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Effect of SAR on water infiltration under a sequential rain–irrigation management system

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ABSTRACT

Existing irrigation water quality criteria related to sodium and salinity are based primarily on short-term laboratory column studies. These earlier studies measured infiltration or hydraulic conductivity of disturbed soil under continuously saturated conditions. Application of these standards to field conditions is uncertain, as it does not account for wetting and drying conditions, formation of crusts and impact of rain events, etc. In this study we examine water infiltration into loam and clay soils irrigated at EC = 1.0 and 2.0 dS m^{-1} at SAR of 2, 4, 6, 8, and 10 in a management system with alternating (simulated) rain and irrigation and drying between irrigations. For the loam soil the adverse impacts of sodium on infiltration were evident above SAR 2, while for the clay soil adverse impacts occurred above SAR 4. In both soils the SAR behavior was similar for both EC values, 1.0 and 2.0 dS m^{-1}, indicating that in this range, EC did not affect infiltration. Reductions in infiltration were evident during both the irrigation and rain events, with lower infiltration, as expected during the rain simulations. These results show a greater sensitivity to SAR than indicated in laboratory column studies and existing water quality criteria.

1. Introduction

Water quality criteria for irrigation must consider both the direct impact on crop yield and the indirect impact related to effects on soil chemical and physical properties. It is well recognized that the salinity of a irrigation water and the sodium adsorption ratio (SAR), defined as $Na/(Ca + Mg)^{0.5}$ in solution, where concentrations are expressed in mmol L^{-1}, have an interactive effect on soil physical properties. Elevated values of SAR result in decreased hydraulic conductivity, decreased aggregate stability, clay dispersion, swelling of expandable clays, surface crusting and reduced tilth. For a given SAR value, the adverse impacts on soil physical properties are reduced with increasing salinity. Salinity is commonly reported as electrical conductivity (EC) in dS m^{-1} of the solution. The SAR is a useful parameter that it is closely related to the exchangeable sodium percentage (ESP) in the soil.

Most water quality criteria are based on short-term laboratory experiments with continuous water flow in packed soil columns. Rain events on a sodic soil cause a reduction in soil electrical conductivity and hence may have an adverse impact of soil physical properties. It is recognized that application of a Ca source such as gypsum is beneficial to infiltration of winter rains when irrigating with waters of elevated SAR in Mediterranean climates. Under these circumstances the management system is considered as two distinct conditions—using the existing water quality criteria during the irrigation season and applying gypsum before the winter rains sufficient to decrease the ESP in the surface soil to almost zero. When rain is interspersed throughout the irrigation season it is not feasible to surface apply gypsum after each

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event, thus the rain hazard must be considered within the irrigation water quality criteria. Information is lacking on suitable water quality criteria when waters of elevated SAR are irrigated under climatic conditions where rain events occur during the cropping season.

This experiment was designed to test infiltration and hydraulic conductivity of the near surface horizons of two Montana soils, Kobase silty clay fine-montmorillonitic Borollic Camborthid, from the Tongue River area and Glendive very fine sandy loam, coarse-loamy, mixed (calcareous) frigid Ustic, Torrifluvent, from the Powder River area, both irrigated with 10 simulated river waters with two EC and five SAR levels and subjected to alternating rainfall.

The objective of the present study is to establish irrigation water suitability criteria under conditions of combined rain and irrigation—a distinctly different condition from that of most earlier studies and standards. Under a combined rain–irrigation system the soil may go from a relatively saline condition, for example EC 3.0 dS m^{-1} and SAR 10, to a non-saline condition with EC <0.5 dS m^{-1} in the upper part of the profile after a significant rain. The decrease in SAR will be slower than the decrease in EC, depending on the cation exchange composition and extent to which Darcy flow is approximated. This condition causes a potential sodium hazard, potentially leading to dispersion, loss of aggregate stability, and decrease in infiltration rate, during the rain event under conditions when the soil may have been stable under irrigation. In such systems the hazard is considered greatest during a rain event, thus the irrigation water criteria must consider not only the direct effect of the irrigation water but more importantly, the resultant effect of a subsequent rain event.

2. Review of the literature

There is an extensive series of scientific reports on the adverse effects of waters of varying quality on soil hydraulic properties. Almost all the research consisted of laboratory studies with disturbed soil in columns under continuous water flow and saturated conditions. In a series of studies McNeal characterized the effects of EC and SAR on soil hydraulic conductivity and soil swelling (McNeal and Coleman, 1966; McNeal et al., 1966, 1969; McNeal, 1968). For arid land soils of the southwestern U.S. they observed a range in stability, concluding that soils high in kaolinite and sesquioxides appeared to be most stable and soils high in montmorillonite appeared to be the least stable (McNeal and Coleman, 1966). For the most sensitive Gila soil there was a 25% reduction in hydraulic conductivity at EC = 2 and SAR = 5 (no data below EC = 2 and SAR = 5).

Frenkel et al. (1978) examined three southern California soils in laboratory columns, with predominant clay mineralogy of kaolinite, vermiculite and montmorillonite. They leached soils with waters of either SAR 10, 20 or 30 with successively more dilute waters of EC 10, 5, and 1 dS m^{-1} and distilled water. At SAR 10, decreases in hydraulic conductivity for montmorillonitic soil occurred at EC = 1 dS m^{-1}, relative to hydraulic conductivity at EC = 5. The kaolinitic soil decreased in hydraulic conductivity only for distilled water, as compared to EC = 1 dS m^{-1}. The vermiculitic soil showed a slight decrease at EC = 1 (8%), as compared to EC = 5 dS m^{-1} and a sharp decrease with distilled water. While useful, these experiments lack information below SAR 10 and provide no information between EC = 1 dS m^{-1} and distilled water.

There are a limited number of studies where rain or dilute waters were applied after saline waters and infiltration or hydraulic conductivity was measured. Shainberg et al. (1981a) reported decreases in relative hydraulic conductivity to, respectively, 20% and 10% of the initial value when soil–sand mixtures of a soil, previously leached with saline solutions of, respectively, SAR 5 and 10, were subsequently leached with deionized water. The adverse response was likely accentuated by the mixing of soil and sand and subsequent high flow rates of the solutions through the columns. High flow rates enhance particle detachment from aggregates and clay migration. However, the extent to which a sodic soil adversely responds to deionized water is also related to the extent to which the soil can maintain an elevated EC as a result of mineral dissolution, primarily presence and reactivity of calcium carbonate (Shainberg et al., 1981b), as well as the exchangeable sodium and salinity of the soil. The soil examined by Shainberg et al. (1981a) contained only traces of calcite and leached quickly to low EC values.

Agassi et al. (1981) determined that the infiltration rate was more sensitive to the effects of sodicity when applying the water via rainfall simulator as compared to changes in hydraulic conductivity in saturated column studies. These differences were attributed to particle disturbance on the soil surface.

Kazman et al. (1983) used disturbed soil prepared at various ESP values, packed in soil trays and leached with a rainfall simulator. The infiltration rate decreased as the ESP increased from 1.0 to 2.2 to 4.6 for Hamra-Netanya soil, from ESP 1.8 to ESP 6.4 for Nahal-Oz soil, and from ESP 2.5 to ESP 5.5 for Kedma soil. These laboratory data were based on a single rain application to a disturbed soil sample but indicate that even in the range of ESP 1.0–6.4, there may be a reduction in infiltration during rain events. Kazman et al. (1983) also noted that the sensitivity to sodium was greater for the infiltration rate of rain than for the hydraulic conductivity of a saturated soil with the same solution composition.

In one of the few studies of longer duration with wetting and drying, Oster and Schroer (1979) reported on infiltration studies from undisturbed cropped soil columns in a greenhouse. Eighteen waters of varying composition were applied, one container for each treatment. They were grouped around three salinities, corresponding to approximately EC 0.5, 1.2 and 3.0 dS m^{-1} and three SAR values of 3, 10, and 22. Two other treatments consisted of distilled water and alternate irrigation with distilled water and water of EC = 3 dS m^{-1} and SAR 20. They concluded that even for the set of waters around SAR 2–4.6 there was increased infiltration as the irrigation water increased from EC 0.5–2.8. The container with alternate irrigation with EC = 3 dS m^{-1} at SAR 20 and distilled water had a lower infiltration rate than the container irrigated only with EC = 3 dS m^{-1} at SAR 20 irrigation water. Although statistical significance cannot be evaluated, the data suggest that decreases in infiltration may occur at SAR values as low as 2–4.6 when the irrigation water is at or below EC 0.5 dS m^{-1}.

