of aggregate breakdown in hardsetting soils is often dominated by the physical process of slaking (Isbell, 1995) and may occur without significant clay dispersion. This suggests that the main mechanism influencing the development of the apedal layer is physically, rather than chemically based, and perhaps explains why the apedal layer formed irrespective of the water quality applied. However, the density of this layer at the end of the season increased with EC-SAR of the water applied (Table 3) suggesting that either clay swelling or dispersion due to elevated sodium levels, even where a high EC exists, may have influenced structural breakdown in this layer.

The density of the soil (5-10 cm) underlying the apedal surface layer was related to the EC-SAR of the irrigation water with the high EC-SAR treatment showing a statistically significant higher density of 1.39 g cm^{-3} compared to 1.33 g cm^{-3} for the low EC-SAR treatment (Table 3). Hence, the processes influencing structural breakdown in this layer are influenced by the chemical changes within the profile. However, the soil immediately below the apedal surface layer was less dense than the surface soil (Table 3), possibly because the surface apedal layer acted to reduce infiltration and hence, the rate of wetting and the physical breakdown of the soil aggregates in this layer.

The aggregate stability of the surface soil decreased (MWD = 0.650 to 0.563 mm) during the season with the application of the low EC-SAR water (Table 3). However, the application of the high EC-SAR water was associated with a decrease in MWD (0.267 mm) to less than half of that measured for the soil irrigated with the low EC-SAR water (MWD = 0.563 mm). The change in aggregate stability is consistent with the changes in SAR for each treatment and previous results (eg. Agassi *et al*., 1981).

Effect on infiltration

The infiltration under field conditions was inversely ($P<0.01$) related to the SAR of the applied water with the high EC-SAR treatment infiltrating 15% less water than the low EC-SAR treatment over the last eight irrigations (Table 2). Significant ($P<0.05$) differences in final infiltration rate were also associated with both the number of irrigations applied and the quality of the water used (Figure 1). The final infiltration rate (expressed as a volumetric rate per metre length of furrow) decreased from 14.6 to 10.7×10^{-5} m^3 min^{-1} during the first four irrigations which all used the low EC-SAR water. This reduction in infiltration rate is commonly associated with slaking and hydraulic seal development due to the wetting and drying cycles associated with initial irrigations (eg. Elliot and Walker, 1982; Shafique and Skogerboe, 1983). However, in the current trial, it seems likely that the infiltration reduction is associated with the formation of the 5 cm thick apedal surface layer.

Where the low EC-SAR water was applied for the remainder of the season (ie irrigations 5 to 12), there was no further significant ($P<0.05$) change in the final infiltration rate (Figure 1). However, where moderate and high EC-SAR water was applied for the last eight irrigations, the final infiltration rate was found to progressively decrease to 7.5 x 10^{-5} m^3 min^{-1} and 5.5 x 10^{-5} m^3 min^{-1}, respectively (Figure 1). The shape of the curves fitted for the moderate and high EC-SAR water suggest that successive irrigations with the moderate and high SAR water were continuing to reduce the final infiltration rate.

The decrease in final infiltration rate with successive applications of moderate and high EC-SAR water (Figure 1) suggests that the change in soil physical behaviour is associated with the progressive change in the chemical properties of the soil solution. It is interesting to note that this change has occurred after the slaking and development of hardsetting associated with the initial four irrigations. Hence, the apparent increasing rates of decline in the final infiltration rate are associated with incremental changes in the soil solution chemical properties.

