Effects of leaching on soil desalinization for wheat crop in an arid region

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ABSTRACT

Leaching is one of the most practical methods for improvement of saline soils and both the quality and the quantity of leaching water play an important role in desalinization of these soils. To determine the effects of different qualities and quantities of leaching water on salinity of drainage water during the growing season of wheat, pot experiments were conducted with a silty clay loam soil, a typical salt-affected soil in an arid region of central part of Iran. The experiment comprised the treatments of three irrigation water salinities (4, 9 and 12 dS/m) and four leaching levels (3, 20, 29 and 37%), using a factorial design with seven replications for each treatment. The results showed that at the beginning of the growing season the drainage water salinity was highest for all treatments. Then it started to decrease and depending on the quality and quantity of leaching water it became nearly constant or continued to decrease until the end of the growing season. The leaching of salts from the soil profile was more efficient during the first few irrigations and thereafter became less efficient. The increase of leaching level had a significant effect on the decrease of drainage water salinity. The comparison with steady-state mass balance of soil salt, sodium and chloride showed that the simple ratio of chloride in irrigation water to chloride in drainage water can be used to estimate the leaching fraction of saline soils with high accuracy.

Keywords: irrigation water quality; drainage water quality; leaching; wheat

Salinity of agricultural soils and water resources is a worldwide problem in irrigated areas and causes land degradation (Katerji et al. 2005). Nearly half of the irrigated surface is seriously affected by salinity and/or secondary alkalinity (Flagella et al. 2002). The cost of salinity to agriculture was estimated to the amount of about 12 billion US dollars per year (Ghassemi et al. 1995). Use of poor quality groundwater has become inevitable for irrigation to compensate rapidly increasing water demands due to increasing water requirements for irrigation and the competition between human and industrial water use, especially in arid and semi-arid regions (Katerji et al. 2000, Qadir et al. 2001). Use of saline water, shallow watertables, agronomic practices such as fertilization, an intense evapotranspiration with insufficient leaching, lack of suitable lands and lack of appropriate irrigation and drainage management are the main reasons for soil salinization (Rhoades et al. 1993, Slavich et al. 1999, Villa-Castorena et al. 2003). Deleterious effects of salinity not only significantly decrease crop yields, but also, especially in heavy soil textures, cause dispersion of clay particles, reduction in soil permeability by clogging of soil pores, decrease in soil porosity and soil hydraulic conductivity (Rowell et al. 1969, Shainberg and Levy 1992, Ame'zketa 1999). Some researchers investigated the degradation of soil physical properties due to salinity and sodicity by using the index of aggregate stability in water and reported that this index is inversely correlated to the NaCl quantity delivered with irrigation water and directly correlated to the exchangeable sodium percentage of the soil (Tedeschi and Dell'Aquila 2005). To overcome the soil salinity problems, some researchers recommended methods such as mixing agricultural drainage water with good quality irrigation water, plant breeding (selection of salt tolerant cultivars) and alternating good

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quality irrigation water with saline water (Khosla et al. 1979, Pasternak and De Malach 1993, Abdel Gawad and Ghaibeh 2001, Yurtseven et al. 2005). These practices are important for reducing salinity problems but they cannot prevent soil degradation due to salinity and sodicity. Therefore, the use of appropriate irrigation water for leaching with suitable drainage systems is one of the best methods for improvement of saline-sodic soils. Several researchers such as Feizi (1993), Garcia-Sanchez et al. (2003) and Flagella et al. (2004) reported advantageous effects of leaching on soil improvement and crop yield. Some researchers also pointed out the disadvantages of soil salt leaching, which causes movement of soil nutrient such as N and K, and its limitations in fine-texture soils where it results in waterlogging and other environmental problems (El-Haddad and Noaman 2001, Yurtseven et al. 2005, Kolahchi and Jalali 2007). The required amount of leaching significantly depends on salinity of irrigation water and crop salt tolerance. El-Haddad and Noaman (2001) reported that the leaching level LF of 0.25 at irrigation water salinity of 40 g/l is inadequate to attain a steady-state salt balance during the growing period of halophytes, although the drainage water salinity more than 90 g/l has been reached.