While very useful, the direct application of these studies to field conditions is limited by examination of short-term effects and, except for the study by Oster and Schroer (1979) by omission of wetting and drying cycles. In non-desert regions, where rainfall is a factor, the application of these studies is uncertain due to the lack of information on the interactive effects of rainfall and irrigation water. The impact of rainfall is particularly important in regions where rain is a substantial component of the total amount of water and is especially important if the rainfall is distributed over the year and during the growing season.

Almost all research on the response of a soil to solution salinity and composition has been conducted on arid land soils with the objective of determining the suitability of water for irrigation without consideration of rain, usually only EC and SAR of the irrigation water. Also these hydraulic conductivity studies were almost all based on disturbed soils packed into laboratory columns and run under continuously water-saturated conditions. Based on these studies done at the U.S. Salinity Laboratory and on field observations, Rhoades (1977) and subsequently Ayers and Westcot (1985) developed water suitability relationships, later adopted by Hanson et al. (1999), among others.

Other water quality classifications include that of Gupta (1994), who classified all waters with EC <2 dS m^{-1} and SAR <10 as good, based on studies with soils in India. Quirk and Schofield (1955), based on laboratory studies, developed a permeability relationship related to exchangeable Na and electrolyte concentration. They considered waters at 2 $mmol_c$ L^{-1} to result in decreasing permeability at all ESP levels, at 10 $mmol_c$ L^{-1} to result in decreasing permeability for ESP above 25 (corresponding to about SAR 23), and at 20 $mmol_c$ L^{-1} to result in decreasing permeability for ESP below 37 (corresponding to about SAR 35). For the present discussion we can convert the Quirk and Schofield (1955) concentration data to EC with the approximate relationship 10 $mmol_c$ L^{-1} = EC 1 dS m^{-1}.

The Quirk and Schofield (1955) criteria were also used by Frenkel (1984). Pratt and Suarez (1990) concluded that based on existing data, a ''general relationship cannot be predicted because soils greatly differ, but a good SAR versus concentration relationship for a set of soils from a region or locality is possible''. They further state that differences among soils are at least partly due to different experimental procedures.

The guidelines adopted by Ayers and Westcot (1985) and currently used throughout the world are based on earlier studies and guidelines, including those by Rhoades (1977) and Oster and Schroer (1979). Based on Fig. 1 from Ayers and Westcot (1985), at an EC of 1 dS m^{-1} it is considered that there is no impact in infiltration below SAR 3 and a severe reduction only above SAR 13, while at EC = 2 dS m^{-1} the corresponding SAR values for no impact are below 10 and for severe reduction, above 21. The guidelines given by Oster et al. (1992) indicate that infiltration problems are unlikely for SAR values in the range 3–6 when the EC is greater than 1.0 dS m^{-1} and likely when EC is less than 0.4 dS m^{-1}.

Ayers and Westcot (1985), (Table 1) cited the UC Committee of Consultants report (1974) and classified all water at SAR 1–3 as having no restriction on use if the EC was greater than

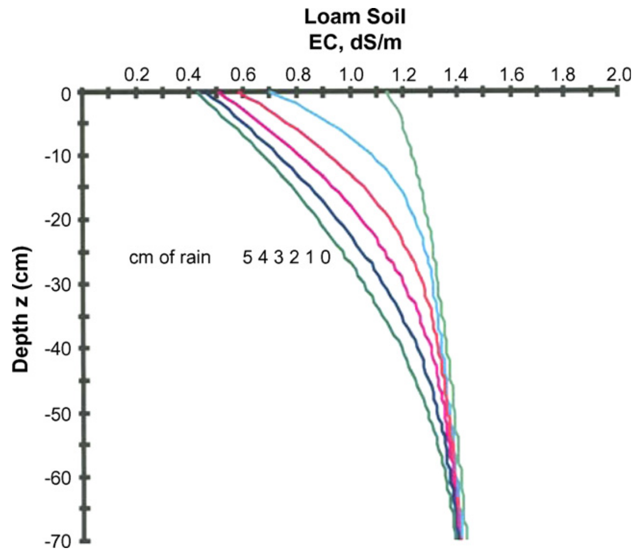

Fig. 1 – Predicted relationship of EC with depth and quantity of rain infiltrated for Glendive loam soil. The initial condition was based on earlier irrigation with water of EC = 1.0 dS m^{-1} and SAR = 10. Each curve represents addition of 1 cm of rain.

0.7 dS m^{-1}, and slight to moderate restriction if EC was 0.7–0.2 dS m^{-1}. For waters of SAR 6–12 they rated waters of EC >1.9 dS m^{-1} as having no restriction on use and waters of 1.9–0.5 dS m^{-1} as having slight to moderate restriction on use due to effects on infiltration. In a discussion of assumptions in the guidelines they state ''in a monsoon climate or areas where precipitation is high for part or all of the year, the guideline restrictions are too severe''. However, this statement is contrary to the criteria of most guidelines, where more dilute waters, such as rain, are more limiting in terms of infiltration. We thus assume that the statement refers primarily to the criteria related to salt tolerance and not to sodicity and rate of infiltration.

There is a very limited set of data on the effect of chemistry on infiltration under rain and these limited data were obtained in experiments without the critical wetting and drying cycles representative of field conditions. The soils and conditions in the desert south west of the U.S.A. and in Mediterranean climates are also distinct from those in the Upper Great Plains of the U.S.A. In the Mediterranean climate almost all rain falls in the winter, thus the hazard and dispersing effect likely occurs only once a year during the transition of water supply from irrigation to rain. Similar conditions exist in the Central Valley of California, U.S.A., but with much lower relative inputs of rain, and again all in the winter. In the Upper Great Plains as well as in other irrigated regions, such as the southeastern U.S.A., rain is more evenly distributed throughout the year and there is a mixture of rain and irrigation through the cropping season.

As discussed earlier, there are differences in stability among soil types—some soils are much more stable and others are less stable than indicated by a single stability line. The variation among soil types in laboratory studies is large, as indicated by Pratt and Suarez (1990). In addition, elevated pH

Table 1 – Montana river water and Riverside experiment irrigation water composition

	EC (dS m^{-1})	Na ($mmol_c$ L^{-1})	K ($mmol_c$ L^{-1})	Ca ($mmol_c$ L^{-1})	Mg ($mmol_c$ L^{-1})	Sum+ ($mmol_c$ L^{-1})	SAR ($mmol_c$ L^{-1})	SO_4 ($mmol_c$ L^{-1})	Cl ($mmol_c$ L^{-1})
Montana Rivers									
Tongue	0.77	2.52	0.14	3.05	3.49	9.20	1.39	4.22	0.11
Powder	2.07	12.5	0.23	7.28	5.41	25.5	4.97	17.4	2.13
Control	0.88	1.73	0.06	5.15	2.79	9.73	0.87	5.37	0.71
EC 1 dS m^{-1}, SAR 2	1.03	3.81	0.00	3.76	3.60	11.2	1.98	7.56	1.73
EC 1 dS m^{-1}, SAR 4	1.08	6.02	0.00	2.88	2.12	11.0	3.80	7.65	1.96
EC 1 dS m^{-1}, SAR 6	1.06	7.26	0.00	1.66	1.54	10.5	5.74	7.14	1.61
EC 1 dS m^{-1}, SAR 6	1.08	8.04	0.00	1.05	1.12	10.2	7.72	7.10	1.76
EC 1 dS m^{-1}, SAR 10	1.09	9.01	0.00	0.90	0.73	10.6	9.98	6.39	2.58
EC 2 dS m^{-1}, SAR 2	1.99	6.22	0.05	5.45	13.0	24.7	2.05	16.9	3.53
EC 2 dS m^{-1}, SAR 4	2.06	10.7	0.04	5.52	8.80	25.1	4.00	17.4	3.40
EC 2 dS m^{-1}, SAR 6	2.06	13.3	0.04	4.71	4.80	22.9	6.11	16.7	2.45
EC 2 dS m^{-1}, SAR 8	2.09	15.6	0.04	3.31	3.93	22.9	8.18	17.1	2.34
EC 2 dS m^{-1}, SAR 10	2.16	16.4	0.03	3.18	2.42	22.0	9.82	12.6	6.59

has an adverse impact on soil stability as determined by Suarez et al. (1984).

