Infiltration as Influenced by Irrigation Water Quality[1]

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ABSTRACT

After 19 months of irrigation with waters of different quality, columns of Heimdal loam cropped to alfalfa had infiltration rates that were correlated better with irrigation water sodicity and salinity than with soil surface (0–76 mm) or column average (0–530 mm) exchangeable sodium and soil salinity. Two sets of irrigation water parameters were tested: (i) total cation concentration (C_c) in $mol_c\ m^{-3}$ (meq $liter^{-1}$) and sodium adsorption ratio (SAR_c) of the irrigation water in equilibrium with solid phase $CaCO_3$ at a P_{CO_2} of 0.07% based on ion activities corrected for ion pairing; and, (ii) total cation concentration of the irrigation water as prepared and the adjusted sodium adsorption ratio based on the calculated pH of the water in equilibrium with $CaCO_3$. On the basis of multiple linear regression analyses, the best correlation was obtained with the lime-equilibrated water parameters ($R^2 = 0.87$). The corresponding relationship between infiltration rate (I) in mm $hour^{-1}$ and the chemical parameters was $I = 6.80 - 1.10\ SAR_c + 0.79\ C_c$. Cation concentration greatly affected infiltration rates even at low SAR levels ($2<SAR<5$). Apparently, the mechanical action of the applied water greatly enhances the effects of exchangeable sodium and soil solution concentration on swelling and dispersion at the soil surface which, in turn, has a large effect on infiltration rates.

Additional Index Words: clay dispersion, hydraulic conductivity, soil crusting, sodicity, salinity, udic Haploboroll.

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Several workers (Felhendler et al., 1974; Frenkel et al., 1978) have shown that clay dispersion and consequent lodgement within a soil column reduces hydraulic conductivity. With direct scanning electron microscopic techniques, Chen and Banin (1975) observed a separation of fine particles from larger particles and aggregates, and the development of a continuous soil network as a result of fine particle lodgement in soil voids. Such dispersion and lodgement can occur within a soil column at a relatively low (~10) sodium adsorption ratio (SAR)[3] (Frenkel et al., 1978) and may be especially pronounced at the soil surface because of the mechanical action of the applied water and the absence of a soil matrix. Thin surface crusts can greatly reduce infiltration rates (McIntyre, 1958). Thus, the hydrologic behavior of soils may depend more on the sodium levels at the soil surface than on the chemistry of the remainder of the soil. This paper reports infiltration data obtained after long-term irrigation of cropped, undisturbed soil columns with waters of different quality[4] which permit an evaluation of the surface-dislodgement hypothesis.

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[3] $SAR = C_{Na}/[C_{Ca} + C_{Mg}]^{1/2}$, where all concentrations, C, are expressed in mole m^{-3} or mmole $liter^{-1}$.

[4] F. W. Schroer. 1970. A study of the effect of water quality and management on the physical and chemical properties of selected soils under irrigation. Technical Completion Report. OWRR Project No. A-005-NDAK, 48p.

Table 1—Physical and chemical properties of Heimdal loam (udic Haploboroll).

Depth	Horizon	Particle size distribution				CEC	Organic matter	pH_e	ESP†	Sat. extract elect. cond.	Water content		
		19–2 mm	2–0.02 mm	0.02–0.002 mm	<0.002 mm						Saturated	−33 kPa§	−1500 kPa§
mm		%				$mol_c kg^{-1}$	%		%	Sm^{-1}‡	% dry wt.		
0–180	Ap	0.3	61.4	19.9	18.5	212	2.8	6.0	0.6	0.04	48	22.7	10.9
180–410	B21	0.3	54.4	24.6	20.9	195	1.4	6.4	0.5	0.04	48	20.9	10.6
410–530	B22	0.1	58.5	21.6	19.9	189	1.0	7.0	0.7	0.03	50	20.5	9.7

† ESP represents exchangeable sodium percentage.
‡ 1 Sm^{-1} equals 10 mmho cm^{-1}.
§ 1 kPa = 10 mbar.