The post-irrigation soil SAR data (Table 2) indicates that the soil solution in the 0-30 cm layer had not reached equilibrium with the applied water. Assuming that chemical equilibrium is achieved after leaching approximately five times the pore volume through a soil layer (McNeal and Coleman, 1966), then the 238-263 mm applied in the moderate and high EC treatments (Table 2) would have been sufficient for only the surface 5 cm of soil to reach equilibrium conditions. Hence, the underlying soil (ie. greater than 5 cm depth) may not have reached equilibrium with the applied water and the reduction in infiltration as the soil EC-SAR changes with successive irrigations may be associated with either dispersion, clay tactoid swelling or even slumping as evidenced by the increasing bulk density of the 5- 10 cm layer (Table 3). As the change in infiltration is greatest in the treatment with the high EC water where dispersion is least likely to occur, it seems likely that dispersion is not playing a significant role in reducing infiltration. Hence, the effect on infiltration rate is most likely related to the SAR of the soil solution.

Alperovitch *et al*. (1985) found that decreases in hydraulic conductivity on soils with high exchangeable sodium and electrolyte concentrations were primarily associated with an increase in clay tactoid swelling. In these soils, the increase in tactoid swelling reduced the diameter of the water conducting pores increasing the resistance to flow. Similarly, clay swelling has been found to increase with SAR (McNeal *et al*., 1966) and is less affected by EC than is dispersion (Shainberg and Letey, 1984). Hence, one explanation for the reduction in infiltration rate observed in this trial is that there is a progressive increase in clay tactoid swelling due to the increase in soil solution SAR with successive irrigations. This clay tactoid swelling may be reducing the conductance of micropores either in the apedal surface layer and/or in the underlying soil. However, if the thickness of the apedal surface layer is also increasing due to the changes in the SAR of the underlying soil, then the conductance will also be reduced simply due to an increase in total flow path resistance. Further research is required to adequately identify the specific mechanism influencing the decline in infiltration with successive irrigations.

Implications for irrigation management and performance

The furrow irrigation performance was affected by the irrigation water quality. For example, the last irrigation (ie. irrigation 12) was conducted for 250 mins and the cumulative infiltration for the low, moderate and high EC-SAR treatments were significantly ($P<0.01$) different at 42, 35 and 24 mm, respectively. The performance of an irrigation having a target root zone deficit of 35 mm was calculated using the surface irrigation model SIRMODII (Walker, 1996) and the measured infiltration functions for the last irrigation. Under these conditions, the low EC-SAR treatment would need to be applied for ~200 mins and the high EC-SAR treatments for ~350 mins. The increased duration of irrigation would increase run-off from 1.2 to 3.3 m^3 per furrow reducing the application efficiency for this system without tailwater recycling from 40 to 21 %.

It should be noted that the development of the impeding surface layer and the decline in the infiltration rate of the soil were evaluated using water with moderate and high EC and that no rainfall was received at the site during the trial. However, if low EC water is applied, either by rainfall or from another source, to the soil irrigated with the moderate and high SAR water, the subsequent decline in the soil solution EC would be expected to result in a reduction in aggregate stability (Table 3) with a high likelihood of both spontaneous dispersion and a rapid decrease in infiltration. Hence, under these conditions, the effect on the infiltration and irrigation performance of using moderate and high SAR water could be expected to be greater than measured under this trial.

The application of gypsum to sodium affected soil has been used to improve aggregate stability and improve infiltration rates (eg. Agassi *et al.*, 1981; Keren and Shainberg, 1981). In many cases, gypsum is applied to increase the EC and decrease the SAR of the water applied and reduce dispersion. However, where high EC water is used, dispersion does not occur (due to compression of the diffuse double layer) and the benefits associated with gypsum application are directed at reducing the SAR of the applied water and hence, clay tactoid swelling. Given that the initial development of the apedal surface layer in this trial work was dominated by physical processes most closely related to texture, the application of gypsum to this soil or the applied water would not be expected to influence the development of this layer. However, the application of gypsum would be expected to reduce clay tactoid swelling where the EC of the applied water is high and also reduce the soil solution SAR so that dispersion is reduced where low EC water is subsequently applied either as irrigation or rainfall.