There is still uncertainty as to how these published results from other studies and recommendations may relate to Montana soils, under a combined rain and irrigation water sequence. Water quality standards to protect agricultural production where the combination of rain and irrigation occurs regularly may be different from existing standards for arid areas. There are no quantitative data on the response of soils to various EC and SAR waters in a combined rain–irrigation system with surface wetting and drying. Farmers in Montana believe that problems with rate of infiltration may start to occur with use of irrigation waters in the range of SAR 4–5. Although useful, such observations do not meet scientific criteria of controlled studies. Thus, there is a need to test the water quality impacts on Montana soils under cycles of wetting and drying comparable to field conditions.

3. Materials and methods

3.1. Soils

Cultivated surface soils were collected in Montana U.S.A. in May of 2003. Kobase silty clay, fine-montmorillonitic Borollic Camborthid, was collected near the Tongue River north of Miles City Montana (46.47607N, 105.77404W). Glendive very fine sandy loam, coarse-loamy, mixed (calcareous), frigid ustic Torrifluvent, was collected near the Powder River east of Miles City Montana (46.49131N, 105.32401W). Soils were transported to Riverside, California, crushed and passed through a 5 mm screen, air dried, and analyzed for texture and chemical characteristics. Tongue and Powder River water samples were also collected to enable comparable water compositions to be used in the Riverside, California experiment.

3.2. Experimental design

Plastic containers 29 cm tall with a diameter of 19.4 cm at the base and 25 cm at the top were fitted with 5 by 6 cm ceramic extractors buried in the bottom of the containers into 7 cm of number 90 fine quartz sand. After mixing each of the individual soils, 17 cm of soil was uniformly placed above the sand with light packing.

For each soil we prepared 33 containers. Four empty containers were also positioned in four rows all in an open outdoor area under the rainfall simulator. The plots were subjected to alternating simulated rain and irrigation events. A vacuum of 50 kPa (0.5 bars) was applied to the extractors before, during and after each water application but was shut off when flow ceased. Soils were allowed to dry between water applications. The simulated rain water consisted of partially deionized Riverside tap water with an EC of 0.016 dS m^{-1}.

An overhead traveling rainfall simulator was designed to sprinkle rain water uniformly over the buckets. The sprinkler heads, H 1/2 U SS 8070 (Spraying Systems Co., Wheaton, IL[1]), were designed to simulate rain drop sizes of 1.6 mm in

[1] Trade names are provided for the benefit of the reader and do not imply endorsement by the USDA.

diameter with terminal velocity representative of rain. They were inserted into a chain-driven overhead boom that traveled approximately 100 cm beyond each end of the rows of containers. The distance between the sprinkler heads were adjusted to optimize uniformity. Each container had a sprinkler overlap from two sprinkler heads. The system, 140 cm above the soil surface, delivered 100 mL per container or 0.25 cm of rain per pass at an intensity of 0.21 cm s^{-1}. Accuracy of the rain applicator, expressed as uniformity of the application as measured in random open containers inserted into each of the container rows, was better than ±10% for each pass and almost always better than ±5%. A complete rain event consisted of 20 passes in small groups to allow drainage and to deliver a total of 2.00 L (5 cm) as measured in the empty containers. Passes were made in sequence to form temporary ponded conditions in order to measure infiltration times for the applied depth of water to disappear into the soil surface.

The simulated irrigation waters consisted of two different salinities, corresponding to EC = 1.0 and 2.0 dS m^{-1}, at SAR 2, 4, 6, 8, and 10, and one control consisting of Riverside tap water with EC = 0.5 dS m^{-1}, SAR <1. The irrigation waters were applied on the surface (flood) at applications of 2 L or 5 cm. Irrigation waters were stored in 11 barrels of 240 L each.

The EC–SAR combinations and the control were replicated three times for each soil. During water applications, infiltration in minutes and cm per day were calculated for each plot. For rain applications, infiltration was measured during several intervals for all applications. Local potential evapotranspiration was determined from an on-site weather station (ET_0) and total water applied was recorded. At the end of the year, undisturbed soil cores and bulk soil samples were taken from each container for analysis.

3.3. Statistical analysis of infiltration data

Within the year, the infiltration data consisted of repeated measurements collected from a completely randomized, two-way factorial design. The factors in this study include two EC levels: 1.0 and 2.0 dS m^{-1}, and five SAR levels: 2, 4, 6, 8 and 10. The response variable considered in this analysis is the natural log (ln) transformed infiltration time of the applied rain water. Note that the ln transformation of the infiltration time data was used to help stabilize the variance and induce approximate symmetry in the response measurements collected during each sampling period.

For each sampling period, a balanced two-way factorial model, i.e. a traditional two-way ANOVA model with interaction, was used assess the effects of EC and SAR on the ln transformed infiltration time data. The ln transformed infiltration time data was analyzed separately by soil type. A multivariate testing approach was adopted to formally test for changes in the estimated EC and/or SAR parameters across multiple sampling periods (Davis, 2002).

3.4. UNSATCHEM simulations

We utilized the UNSATCHEM model (Suarez and Simunek, 1997) to simulate the effect of rain on soil salinity and SAR after the soil had been irrigated with SAR = 10 and EC = 1 dS m^{-1} water. The simulations used the specific cation exchange capacity and irrigation waters used in the field experiments.

4. Results

4.1. Water chemistry

Major ion analyses of the Tongue and Powder Rivers, sampled in May 2003 are presented in Table 1. On the sampling dates the EC values were 0.77 dS m^{-1} for the Tongue River north of Miles City and 2.07 dS m^{-1} for the Powder River east of Miles City, and the SAR values were 1.39 and 4.97, respectively. The analysis of the experimental irrigation waters, given in Table 1, indicates that all waters are close to the target EC and SAR values. The EC of the simulated rain water was in the range of 0.015 dS m^{-1}. Rain water is variable in composition with time and space; this simulated water is likely towards the lower range in EC for western U.S.A. rain.

4.2. Soil properties

The soil texture of the soils and calculated bulk density of the packed containers is given in Table 2. As expected the two soils provide a contrast in soil texture. The Glendive soil contains high amounts of sand and more silt than clay. The Kobase soil is low in sand content, containing only 1.3% sand and 54% clay. The texture classification of our soil samples corresponds to the classification in the soil names. The bulk density values in Table 2 were based on settling of the overall column and may be slightly overestimated due to the assumption that the sand layer did not settle. The sand layer was placed in the bottom of the containers to allow for a constant pressure head at the bottom of the soil when vacuum is applied, thus allowing for meaningful comparisons of infiltration rates.

4.3. UNSATCHEM computer simulations

The UNSATCHEM (Suarez and Simunek, 1997) computer simulations were made to evaluate the effect of the simulated

Table 2 – Physical properties of packed soils

	Glendive "loam"	Kobase "clay"
Initial dry packing		
Bulk density (g cm^{-3})	1.35	1.19
Depth (cm)	17	17
Weight (kg)	8.72	7.69
Wetted and settled		
Depth (cm)	16	14
Bulk density (g cm^{-3})	1.46	1.5
Texture (%)		
2–5 mm rock	0.88	0
50 μm to 2 mm sand	46.4	1.34
2 μm to 50 μm silt	28.5	44.7
<2 μm clay	24.2	53.9
Cation exchange capacity ($mmol_c$ kg^{-1})	58	208

Containers were pre-filled with 7 cm of fine sand.

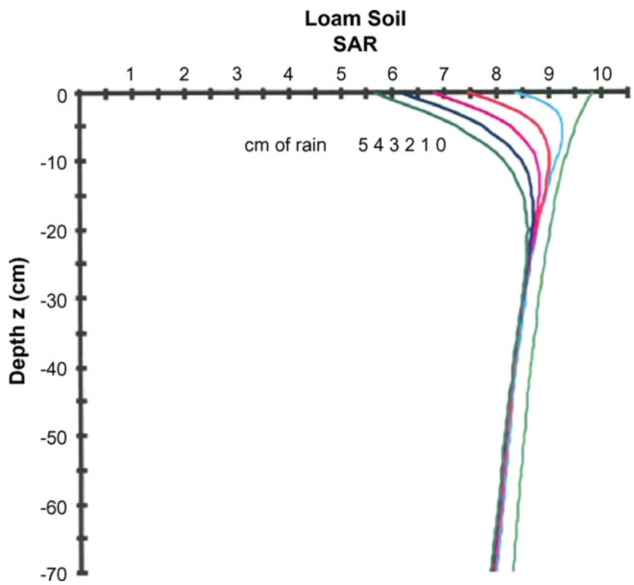

Fig. 2 – Predicted relationship of SAR with depth and quantity of rain infiltrated. The initial condition was based on earlier irrigation with water of EC = 1.0 dS m^{-1} and SAR = 10. Each curve represents addition of 1 cm of rain.