MATERIALS AND METHODS

Undisturbed columns (0.20 m in diameter and 0.53 m long) of Heimdal loam (coarse-loamy, mixed udic Haploboroll), a nonsaline, nonsodic soil (Table 1), were obtained by pressing 0.60-m-long galvanized cylinders into the ground with a hydraulic coring machine. Metal bottoms, fitted with ceramic plates and covered with a thin layer of sand, were attached to the cylinders. They were then moved into a greenhouse, tilled to a depth of 0.12 m, and seeded with alfalfa (*Medicago sativa* L. cv. 'Sonora'). The stand was eventually thinned to 6-7 plants. The columns were watered weekly with 25 mm of distilled water for 3 months to establish well-rooted plants. During the next 19 months, each column was irrigated with one of 18 synthetic irrigation waters (Table 2). The waters were grouped into three salinity levels of 5, 12, and 30 $mol_c\ m^{-3}$ total cation concentration, where the subscript c represents charge. (Hence, these values are equivalent to 5, 12, and 30 meq/liter.) Each salinity level was subdivided into SAR levels of approximately 3, 10, and 22 $(mol\ m^{-3})^{1/2}$ and each of these was further divided into a high and a low HCO_3^- concentration. Sulfate was the other anion varied. Other water treatments included irrigation with only distilled water and alternate irrigation with distilled water and a synthetic water. The water treatments were replicated five times. The data reported here were obtained from 100 soil columns.

After the plants were well established, the columns were irrigated with 50 mm of irrigation water by pouring the water from a height less than 100 mm, on the soil surface whenever the gravimetric soil water content was about 0.16 g/g as indicated by column weight. Occasionally, during periods of high water use, as much as 85 mm of irrigation water was applied. This water management resulted in little to no overall leaching. Drainage from the soil columns was insignificant. Ammonium phosphate fertilizer was applied twice at a rate of 224 kg/ha. The columns were rotated monthly about the greenhouse to equalize lighting exposure. Diurnal fluctuation of greenhouse temperature was controlled between 18 and 30°C, and the relative humidity between 30 and 50%. Photo flood incandescent lamps were used to supplement daylight during October through April.

Final infiltration rates were determined 6 to 10 days after the first irrigation following the 22nd of 23 alfalfa cuttings. Sufficient irrigation water was applied at this irrigation to achieve a gravimetric water content of 0.21 g/g. Additional water, equal to the estimated daily evapotranspiration (25 mm) times the number of days elapsed after irrigation, was applied the day before the infiltration determination. The next day, 20 to 30 mm of water was applied, and the depth of the ponded water was measured with a hook gauge at 5- to 10-minute intervals for 50 minutes. Mean infiltration rates were calculated from data obtained during the latter half of this period, after the rates had become nearly constant. Many of the columns that exhibited low infiltration rates were ponded from the previous day's watering and were still ponded 1 to 2 days after the infiltration test. Infiltration rates also were determined soon after the experiment began and at the end of 1 year. Each column was sectioned at the end of the experiment into 7 segments, each 76 mm thick. Procedures used to determine exchangeable cation and saturation composition were based on standard methods (U. S. Salinity Laboratory Staff, 1954) with the following modifications: Na^+, Ca^{2+}, and Mg^{2+} were determined by atomic absorption spectrophotometry on diluted water and NH_4OAC extracts containing 0.5% La^{3+}; and Cl^- was determined by electrometric titration with $AgNO_3$.

Table 2—Chemical properties of irrigation water and soil columns and infiltration rates as a result of long-term irrigation with waters of different quality.