Conclusions

Irrigation water quality has been found to significantly affect the soil chemical and physical properties including infiltration. These changes occurred in the presence of high solute concentrations normally associated with maintaining soil aggregate stability and continued throughout the irrigation season. This suggests that the initial reduction in furrow infiltration under field conditions at this site is associated with the development of an apedal surface layer while subsequent declines are associated with either clay tactoid swelling or dispersion processes which in turn reduce pore size and connectivity. However, further work is required to more fully explain the mechanisms affecting the temporal variation in soil structure within the soil profile and the consequent effect on infiltration and irrigation performance.

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Table 1. Selected initial soil physical and chemical properties for the trial site

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	pH_{se}	EC_{se} (dS m^{-1})	P	K	Ca	Mg	Na	HCO_3	Cl	SO_4	SAR
						---- (mg kg^{-1}) ----		---------------------- (mequiv $100g^{-1}$) ----------------------						
0-30	25.4	45.4	29.2	7.9	0.6	8.2	204	3.6	3.2	1.7	2.8	5.0	0.7	0.9
30-60	27.4	47.4	25.2	7.9	1.0	3.6	128	6.4	5.2	2.8	2.4	4.0	8.0	1.2

Table 2. Effect of irrigation water quality on selected soil physical and chemical properties for the trial site.

Irrigation water treatment	Total depth infiltrated[1] (mm)	Depth (cm)	pH_{se}	EC_{se} (dS m^{-1})	Ca	Mg	Na	HCO_3	Cl	SAR
					-------------------------- (mequiv $100g^{-1}$) --------------------------					
EC = 0.6 dS m^{-1} SAR = 0.9	280 [a]	0-30	8.0 [a]	1.0 [a]	6.0 [a]	0.8 [a]	2.7 [a]	2.3 [a]	2.6 [a]	1.5 [a]
		30-60	8.0 [a]	1.1 [a]	7.2 [a]	1.8 [ab]	3.1 [a]	2.1 [a]	2.7 [a]	1.5 [a]
EC = 2 dS m^{-1} SAR = 10	261 [b]	0-30	8.0 [a]	2.4 [b]	6.8 [a]	0.6 [a]	16.7 [b]	2.5 [a]	18.3 [b]	8.7 [b]
		30-60	7.8 [a]	3.2 [c]	17.6 [c]	6.2 [c]	6.8 [a]	1.7 [a]	19.6 [b]	2.0 [a]
EC = 6 dS m^{-1} SAR = 30	238 [c]	0-30	7.7 [a]	6.1 [d]	14.2 [b]	3.0 [b]	41.0 [d]	1.5 [a]	47.3 [c]	14.0 [c]
		30-60	7.7 [a]	7.4 [e]	38.6 [d]	13.2 [d]	20.0 [b]	1.7 [a]	56.6 [d]	3.9 [a]

Superscripts indicate significant ($P<0.01$) differences between treatments within columns. Comparisons should be made between the same soil layers in each treatment or between the two soil layers within each treatment.

[1] Volume infiltrated during irrigations 5-12 where different water qualities were used

Table 3. Effect of irrigation water quality on selected soil physical properties.

Irrigation water treatment	Mean weight diameter (mm)	Apedal surface layer density[1] (g cm^{-3})	Bulk density[2] (g cm^{-3})
Control (prior to irrigation)	0.650^{a}	1.38^{a}	-
EC = 0.6 dS m^{-1}, SAR = 0.9	0.563^{b}	1.41^{a}	1.33^{a}
EC = 2 dS m^{-1}, SAR = 10	0.470^{c}	1.44^{ab}	1.35^{ab}
EC = 6 dS m^{-1}, SAR = 30	0.267^{d}	1.48^{b}	1.39^{b}

Superscripts indicate significant (P<0.01) differences between treatments within columns.
[1] surface layer not apedal prior to irrigation [2] measured on the 5-10 cm layer