The above studies show that soil salt leaching plays an important role in soil desalinization and soil improvement. The objectives of this study are to investigate the effects of different quality and quantity of leaching water on the actual leaching of soil salt, sodium and chloride during the growing season of wheat, to compare them with the corresponding steady-state mass balance and to recommend the appropriate management practices for leaching of salts from a typical salt-affected soil of an arid region.

MATERIAL AND METHODS

In the Isfahan province, more than 60 000 ha of agricultural lands are suffering from different saline-sodic problems (Feizi 1993). Roudasht district with the area of about 50 000 ha, which is located about 65 km east of Isfahan (32°29'N, 52°10'E), is one of the salt-affected zones of the Isfahan province (Houshmand et al. 2005). In this district, shallow saline groundwater with the depth of about 2–4 m below soil surface and salinity of about 13 dS/m, low annual precipitation about less than 100 mm per year, high evapotranspiration and the use of saline drainage water for irrigation, caused several problems for soil and agricultural production, especially for wheat (Feizi 1993). To recommend the appropriate management practice for leaching of salts from these soils and to study the effects of different leaching levels on actual leaching and the ease of attainment of steady-state mass balance of salt, wheat as a typical crop and a typical soil of the area were selected and pot experiments were conducted in a greenhouse at the Isfahan University of Technology. Treatments with three irrigation water salinities of 4, 9 and 12 dS/m and four leaching levels of 3, 20, 29 and 37% were applied, using a factorial design with seven replications for each treatment. It should be noted that the salinity of irrigation water used commonly in the study area is about 4 to 10 dS/m, because farmers mix saline drainage water with river water and use it for irrigation. The characteristics of irrigation water used in this study are shown in Table 1. Total of 84 plastic pots (each pot with 32 cm diameter and 42 cm depth) were used. Each of them was filled with 14 kg of typical soil of the Roudasht district wheat farms, having silty clay loam texture (EC_e = 13.2 dS/m, pH = 7.22, ρ_b = 1.34 g/cm^3 and SAR = 11.31). The soil samples were repacked in the pots to have the bulk density similar to the study area. The soil electrical conductivity (EC_e) was measured by an EC meter in the soil-saturated paste extract, and the soil pH was measured by a pH meter in the soil-saturated paste. At both irrigation and drainage water, chloride concentration was measured using titration with $AgNO_3$ and sodium was measured using flame photometry.

Table 1. Irrigation water characteristics

Water salinity level	EC_{iw} (dS/m)	pH	Na^+	$Ca^{2+} + Mg^{2+}$	Cl^-	SO_4^{2-}	HCO_3^-	SAR
			(meq/l)					
1	4.06	7.3	29.6	17.2	28.2	14.3	3.3	1.72
2	9.08	7.25	60.7	32.5	65.3	26.9	5	2.02
3	12.1	7.5	102.8	38	88.5	46.9	4.4	2.7

The sodium adsorption ratio (SAR) for irrigation water was calculated by the following equation:

$$\text{SAR} = \frac{Na^+}{\sqrt{Ca^{2+} + Mg^{2+}}} \quad (1)$$

where: Na^+, Ca^{2+} and Mg^{2+} are the concentrations of ions in meq/l

The bottom of each pot had a hole for drainage. To ease the removal of drainage water, the bottom of each pot was covered with 5 cm gravel. Under each pot, a container was placed to collect drainage water. The pots were weighed at two soil moisture levels of field capacity and wilting point and these data were used to calculate the irrigation water requirements. The soil field capacity was estimated by weighing the sample pots after irrigation when the drainage stopped. The soil wilting point was estimated based on soil texture and soil moisture characteristic curve. Spring wheat was planted and 10 irrigations were applied during the growing season. To prevent water stress, all pots were irrigated when the available soil moisture in the pots irrigated with water having electrical conductivity EC_{iw} = 4 dS/m, at the leaching level LF = 37%, reached its 50% depletion of the field capacity. Therefore, the amount of irrigation water applied to each pot was different. There was no noticeable settling of the soil during the season after the initial soil compaction. The volume of irrigation water for each pot was calculated based on the following equation:

$$V_{iw} = \frac{M_{fci} - M_i}{1 - \text{LF}} \quad (2)$$

where: V_{iw} is the volume or mass of irrigation water (l or kg), M_{fci} is the pot mass at field capacity (kg), M_i is the pot mass before irrigation (kg) and LF is the desired leaching level (%)