Water no.	Irrigation water composition†				Calculated chemical properties of irrigation water			Soil properties				
	SO_4	HCO_3	Total cations	SAR	SAR_a	SAR_c	Total cations	ESP 0–76 mm	Total cations 0–76 mm	Avg. ESP 0–530 mm	Avg. total cations 0–530 mm	Infiltration rate
	$mol_c\ \mu m^{-3}$				$(mol\ m^{-3})^{1/2}$		$mol_c\ \mu m^{-3}$	%	$mol_c\ \mu m^{-3}$	%	$mol_c\ \mu m^{-3}$	$mm\ hr^{-1}$
1	3.3	1.5	5.0	3	3.45	2.5	5.8	3.5	8.2	5.3	22.2	8.7
2	0.0	4.8	5.0	3	4.95	3.4	4.6	5.2	5.3	6.7	6.1	2.1
3	4.6	0.2	5.0	13	0.0	4.3	7.1	6.8	6.9	7.0	30.6	7.8
4	0.5	4.3	5.0	13	16.6	7.6	5.5	15.6	11.0	9.3	10.6	1.0
5	4.8	0.05	5.0	24	0.0	4.3	7.3	7.3	7.8	7.7	31.0	6.8
6	0.7	4.1	5.0	24	40.8	7.8	5.6	17.0	9.0	9.0	10.8	0.9
7	8.6	3.2	12.0	3	5.8	3.3	11.0	3.8	10.6	7.8	47.0	16.0
8	1.4	10.4	12.0	3	7.3	4.6	8.4	4.2	8.6	10.2	15.4	9.1
9	10.3	1.5	12.0	10	9.3	8.1	13.1	11.5	15.1	14.4	59.5	4.5
10	5.9	5.9	12.0	10	16.6	12.0	11.5	15.2	16.7	18.3	42.3	1.7
11	11.4	0.4	12.0	22	0.0	9.9	14.1	14.8	18.4	16.7	71.0	6.4
12	7.3	4.5	12.0	22	22.0	16.6	12.4	26.2	33.5	18.7	63.0	0.7
13	26.6	3.2	30	2	4.8	2.0	28.2	3.0	15.6	6.7	88.8	27.8
14†	1.8	22.6 (28)	24.2(30)	2.6	7.2	4.2	14.2	6.5	6.1	15.2	26.6	13.9
15	26.6	3.2	30.0	8	16.4	8.5	28.8	12.0	22.7	23.4	138.5	15.5
16	14.8	15.0	30.0	8	21.8	13.1	23.1	12.5	14.1	25.6	112.5	13.3
17	26.6	3.2	30.0	20	31.0	19.9	30.0	26.0	27.0	28.6	165.2	9.6
18	22.3	7.5	30.0	20	39.2	25.8	28.6	30.0	19.0	33.1	148.6	7.5
Distilled water	0.0	0.0	0.0	0	0.0	0.0	2.0	0.6	2.0	0.6	2.0	13.1

† Values within parenthesis give the composition of the water as initially prepared; the other values are those obtained after the water was exposed to hot greenhouse conditions.

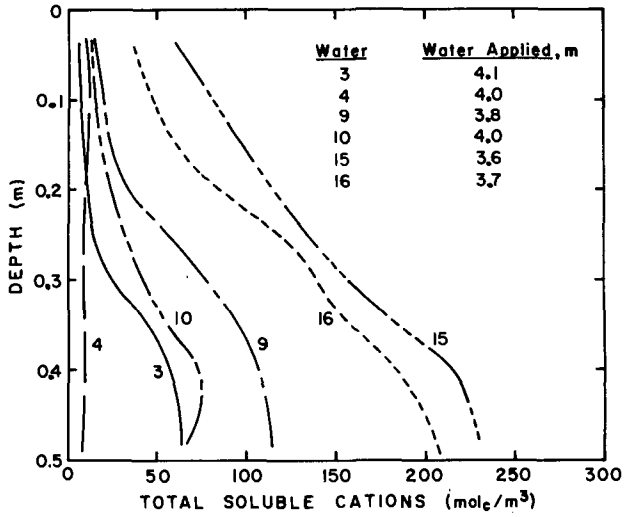

Fig. 1—Depth distributions of cation concentrations in the saturation extracts of Heimdal loam soil columns after 19 months of irrigation with different quality irrigation waters as indicated by the number associated with each line. The water composition for each number is given in Table 2.

RESULTS AND DISCUSSION

The effects of irrigation water composition on soil chemistry are illustrated in Fig. 1 and 2 for the waters of intermediate SAR ($8<SAR<13$). Figure 1 shows the depth distributions of total cation concentration in the saturation extract, whereas Figure 2 portrays the exchangeable sodium distribution. As expected, the ion concentration increased with depth because of plant water uptake. For a given total cation concentration of the irrigation water, the cation concentration of the saturation extract was lower for the high bicarbonate water (even numbers) than for the low bicarbonate water (odd numbers) due to precipitation of HCO_3^- as $CaCO_3$. The exchangeable sodium levels also tended to be greater for the high HCO_3^- waters (Fig. 2). The distributions of exchangeable sodium with depth indicate that the columns had not reached steady state; the maximum levels for waters 4 and 10, for example, occurred in the upper half of the soil column. Further application of water would have eventually raised the exchangeable sodium levels in the lower half of the column because SAR and exchangeable sodium increase with increasing total cation concentration as water is removed by growing plants from soils irrigated with a given irrigation water. However, the exchangeable sodium percentage (ESP) of the top soil segment (0-76 mm) was well correlated with the SAR of the irrigation water as corrected for effects of $CaCO_3$ dissolution or precipitation. Based on the pH_c concept (Rhoades, 1972) the adjusted SAR, SAR_a, was calculated according to