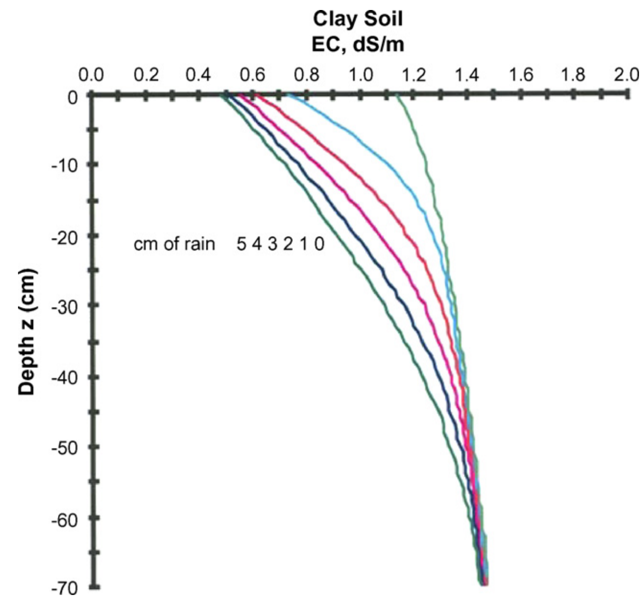

Fig. 3 – Predicted relationship of EC with depth and quantity of rain infiltrated into the clay soil. The initial condition was based on earlier irrigation with water of EC = 1.0 dS m^{-1} and SAR = 10. Each curve represents addition of 1 cm of rain.

rain events on soil SAR and EC. These simulations consider that both soils contain significant amounts of calcium carbonate and thus assume that the soil solution will equilibrate with the calcium carbonate. The simulation inputs included the measured cation exchange capacity (CEC) of the Glendive loam soil (58 mmol$_c$ kg^{-1}) and that of the Kobase clay soil (208 mmol$_c$ kg^{-1}). In the computer simulations shown in Figs. 1–4, we first equilibrated the soils by irrigating with the EC 1.0 dS m^{-1}, SAR 10 water of composition given in Table 1.

The actual soil water EC before application of rain, shown as 0 cm of rain in Fig. 1, is higher than the input irrigation water due to dissolution of calcite in the soil. Increasing EC with depth is due to the simulated increase in carbon dioxide in the soil profile, resulting in more dissolution with depth. As shown in Fig. 1 for the loam soil, the predicted EC at the surface decreased during the rain event, decreasing to 0.42 dS m^{-1} at the surface after infiltration of 5 cm of rain. Again, the soil water EC is maintained above the rainfall EC (0.016 dS m^{-1}) due to calcite dissolution. Calcite dissolution during the rain event is further enhanced by the exchange of solution Ca for Na on the exchange sites, thus causing a reduction in the ESP with time. As shown in Fig. 2, the SAR of the loam soil also decreased during the infiltration of rain but was still at SAR = 5.5 at the surface after 5 cm of rain. The decrease in SAR is not sufficient to compensate for the decrease in EC thus the sodium hazard is increased during the rain event. The surface SAR values are likely upper limits since the soil surface does not likely achieve calcite equilibrium during a rapid infiltration event.

The decrease in EC as related to application of rain for the clay soil is simulated in Fig. 3. Note that the decrease in EC at the surface is very similar but slightly less than that observed for the loam soil (Fig. 1). This is caused by the increased dissolution of calcite due in turn to the increased cation exchange of the clay soil. Calcite dissolution in the absence of exchange would result in an EC of only about 0.15 dS m^{-1}.

As shown in Fig. 4, the SAR of the clay soil was only slightly affected by the infiltration of 5 cm of rain. The higher CEC of the clay soil as compared to the loam soil means that the soil exchange sites are able to buffer the solution SAR. The soil surface of the clay soil at the end of the rain event is thus at low EC with almost no decrease in SAR relative to the pre-rain

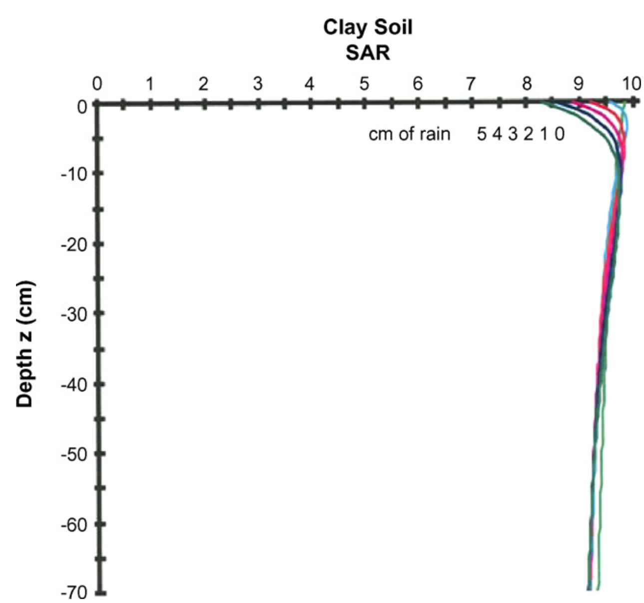

Fig. 4 – Relationship of SAR with depth and quantity of rain infiltrated into clay soil. The initial condition was based on earlier irrigation with water of EC = 1.0 dS m^{-1} and SAR = 10. Each curve represents addition of 1 cm of rain.

condition. These simulations suggest that the chemical effects related to the infiltration hazard of rain on a sodic soil would be greater for soils of greater cation exchange capacity.

4.4. *Infiltration studies*

The experiment was conducted from 19 August 2003 until 27 January 2004. The individual dates of the water applications and quantities are given in Table 3. The cumulative application of water and potential evapotranspiration, ET_0, with time is given in Fig. 5. The total applied water was 71 cm and the ET_0 was 44 cm. Actual ET was not determined, but is significantly less than ET_0, as the soil was bare. Due to the hotter, drier climate in Riverside California, as compared to eastern Montana, this experiment simulates more than 1 year of water applications in Montana.

During the experiment, infiltration was not measured during the first irrigation as the soil was dry and settling. As shown in Fig. 6, the subsequent rain infiltration rates already showed trends with SAR after that one irrigation event. These data were collected after application of only 0.5 cm of rain, thus the soil was relatively dry and the infiltration rate for the clay soil exceeded that for the loam soil. These single event data are likely comparable to conditions in reported results in the literature for effects with rain infiltration. Infiltration rates in the containers may be lower than field rates under comparable conditions due to air entrapment and compression below the wetting front (Peck, 1965; Raats, 1973). We report infiltration rates for the intermediate passes of the rainfall simulator when the upper soil is already near saturation and for conditions when ponded water heights did not exceed 0.4 cm.

The data shown in Fig. 7 represent the infiltration rates for the loam soil during the last rain event at the end of the experiment. As can be seen, there was a decrease in infiltration as the SAR increased from 2 to 4, for both the EC = 1 and 2 dS m^{-1} treatments, and further decreases in infiltration with higher SAR treatments. There appeared to be little difference in response to SAR for the two different salinity waters, suggesting that for this soil and in this salinity range, EC is not important. The clay soil had a much lower infiltration rate, as shown in Fig. 8 with an expanded scale. The relative changes in infiltration with SAR are similar for both soils. From Fig. 8 we conclude that at SAR = 2 there was no decrease in infiltration relative to the control, but that at SAR 4 there was a large, significant, 30% decrease in infiltration rate. The infiltration rate continued to decrease with increasing SAR. There were some differences in infiltration of the clay soil between EC = 1 and 2 dS m^{-1}, however, they are relatively minor for this one time measurement and mostly within the statistical uncertainty.