The amount of salt accumulation in the soil is related to the quantity and quality of irrigation and drainage water. The following equations were used to compute salt accumulation (Grattan 2002):

$$\text{TDS} = 640 \times \text{EC (for EC} \leq \text{5dS/m)} \quad (3)$$

$$\text{TDS} = 800 \times \text{EC (for EC} > \text{5dS/m)} \quad (4)$$

$$\text{salt accumulation} = (\text{TDS}_{iw} \times V_{iw}) - (\text{TDS}_{dw} \times V_{dw}) \quad (5)$$

where: TDS_{iw} is the concentration of total dissolved salt in irrigation water (mg/l), TDS_{dw} is the concentration of total dissolved salt in drainage water (mg/l) and V_{dw} is the volume or mass of drainage water (l or kg)

The amounts of sodium and chloride in irrigation and drainage water were determined by the following equations:

$$\text{amount of sodium (g)} = V \times Na^+ \times \text{atomic weight of Na/1000} \quad (6)$$

$$\text{amount of chloride (g)} = V \times Cl^- \times \text{atomic weight of Cl/1000} \quad (7)$$

where: V is the volume of irrigation or drainage water and Na^+ or Cl^- is the concentration of sodium or chloride in irrigation or drainage water in meq/l

The following equations were used to compute hypothetical steady-state drainage water salinity parameters and to relate them to the leaching level (LF) and to the irrigation water salinity parameters, assuming that the input of salt into the soil via irrigation equals its output via drainage:

$$EC_{dw} = \frac{EC_{iw}}{LF} \quad (a) \qquad V_{dw} = V_{iw} \times LF \quad (b)$$

$$Na^+_{dw} = \frac{Na^+_{iw}}{LF} \quad (c) \qquad Cl^-_{dw} = \frac{Cl^-_{dw}}{LF} \quad (d) \qquad (8)$$

In equation (8), the subscripts $_{iw}$ and $_{dw}$ refer to irrigation and drainage water, respectively

RESULTS AND DISCUSSION

Volume of irrigation and drainage water

Figure 1, which presents average results for ten applied irrigations over the crop growing season and for all four leaching levels, shows that as the salinity of irrigation water increases, the required volume of irrigation water to satisfy soil moisture depletion decreases and consequently the drainage water decreases. For all treatments, the irrigation time was based on 50% depletion of available water from the field capacity for the pots with EC_{iw} of 4 dS/m and LF = 37%. Under this condition, the greatest volume of applied water corresponds to the lowest salinity level (4 dS/m) and, as the salinity level increases to 9 and 12 dS/m, the volume of irrigation water decreases by 19.2 and 25.4%, respectively. The highest and the lowest volume of irrigation or drainage water belong to irrigation water salinity levels of 4 and 12 dS/m, respectively. Monteleone et al. (2004) reported similar results. Effects of different leaching levels and different irrigation water salinities on the volume of irrigation water are shown in Figure 2. As the leaching

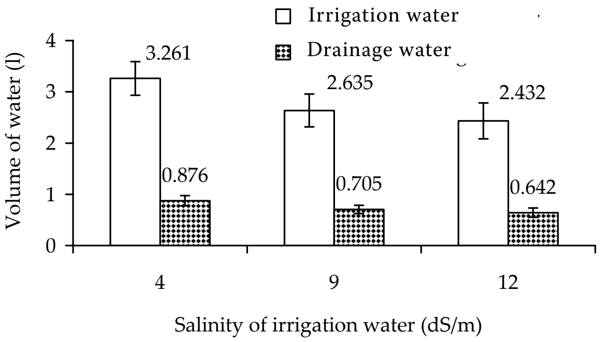

Figure 1. Average volume of irrigation and drainage water per pot per irrigation as affected by the irrigation water salinity EC_{iw}. The figures indicate particular average volumes; vertical intercepts indicate their standard errors