$$SAR_a = SAR_i\ [1 + (8.4 - pH_c)],$$

where SAR_i is the initial SAR of the irrigation waters, and pH_c is the calculated pH (Bower et al., 1965) of the water in equilibrium with solid phase $CaCO_3$. A second procedure used to correct SAR for $CaCO_3$ equilibria assumed the composition would be that in equilibrium with $CaCO_3$ where its effective solubility and effect on irrigation water composition was calculated from ion activities as corrected for ion pair

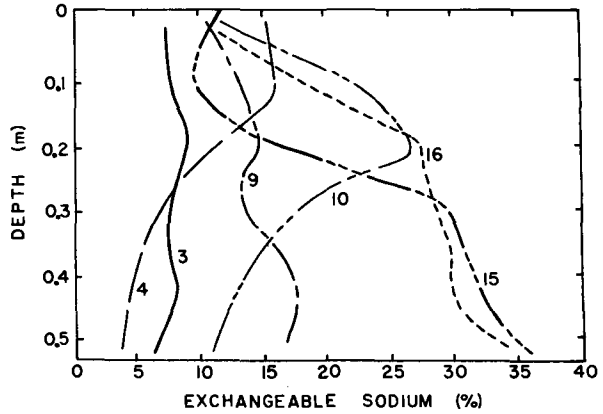

Fig. 2—Exchangeable sodium distributions with depth.

formation (Oster and Rhoades, 1975). This calculated SAR will be referred to as SAR_c. The appropriate linear regression equations were:

$$ESP_{0\text{-}76\ mm} = 0.52\ SAR_a + 5.16,\ r^2 = 0.64;$$

and,

$$ESP_{0\text{-}76\ mm} = 1.25\ SAR_c + 1.76,\ r^2 = 0.89.$$

The use of pH_c to correct the SAR for the effects of $CaCO_3$ equilibria results in an underprediction of the effective solubility of $CaCO_3$ and, as a result, in SAR values which are too high (Oster and Rhoades, 1977). This is consistent with the SAR given in columns 6 and 7 of Table 2; in every case, SAR_a is greater than SAR_c. Hence, the approach used to calculate SAR_c is the preferred method to correct SAR for the effects of $CaCO_3$ equilibria.

A grey, granular, very friable, surface crust 10 to 20 mm thick was observed at sampling time on most of the soils irrigated with low HCO_3^- water. In contrast, surface crusts on the columns irrigated with high HCO_3^- waters were dark colored, vesicularly structured, and hard to very hard when dry. Soil structure in the remainder of the A horizon and in the B horizon was not visibly altered by irrigation.

Initial infiltration rates determined after the second alfalfa harvest, 3 months after planting, were all high (217 to 604 mm $hour^{-1}$). One year and 55 irrigations later, the rates ranged from 2.7 to 26.5 mm $hour^{-1}$. The averages ($n = 45$) for the low and high HCO_3^- waters were 11.2 and 16.9 mm $hour^{-1}$, respectively. After 24 additional irrigations, the corresponding averages of the final infiltration rates were 5.6 and 11.5 mm $hour^{-1}$. Individual treatment averages are given in the final column of Table 2. In another treatment to which Water 17 and distilled water were applied alternately the final infiltration rate was only 0.3 mm $hour^{-1}$. Where only distilled water was applied throughout the experiment the final rate was 13.1 mm $hour^{-1}$. As negligible sodium was added in this case and the initial ESP of the soil was less than 1%, the ESP never exceeded 1% in these columns.

Multiple linear regression analysis was used to determine which set of chemical parameters, based on the chemistry of the irrigation water or of the soil, best correlated with the measured infiltration rates. The soil parameters considered were the soluble cation concentration and ESP for the surface soil layer (0-76 mm) or the average soluble cation concentration and

Table 3—Relationship between final infiltration rate, I, and sodicity (ESP or SAR) and total cation concentration (C) where $I = A + B$ (SAR or ESP) $+ D(C)$.