Table 3 – Water application events

2003 season dates	
19 August	Soil placed in containers with 5 cm tap water then 2 cm of rain applied
22 August	Irrigation 5 cm
27 August	Rain 5.1 cm
04 September	Irrigation 5 cm
12 September	Rain 4.6 cm
17 September	Irrigation 5 cm
23 September	Rain 5.2 cm
30 September	Irrigation 5 cm
08 October	Rain 4.8 cm
30 October	Irrigation 5 cm
13 November	Rain 5.9 cm
09 December	Irrigation 6.3 cm
22 December	Rain 3.6 cm
26 December	Natural rain 1.4 cm
02 January	Irrigation 5 cm
13 January	Rain 3.5 cm

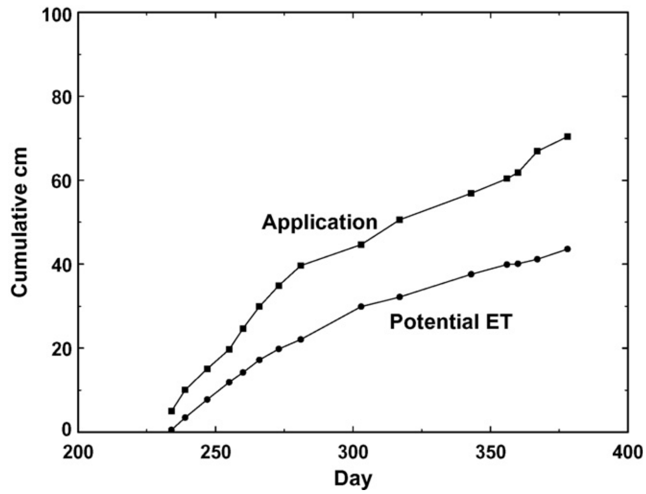

Fig. 5 – Cumulative applied water (rain + irrigation) and potential evapotranspiration (ET_0) at the Riverside Salinity Laboratory, 2003–2004.

4.5. *Statistical analysis of infiltration data*

Determination of infiltration rates was complicated by the differences in initial water contents at different times and

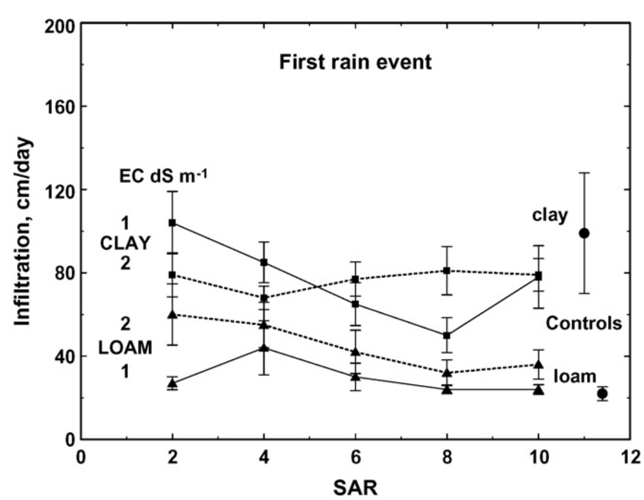

Fig. 6 – Infiltration rate after application of 1.0 cm of water during the first rain event. Each solid symbol represents the mean of three replicates, triangles represent loam soil and squares represent clay soil.

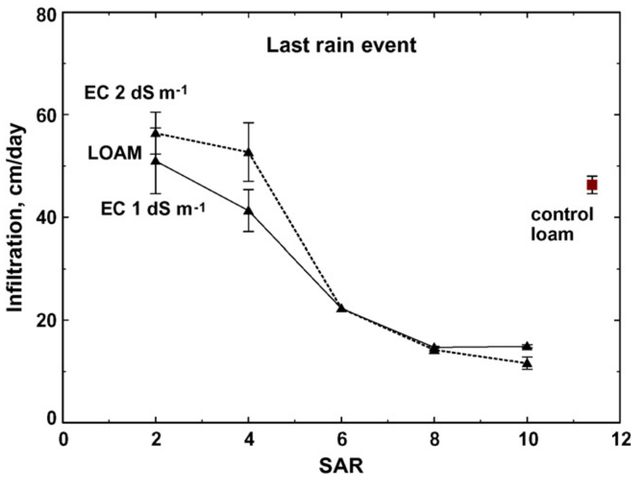

Fig. 7 – Relationship among infiltration rate, SAR and EC for loam soil during the last rain event.

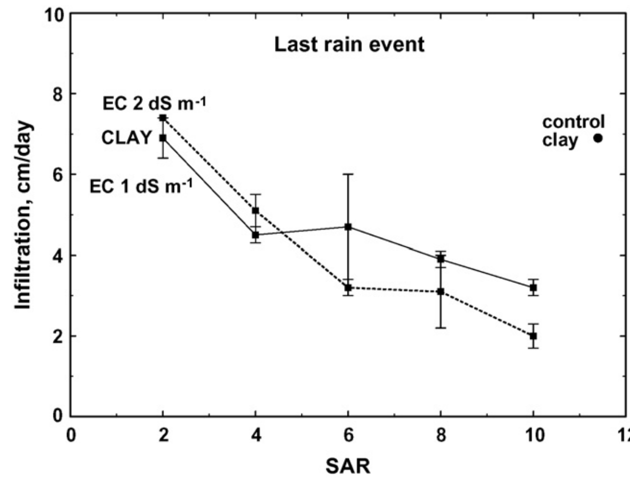

Fig. 8 – Relationship among infiltration rate, SAR and EC for clay soil, during the last rain event.

by the time dependence of the infiltration events. During initial events, cracks in the clay soil resulted in very high infiltration rates for the first cm of water, greatly in excess of the infiltration rates for the loam soil. In some instances the cracks extended to the bottom of the container and the initial water could flow directly into the extraction system at the bottom of the containers. Once the cracks sealed, the infiltration rate of the clay soil decreased dramatically.

As shown in Table 4, rain infiltration data from six sampling periods were analyzed in each of the experiments. Complete infiltration measurements were generally collected between the 4th and 10th pass of the rainfall simulator, corresponding to infiltration after application of 1–2.5 cm of water. In this analysis we have attempted to use readings from different dates collected as close to the sixth pass as possible, in order to minimize the effects of differential water application amounts on the infiltration time readings. In all instances, comparison between treatments was made for the same irrigation or rain event and for the same interval or pass. No outliers were removed.

All statistical analyses presented here were performed using SAS version 8 (proc GLM and MIXED), all results are presented in natural log (ln) transformed infiltration time units, i.e. ln minutes). Note that a full listing of the experimental data analyzed here is given in Appendix A.

Before adopting the multivariate repeated measurement analysis approach, the covariance structures of the ANOVA model residual errors across sampling periods were analyzed. This analysis was performed in order to determine if a mixed linear modeling approach could be adapted to analyze the bare soil experimental data (Davis, 2002). Six mixed linear model covariance structures were estimated in all: (1) *Uns(MV)*: unstructured multivariate, (2) *diagonal*, (3) *toepliz*, (4) *AR-1*: auto-regressive order 1, (5) *ComSym*: compound symmetry, and (6) *Indp*: independent, e.g. no temporal correlation, common variance estimate across time.

The analysis to determine which covariance structure best fit the residual errors; included the minus 2 ln likelihood scores (−2LL), the difference between the −2LL scores, using the unstructured score as the alternative hypothesis in all cases, the number of estimated covariance parameters in each assumed structure (d.f.), and the asymptotic chi-square *p*-value for testing if a simpler covariance structure might be used in place of the unstructured multivariate assumption. These results indicate that only the unstructured multivariate covariance structure adequately describes the temporal residual error correlation patterns associated with the clay soil, and that either the unstructured multivariate or diagonal covariance structure can be used to describe the temporal residual error patterns associated with the loam soil. Based on these results, we adopted a multivariate modeling approach on this repeated measurement data, as opposed to a mixed linear modeling approach.

Table 5 presents the primary statistical results associated with the repeated measurement analysis of the experimental

Table 4 – Monitoring times for rain event infiltration measurements

Season/experiment	Date	Sampling period	Irrigation pass
2003/experiment 1	27 August 2003	1	7
	23 September 2003	2	5
	08 October 2003	3	4
	13 November 2003	4	8
	22 December 2003	5	4
	14 January 2004	6	7

Table 5 – Repeated measures analysis: primary statistical tests

	Clay	Loam
F-test significance levels		
Time averaged model summary statistics		
R-square	0.6481	0.9439
Root MSE	0.1722	0.1254
Overall model *F*-test significance level (n.d.f. = 9, d.d.f. = 20)	0.0042	0.0001
Time averaged experimental effects		
EC (n.d.f. = 1, d.d.f. = 20)	0.7927	0.0001
SAR (n.d.f. = 4, d.d.f. = 20)	0.0002	0.0001
EC $\times$ SAR (n.d.f. = 4, d.d.f. = 20)	0.9828	0.2361
Wilks lambda significance levels		
Time dependent multivariate effects		
Time (n.d.f. = 5, d.d.f. = 16, exact)	0.0001	0.0001
Time $\times$ EC (n.d.f. = 5, d.d.f. = 16, exact)	0.1856	0.0150
Time $\times$ SAR (n.d.f. = 20, d.d.f. = 54, approx.)	0.0085	0.0165
Time $\times$ EC $\times$ SAR (n.d.f. = 20, d.d.f. = 54, approx.)	0.1172	0.1428

data. These results include the time averaged model summary statistics, i.e. the summary statistics associated with the univariate ANOVA model fit to the time averaged ln infiltration data, the *F*-test significance levels associated with the time averaged main factor and interaction experimental effects, and the Wilks lambda significance levels associated with the time dependent multivariate effects, respectively (Johnson and Wichern, 1988).