level increases, the slope of the lines in Figure 2 also increases. The highest difference between the volumes of irrigation water with salinity levels of 4 and 12 dS/m belongs to the leaching level of 37%. For a given leaching level, as the irrigation water salinity increases, the volume of applied irrigation water decreases, due to the reduced available water capacity of the soil and the reduced plant water uptake. This occurs because the soil osmotic pressure increases and crop root depth and its activity decreases as the soil salinity increases (Katerji et al. 2005). Therefore, for saline soils, special attention should be paid to the irrigation water salinity and to the leaching level required.

The above results showed that for irrigation management of saline soils the amount of applied irrigation water should be based on the soil and water salinity status and not only on the crop water requirements. The saline soils hold more water but contain less water available for plant uptake.

Drainage water salinity

Figure 3 shows the effects of leaching level on average salinity of drainage water resulting from ten applied irrigations, using three irrigation water salinities. The minimum and maximum salinities of drainage water were about 14 and 46.4 dS/m, respectively. They resulted from irrigation water salinity of 4 dS/m and leaching level of 37% on the one hand and from irrigation water salinity of 12 dS/m and leaching level of 3% on the other hand. These results are consistent with those obtained by Miyamoto et al. (1996). The slope of the reduction of drainage water salinity due to an increase of leaching level depends on irrigation water salinity. The comparison of line slopes indicates that the highest and the lowest leaching efficiency belong to irrigation water salinity levels of 4 and 12 dS/m, respectively. The difference in leaching efficiency between the irrigation water salinity levels of 4 and 9 dS/m is significant; the line slope was reduced from 0.68 to 0.51 when the irrigation water salinity increased, as shown in equations in Figure 3. Contrary to this, the difference in leaching efficiency between the irrigation water salinity levels of 9 and 12 dS/m is not significant (the line slope increased only from 0.51 to 0.52).

The average salinity of drainage water for each irrigation and for each leaching level over the entire crop-growing season is shown in Figure 4. Each drainage water salinity is an average of three particular values for three different irrigation water salinities. As shown in Figure 4, when the leaching level increases, both the salinity of drainage water and its rate of change over time decreases. For all leaching levels, the most saline drainage water accrued at the few first irrigations due to the lack of equilibrium between soil and irrigation water and high initial soil salinity (13.2 dS/m). The drainage water salinity became nearly constant after a few irrigations, which means that the leaching of salts from the soil profile was more efficient during the first few irrigations and thereafter became less efficient. At the leaching level of 3%, the salinity of drainage water dropped significantly from

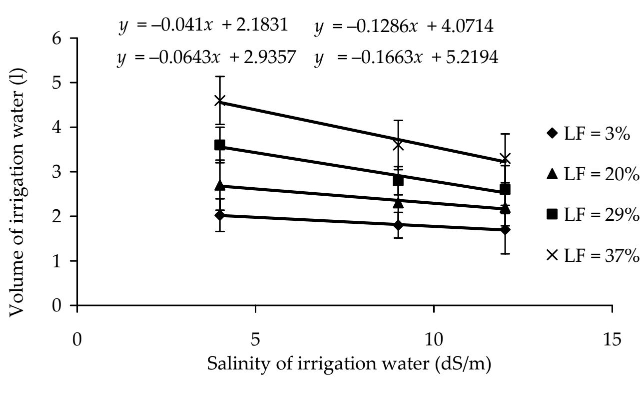

Figure 2. Average volume of irrigation water per pot per irrigation (y) as affected by the irrigation water salinity EC_{iw} (x) for different leaching level (LF) values. The points indicate particular average volumes; vertical intercepts indicate their standard errors