	Parameters		A	B	D	R^2
			mm/hour			
Column avg. (0–530 mm)	ESP	C	11.6	−0.99	0.19	0.54
Surface soil layer (0–76 mm)	ESP	C	10.1	−0.74	0.54	0.37
Irrigation water	SAR_a	As prepared	5.7	−0.31	0.48	0.60
Irrigation water	SAR_c	Calculated	6.8	−1.10	0.79	0.86

the ESP for the entire column (0-530 mm). Column averages were calculated, from plots similar to those shown in Fig. 1 and 2, with the aid of a planimeter (Columns 11 and 12, Table 2). The irrigation water parameters considered were the total cation concentration and SAR. Total cation concentration of the irrigation water as prepared and its SAR_a value constituted one set, calculated concentration (C_c) and corresponding SAR_c in equilibrium with $CaCO_3$ at a partial pressure of CO_2 of 0.07 kPa (.07%) constituted another. The best correlations (Table 3) were obtained using irrigation water parameters ($R_c^2 = 0.86$, $R_a^2 = 0.60$). Standard deviations of the residuals for the two sets (measured-predicted) were 2.8 mm hour^{-1} and 4.5 mm hour^{-1}. Based on an overall average final infiltration rate of 8.6 mm hour^{-1}, these amounted to 32 and 49% of the average final rate. The R^2 values for the entire column and surface soil parameters were lower, 0.54 and 0.37, respectively. According to the regression coefficients (Table 3), the dependence of infiltration rate on the chemical parameters was as expected: infiltration rate decreased with increasing SAR and with decreasing total cation concentration. The infiltration rates were correlated better with C_c ($r = 0.50$) than with SAR_c ($r = -0.35$). The result suggests that total cation concentration is a better parameter for the prediction of infiltration rates than is SAR. From these data we conclude that: (i) irrigation water composition, through its effect on surface soil conditions, has a greater influence on infiltration rate than does the chemistry of the soil column itself, and (ii) the salt concentration of the irrigation water, corrected for lime precipitation, is of at least equal importance to the corrected SAR as a predictor of eventual infiltration rates.

The first conclusion is significantly different than that drawn by Yaron and Thomas (1968). In experiments conducted with disturbed, saturated columns, they observed that the hydraulic conductivity was related to the average exchangeable sodium percentage (ESP) of the entire soil column; our data show that, where the soil surface is continually being subjected to mechanical disruption during water application, the chemical properties of the water are considerably more important than are the resultant soil chemical properties. Recently, (Felhendler et al. (1974) and Frenkel et al. (1978) demonstrated that extensive clay dispersion and movement in saturated soil columns can occur at SAR values as low as 10 if the solution concentration is < 2 to 5 mol$_c$ m^{-3}. Because of the mechanical action of the applied water, aggregate breakdown and dispersion, which result in particle lodgement in soil voids at the soil surface, would be expected to occur at lower SAR values than those at which movement would occur within the column itself. Our data show that even for SAR_c values between 2 and 4.6 (Waters 1, 2, 3, 5, and 8) the final infiltration rate increased from 2 to 28 mm hour^{-1} as the cation concentration of the applied water increased from 5 to 28 mol$_c$ m^{-3}. The effects of concentration suggest that swelling and dispersion, which are reduced with increasing concentration, play an important role in the stability of the soil surface. This provides an explanation of the intermediate infiltration rate (13.1 mm hour^{-1}) obtained for the columns irrigated with distilled water ($C_c = 2.0$ mol$_c$ m^{-3}; $SAR_c = 0$). This rate is equivalent to that obtained after irrigation with waters which contain about 9 mol$_c$ m^{-3} of salt if they have an SAR_c of 2 to 4 (mol m^{-3})$^{1/2}$. As SAR_c increases, higher salt concentrations are required to provide a similar degree of swelling and dispersion. With lower SAR's the reverse is true.

The lowest infiltration rate (0.3 mm hour^{-1}) was obtained from the columns irrigated alternatively with Water 17 ($SAR_c = 19.9$) and distilled water. Thus, the potential for crusting and reduced infiltration rates is particularly great where irrigation periodically supplements normal rainfall (or vice versa). Thus our data show that current sodicity criteria of water quality, which are based on the hydraulic conductivity of saturated soil columns [i.e., that SAR values of 6–16 are satisfactory depending on clay mineralogy if the salt concentration of the irrigation water exceeds 5 mol$_c$ m^{-3} (Ayers and Westcot, 1976)], are subject to question. This should be particularly true where supplemental irrigation is practiced.

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