The univariate ANOVA models associated with both the clay and loam soil data exhibited statistically significant overall model *F*-tests below the 0.01 level: $p = 0.0042$ for the clay soil and $p = 0.0001$ for the loam soil. For the clay soil ANOVA model, only the SAR effect exhibited statistical significance: $p = 0.0002$. For the loam soil ANOVA model, both the EC and SAR main effects were statistically significant: $p = 0.0001$ for the clay soil; $p = 0.0001$ for the loam soil. Neither model exhibited any statistically significant univariate interaction effects.

The Wilks lambda significance levels quantify the degree of time dependent multivariate effects as determined by the MANOVA analyses. In the MANOVA model associated with the clay soil data, the Time effect was highly significant ($p = 0.0001$) and the Time $\times$ EC effect was significant at the 0.01 level ($p = 0.0085$). For the loam soil MANOVA model, the Time effect was again highly significant ($p = 0.0001$) and both the Time $\times$ EC and Time $\times$ SAR effects were significant at the 0.05 level: $p = 0.0150$ and $p = 0.0165$, respectively). Neither MANOVA model exhibited any statistically significant Time $\times$ EC $\times$ SAR effects.

The results are interpreted as follows. The SAR levels significantly influence the time average ln transformed infiltration data associated with the clay soil and these SAR effects appear to change over time. Likewise, both the EC and SAR levels significantly influence the time average ln transformed infiltration data associated with the loam soil and these EC and SAR effects appear to also change over time. Additionally, the mean ln transformed infiltration rates significantly change across the different sampling periods for both soil types, but neither soil type exhibits any time averaged (univariate) or multivariate EC $\times$ SAR interaction effects. In other words, the EC and/or SAR effects, when present, appear to affect the ln transformed infiltration rates in an independent manner.

Table 6 presents some additional results associated with the time averaged ANOVA models. These results include the marginal EC and SAR mean estimates and 95% confidence limits for the clay and loam soil types, as well as the *t*-test significance levels associated with the SAR contrasts, using SAR = 2 as a control. The marginal EC ln transformed infiltration time estimates for the clay soil measurements are virtually identical for each EC level, 3.93 versus 3.91. However, the marginal EC = 2 ln transformed infiltration time estimate of 3.04 associated with the loam soil data is significantly lower than the EC = 1 ln transformed estimate

Table 6 – Marginal mean estimates, with 95% confidence intervals (CI's) and SAR test results (2 vs. 4, 6, 8, 10); soil data, averaged across sampling periods

Effect	Clay			Loam		
	Estimate	95% CI	SAR contrasts	Estimate	95% CI	SAR contrasts
EC (1)	3.93	(3.83, 4.02)		3.26	(3.19, 3.32)	
EC (2)	3.91	(3.82, 4.00)		3.04	(2.97, 3.11)	
SAR (2)	3.61	(3.47, 3.76)		2.68	(2.57, 2.78)	
SAR (4)	3.92	(3.77, 4.07)	0.0061	2.70	(2.60, 2.81)	0.6917
SAR (6)	3.84	(3.69, 3.99)	0.0338	3.20	(3.09, 3.30)	0.0001
SAR (8)	4.05	(3.90, 4.20)	0.0003	3.57	(3.46, 3.67)	0.0001
SAR (10)	4.17	(4.02, 4.32)	0.0001	3.61	(3.50, 3.71)	0.0001

Table 7 – SAR orthogonal contrasts; averaged across sampling periods

Orthogonal contrast	F-test significance levels	
	Clay	Loam
Linear	0.0001	0.0001
Quadratic	0.7615	0.6178
Cubic	0.2008	0.0001
Fourth order	0.0895	0.3966

of 3.26. For both soil-types the marginal SAR time estimates tend to increase with increasing SAR levels. The ln transformed infiltration time levels associated with the clay soil tend to increase in a fairly linear manner, while the levels associated with the loam soil appear to increase in a non-linear manner. Finally, the *t*-test significance levels associated with clay soil indicate that the ln transformed infiltration time estimate at the SAR = 4 level is significantly different from the SAR = 2 level ($p = 0.0061$). In contrast, for the loam soil, the SAR = 4 versus 2 contrast is not statistically significant ($p = 0.6917$), but the SAR = 6 versus 2 contrast is highly significant ($p = 0.0001$).

Table 7 presents the corresponding significance levels associated with the SAR orthogonal contrasts of the marginal mean ln infiltration times in both time averaged ANOVA models. These orthogonal contrast significance levels can be used to determine the appropriate polynomial regression model structure for the SAR effect, given that the SAR levels are viewed as continuous, rather than discrete. The results shown in Table 7 suggest that the trend in the marginal mean ln transformed infiltration times associated with the clay soil is indeed linear, while the marginal mean times associated with the loam soil can be best described using a cubic polynomial regression model.

Based on these results presented in Tables 5–7, the regression models shown in Table 8 below were fit to the time averaged clay and loam soil ln transformed infiltration measurements, respectively. A simple linear regression model was used to describe the clay soil ln transformed infiltration data, i.e. ln transformed infiltration is modeled as a linear function of SAR (with no statistically significant EC effect). A cubic polynomial regression model with an added linear EC effect was used to describe the ln transformed infiltration data associated with the loam soil. The *R*-square values for these models were 0.552 for the clay soil and 0.925 for the loam soil; both models were statistically significant at the 0.0001 level. The predicted versus observed ln transformed infiltration time plot for the clay soil is shown in Fig. 9. Shown in Fig. 10 are the predicted versus observed relationships for the loam soil for EC 1 and 2 dS m^{-1}. Note that the model (and data) indicate that the infiltration time is greater as expected, for the EC 2 dS m^{-1} treatments.

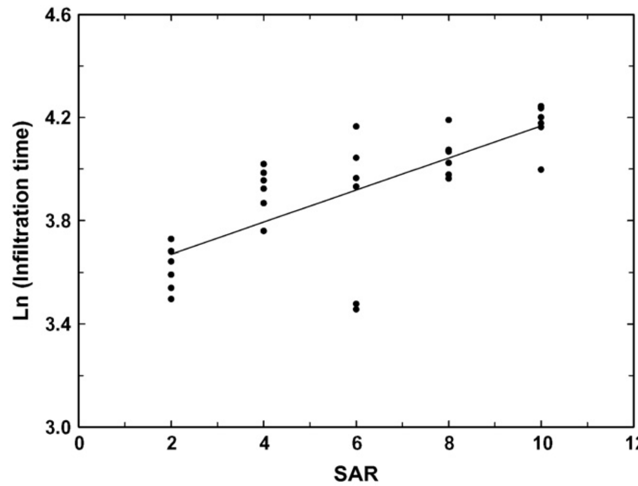

Fig. 9 – Relationship between SAR and ln infiltration time for clay soil; data averaged across sampling periods.

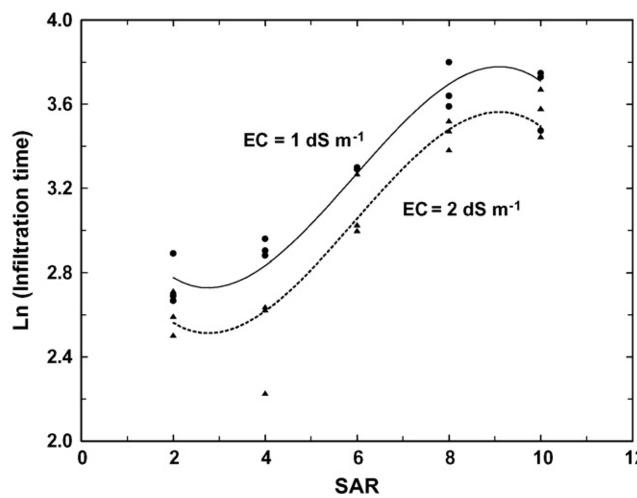

Fig. 10 – Relationship between SAR and ln infiltration time for loam soil, EC = 1 and 2 dS m^{-1}; time averaged across sampling periods.