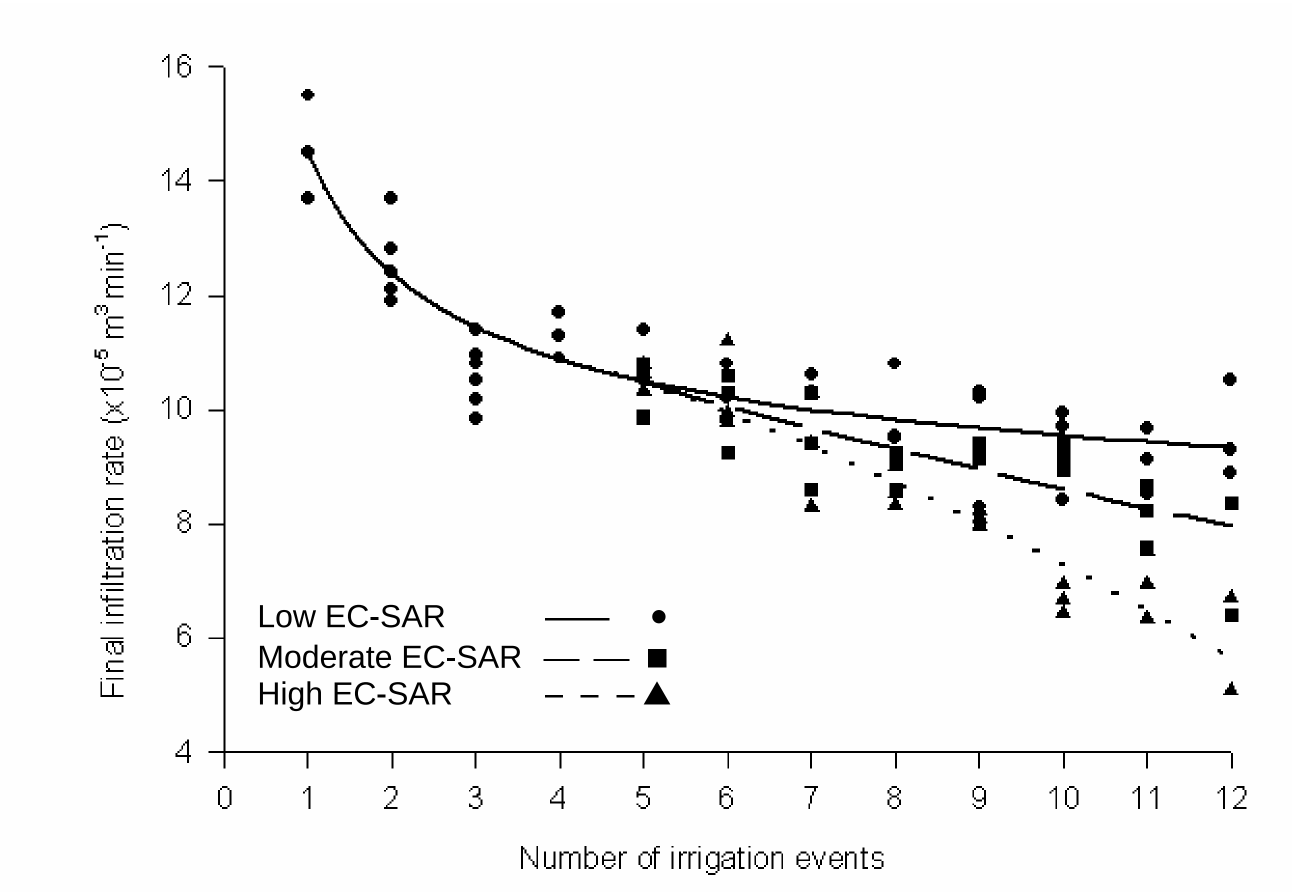

Figure 1. Effect of water quality (low EC-SAR = ●; moderate EC-SAR = ■; high EC-SAR = ▲) on final infiltration rate for sequential irrigations during the season