The time dependent multivariate test results presented previously in Table 5 suggest that the marginal EC and/or SAR effects may have changed somewhat during the course of this experiment. In order to examine these effects more closely, the statistical results from the individual ANOVA models are presented in Tables 9 and 10.

The individual ANOVA model test results for the clay soil (Table 9) and loam soil (Table 10) exhibit some between-period variability in results. However, the general trends present in

Table 8 – Final time averaged ln infiltration time regression models

Soil-type	Fitted regression model (with standard errors)	R-square/root MSE
Clay	$E\{y\} = 3.545_{(0.07)} + 0.062[\mathrm{SAR}]_{(0.011)}$	0.5516/0.1642
Loam	$E\{y\} = 3.716_{(0.27)} - 0.216[\mathrm{EC}]_{(0.047)} - 0.622[\mathrm{SAR}]_{(0.17)} + 0.147[\mathrm{SAR}^2]_{(0.032)} - 0.008[\mathrm{SAR}^3]_{(0.002)}$	0.9248/0.1299

Note: y = ln(infiltration time) and *E*{y} = expected value of y.

Table 9 – Individual sampling period ANOVA model summary statistics and *F*-test significance levels (overall model effect, EC, SAR, and EC × SAR interaction) for clay soil data

Statistic	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
R-square	0.6147	0.5760	0.2855	0.5353	0.1805	0.7984
Root MSE	0.2089	0.1813	0.4920	0.4692	0.3928	0.2371
F-test significance levels associated with specified tests						
Overall	0.0088	0.0190	0.5523	0.0384	0.8646	0.0001
EC	0.0077	0.7159	n/a	0.5738	n/a	0.0465
SAR	0.0058	0.0041	n/a	0.0193	n/a	0.0001
EC × SAR	0.5582	0.2778	n/a	0.1478	n/a	0.1448

both tables are consistent with the previously discussed time averaged models. For example, in both the clay and loam soil ANOVA models, the SAR main effect was always statistically significant, provided that the overall model *F*-test was significant.

Time interaction plots were used to show the changes in the estimated ln transformed infiltration time over the six sampling periods for the various SAR and EC levels. The SAR time patterns, not shown here, indicated some time interaction, but did not suggest any clear, time dependent pattern with respect to either the clay or loam soil. In almost all cases the infiltration time data at each measurement period followed the relationship SAR $10 > 8 > 6 > 4 > 2$. The two EC versus ln transformed infiltration time lines were not statistically different from one another for the clay soil.

Although Table 5 indicates that there were statistically significant time dependent multivariate effects, none of these interaction effects appear particularly pronounced. We conclude that the time averaged ANOVA and regression models can be used to adequately describe and quantify the experimental data for both soil types.

4.6. *Assessment of the SAR risk factors for rain infiltration*

We define the SAR risk factor as the degree in which the ln transformed infiltration time increases as the SAR level increases. These risk factors can be ascertained from the time averaged statistical results in one of two ways: (1) by determining the first SAR level >2 for which a statistically significant increase in the ln transformed infiltration time is detected, using the ANOVA modeling results, or (2) by calculating the relative predicted percent increase in infiltration time per unit increase in SAR, using the estimates SAR parameters derived from the fitted regression models.

Using the first approach, Table 7 indicates that increasing the SAR from 2 to 4 significantly increases the ln transformed infiltration time on the clay soil. Likewise, increasing the SAR from 2 to 6 significantly increases the ln transformed infiltration time on the loam soil. Using the second approach, Table 9 indicates that the relative percent increase in infiltration time per unit increase in SAR on a clay soil without any crop cover is approximately $100 \times [\exp(0.062) - 1] = 6.4$ Note that the relative percent increase in infiltration time is SAR dependent for a loam soil-type but appears to vary between 0% for SAR <4 to a maximum of about 24% in the SAR range of 5.5–6.5. In summary, the regression model predictions are that the SAR increase from 2 to 4 increases the ln transformed infiltration time for clay soil, while for loam soil the ln transformed infiltration time increases above SAR 4.

The actual soil response to rain did show a likely increased sensitivity for the clay soil as expected based on the results of the model simulations, but the overall change in infiltration rate with SAR was similar for both soils: compare Figs. 9 and 10. It appears likely that the increased Na hazard of a clay soil is at least partially counterbalanced by its known greater physical aggregation relative to a lower clay content soil.

Comparison of the results of this experiment with the published water quality guidelines suggests that the combined rain–irrigation sequence increases the infiltration hazard. For example the highly cited guideline SAR–EC relationship (Fig. 21 in Ayers and Westcot, 1985) indicates that at an of EC 2 dS m^{-1} there should be no reduction in rate of infiltration until SAR is greater than 10 and severe reduction only above SAR 22. Alternatively they indicate a severe reduction in infiltration if the water is below EC 0.2 dS m^{-1}, which is the situation for rain water. In the present study adverse effects are indicated above SAR 4 at an EC 2 dS m^{-1}. Thus, the no reduction line (Fig. 21) in Ayers and Westcot should be moved to lower SAR in a irrigation–rain system.

Table 10 – Individual sampling period ANOVA model summary statistics and *F*-test significance levels (overall model effect, EC, SAR, and EC × SAR interaction) for loam soil data

Statistic	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
R-square	0.4736	0.8858	0.7221	0.7818	0.6459	0.9702
Root MSE	0.4851	0.2537	0.3476	0.2852	0.3222	0.1256
F-test significance levels associated with specified tests						
Overall	0.0946	0.0001	0.0005	0.0001	0.0044	0.0001
EC	n/a	0.0001	0.1975	0.2477	0.0491	0.8377
SAR	n/a	0.0001	0.0001	0.0001	0.0010	0.0001
EC × SAR	n/a	0.0204	0.2451	0.3022	0.5036	0.0308

The stability lines recommended by Shainberg and Letey (1984) with data from Agassi et al. (1981) indicate that at an EC of 1 dS m^{-1} the SAR can be as high as 12 and at EC = 2 dS m^{-1}, the SAR can be as great as 20 before there is a 50% reduction in infiltration. In a similar manner the stability lines of Quirk and Schofield (1955), among others would also have to be shifted to lower SAR to correspond to the combination irrigation rain results observed in this study. Only the Oster et al. (1992) recommendations of unlikely infiltration problems at SAR 3–6 if the EC is greater than 1.0 dS m^{-1} is in reasonable agreement with the present data.

5. Conclusions

Increase of SAR of the irrigation water had an adverse impact on water infiltration for both loam and clay soil types. For the clay soil even an increase from SAR 2 to SAR 4 resulted in a significant increase in infiltration time, i.e. decrease in infiltration rate, while for loam soil the increase in infiltration time was significant at the SAR 6 level. The fitted regression model showed that decreases in infiltration rate are also predicted for the clay soil as the SAR increases from 2 to 4. For loam soil the regression model was non-linear and the decrease in infiltration rate starts above SAR 4. The relative increase in infiltration times with increasing SAR was comparable for both soil types. The decreased infiltration rate in the field can be expected to result in increased surface runoff during rain events and thus decreased availability of water to the crop. In conditions where water is limiting, this may adversely affect crop yield. We conclude that for regions where rainfall is significant, the Na hazard is considerably greater than that suggested by simple application of the commonly used EC–SAR hazard relationships.

Acknowledgements

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Appendix A. Experimental data

Experimental data: bare soil

Obs.	Sampling period	Rain pass	Soil type	EC	SAR	Infiltration time (3 reps.)		
						y1	y2	y3
1	1	7	Loam	1	2	72.0	91.0	27.0
2	1	7	Loam	1	4	39.0	92.0	28.0
3	1	7	Loam	1	6	91.0	69.0	115.0
4	1	7	Loam	1	8	71.0	115.0	136.0
5	1	7	Loam	1	10	39.0	91.0	135.0
6	1	7	Loam	2	2	22.0	91.0	28.0
7	1	7	Loam	2	4	41.0	28.0	28.0
8	1	7	Loam	2	6	72.0	28.0	71.0
9	1	7	Loam	2	8	70.0	92.0	114.0
10	1	7	Loam	2	10	71.0	72.0	69.0
11	1	7	Clay	1	2	153.0	136.0	92.0
12	1	7	Clay	1	4	152.0	152.0	137.0
13	1	7	Clay	1	6	154.0	206.0	136.0
14	1	7	Clay	1	8	152.0	153.0	166.0
15	1	7	Clay	1	10	201.0	152.0	152.0
16	1	7	Clay	2	2	70.0	71.0	92.0
17	1	7	Clay	2	4	137.0	92.0	136.0
18	1	7	Clay	2	6	92.0	166.0	155.0
19	1	7	Clay	2	8	168.0	91.0	152.0
20	1	7	Clay	2	10	155.0	153.0	155.0
21	2	5	Loam	1	2	24.0	12.0	14.0
22	2	5	Loam	1	4	25.0	24.0	23.0
23	2	5	Loam	1	6	25.0	25.0	21.0
24	2	5	Loam	1	8	37.0	38.0	56.0
25	2	5	Loam	1	10	25.0	60.0	36.0
26	2	5	Loam	2	2	10.0	11.0	10.0
27	2	5	Loam	2	4	10.0	5.0	11.0
28	2	5	Loam	2	6	24.0	25.0	23.0

Appendix A (Continued)								
Obs.	Sampling period	Rain pass	Soil type	EC	SAR	Infiltration time (3 reps.)		
						y1	y2	y3
29	2	5	Loam	2	8	26.0	25.0	36.0
30	2	5	Loam	2	10	24.0	31.0	31.0
31	2	5	Clay	1	2	37.0	48.0	58.0
32	2	5	Clay	1	4	58.0	48.0	57.0
33	2	5	Clay	1	6	37.0	49.0	49.0
34	2	5	Clay	1	8	67.0	59.0	50.0
35	2	5	Clay	1	10	81.0	81.0	67.0
36	2	5	Clay	2	2	48.0	50.0	36.0
37	2	5	Clay	2	4	49.0	56.0	48.0
38	2	5	Clay	2	6	49.0	59.0	81.0
39	2	5	Clay	2	8	66.0	66.0	49.0
40	2	5	Clay	2	10	80.0	80.0	50.0
41	3	4	Loam	1	2	8.2	4.5	9.5
42	3	4	Loam	1	4	10.5	7.7	9.7
43	3	4	Loam	1	6	17.8	17.0	32.7
44	3	4	Loam	1	8	19.2	20.2	17.3
45	3	4	Loam	1	10	30.5	16.5	18.5
46	3	4	Loam	2	2	6.9	18.4	6.7
47	3	4	Loam	2	4	5.5	4.0	9.5
48	3	4	Loam	2	6	21.2	10.0	8.5
49	3	4	Loam	2	8	17.7	21.5	17.4
50	3	4	Loam	2	10	19.1	19.5	17.0
51	3	4	Clay	1	2	32.0	30.5	5.4
52	3	4	Clay	1	4	32.5	30.5	31.2
53	3	4	Clay	1	6	19.5	19.0	29.0
54	3	4	Clay	1	8	32.5	38.2	38.0
55	3	4	Clay	1	10	28.6	38.3	32.0
56	3	4	Clay	2	2	16.2	20.0	16.7
57	3	4	Clay	2	4	19.0	30.6	30.0
58	3	4	Clay	2	6	6.0	38.0	37.7
59	3	4	Clay	2	8	19.6	18.5	18.3
60	3	4	Clay	2	10	30.5	18.9	32.5
61	4	8	Loam	1	2	24.0	20.0	22.0
62	4	8	Loam	1	4	25.0	23.0	33.0
63	4	8	Loam	1	6	29.0	33.0	50.0
64	4	8	Loam	1	8	65.0	50.0	78.0
65	4	8	Loam	1	10	47.0	83.0	87.0
66	4	8	Loam	2	2	27.0	15.0	37.0
67	4	8	Loam	2	4	30.0	20.0	31.0
68	4	8	Loam	2	6	26.0	36.0	21.0
69	4	8	Loam	2	8	35.0	50.0	32.0
70	4	8	Loam	2	10	93.0	50.0	90.0
71	4	8	Clay	1	2	18.0	29.0	24.0
72	4	8	Clay	1	4	10.0	48.0	37.0
73	4	8	Clay	1	6	53.0	60.0	14.0
74	4	8	Clay	1	8	67.0	80.0	81.0
75	4	8	Clay	1	10	85.0	50.0	75.0
76	4	8	Clay	2	2	28.0	43.0	43.0
77	4	8	Clay	2	4	58.0	70.0	55.0
78	4	8	Clay	2	6	17.0	40.0	29.0
79	4	8	Clay	2	8	49.0	60.0	76.0
80	4	8	Clay	2	10	65.0	75.0	24.0
81	5	4	Loam	1	2	10.0	13.0	13.0
82	5	4	Loam	1	4	16.0	11.0	13.0
83	5	4	Loam	1	6	16.0	20.0	5.0
84	5	4	Loam	1	8	23.0	23.0	25.0
85	5	4	Loam	1	10	27.0	24.0	24.0
86	5	4	Loam	2	2	10.0	6.0	9.0
87	5	4	Loam	2	4	10.0	8.0	9.0
88	5	4	Loam	2	6	17.0	15.0	11.0
89	5	4	Loam	2	8	19.0	17.0	16.0
90	5	4	Loam	2	10	28.0	10.0	20.0
91	5	4	Clay	1	2	20.0	15.0	25.0
92	5	4	Clay	1	4	23.0	20.0	30.0

Appendix A (*Continued*)								
Obs.	Sampling period	Rain pass	Soil type	EC	SAR	Infiltration time (3 reps.)		
						y1	y2	y3
93	5	4	Clay	1	6	23.0	23.0	7.0
94	5	4	Clay	1	8	17.0	7.0	25.0
95	5	4	Clay	1	10	15.0	23.0	28.0
96	5	4	Clay	2	2	18.0	17.0	16.0
97	5	4	Clay	2	4	17.0	16.0	30.0
98	5	4	Clay	2	6	17.0	30.0	12.0
99	5	4	Clay	2	8	23.0	18.0	24.0
100	5	4	Clay	2	10	15.0	24.0	24.0
101	6	7	Loam	1	2	10.0	7.0	10.0
102	6	7	Loam	1	4	9.0	12.0	12.0
103	6	7	Loam	1	6	20.0	20.0	20.0
104	6	7	Loam	1	8	30.0	30.0	31.0
105	6	7	Loam	1	10	30.0	29.0	31.0
106	6	7	Loam	2	2	8.0	7.0	9.0
107	6	7	Loam	2	4	10.0	7.0	9.0
108	6	7	Loam	2	6	20.0	20.0	20.0
109	6	7	Loam	2	8	30.0	35.0	30.0
110	6	7	Loam	2	10	43.0	43.0	32.0
111	6	7	Clay	1	2	60.0	60.0	75.0
112	6	7	Clay	1	4	95.0	95.0	110.0
113	6	7	Clay	1	6	130.0	130.0	61.0
114	6	7	Clay	1	8	110.0	110.0	130.0
115	6	7	Clay	1	10	130.0	130.0	160.0
116	6	7	Clay	2	2	61.0	60.0	60.0
117	6	7	Clay	2	4	95.0	95.0	75.0
118	6	7	Clay	2	6	130.0	160.0	130.0
119	6	7	Clay	2	8	95.0	255.0	160.0
120	6	7	Clay	2	10	240.0	275.0	180.0

Appendix B

Undisturbed core bulk density (g cm^{-1})					
EC	SAR	Rep 1	Rep 2	Rep 3	Mean
Loam					
1	2	1.41	1.39	1.39	1.40
1	4	1.40	1.42	1.38	1.40
1	6	1.40	1.41	1.41	1.41
1	8	1.42	1.40	1.44	1.42
1	10	1.43	1.43	1.43	1.43
2	2	1.39	1.40	1.39	1.39
2	4	1.40	1.38	1.37	1.38
2	6	1.41	1.36	1.36	1.38
2	8	1.39	1.39	1.38	1.39
2	10	1.35	1.35	1.41	1.37
Control		1.42	1.36	1.36	1.38
Clay					
1	2	1.23	1.18	1.18	1.20
1	4	1.26	1.22	1.26	1.25
1	6	1.18	1.23	1.19	1.20
1	8	1.17	1.17	1.18	1.17
1	10	1.20	1.17	1.19	1.19
2	2	1.30	1.24	1.32	1.29
2	4	1.31	1.26	1.30	1.29
2	6	1.29	1.30	1.32	1.30
2	8	1.23	1.25	1.31	1.26
2	10	1.31	1.32	1.30	1.31
Control		1.24	1.26	1.20	1.23

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