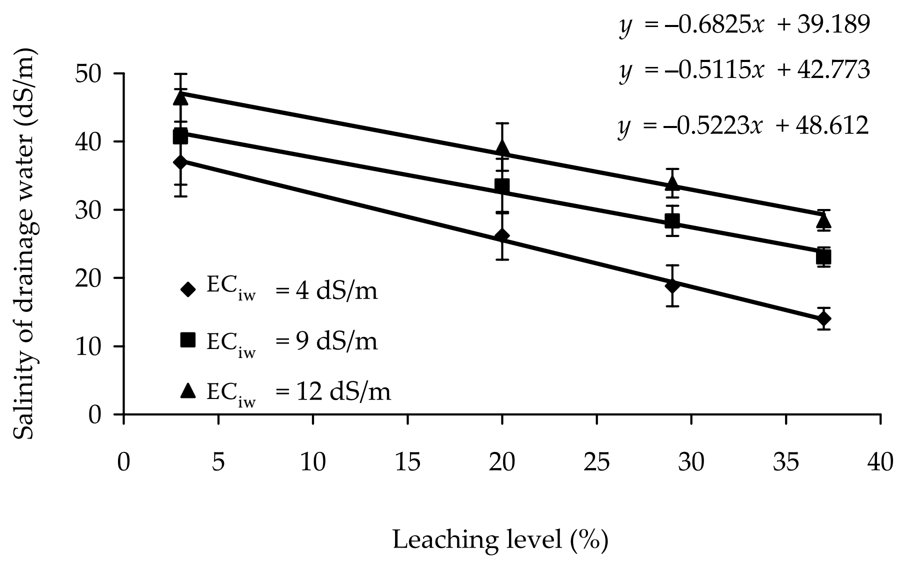

Figure 3. Average salinity of drainage water (y) as affected by the leaching level LF (x) and the irrigation water salinity EC_{iw}. The points indicate particular average values; vertical intercepts indicate their standard errors

97.7 dS/m at the beginning of the season to 32.1 dS/m after the third irrigation, then increased again to final 39.6 dS/m at the end of the growing season. At the leaching level of 37%, the drainage water salinity remained almost constant after the third irrigation (being 21.7 dS/m after the third irrigation and 19.5 dS/m at the end of the growing season).

Soil salt balance

The amount of salt added to the soil and the salt removed from the soil increased due to the increase of both the irrigation water salinity and the leaching level (Table 2). The highest amount of salt added to the pot via irrigation (315.8 g) and salt removed from the soil via drainage (282.9 g) during the entire plant growing season belong to the irrigation water salinity of 12 dS/m and the leaching level of 37%. The difference between the salt added to soil and the salt removed from soil depends on the quality and quantity of leaching water. For irrigation water salinity of 4 dS/m, the salt accumulation in soil was positive (29.9 g) only in the case of leaching level of 3%, while for the higher leaching levels the salt accumulation was negative and the soil was desalinized. For irrigation water salinities of 9 and 12 dS/m, the salt accumulation accrued during the crop growing

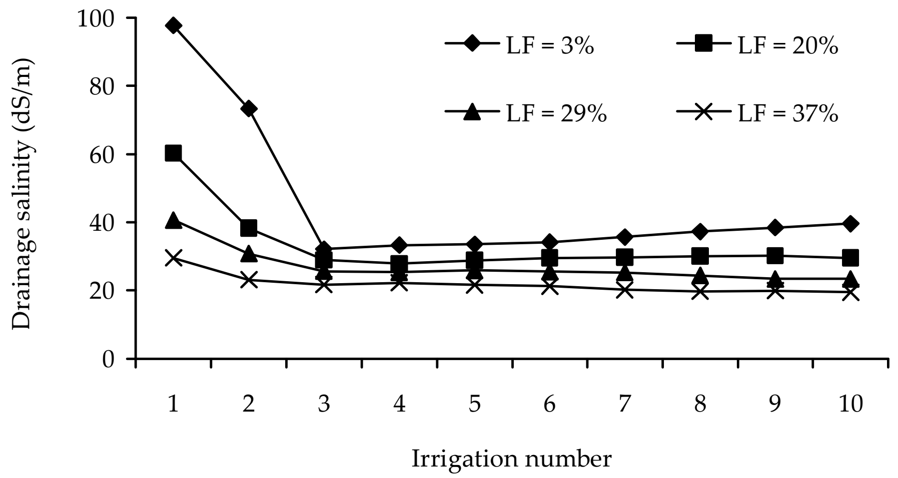

Figure 4. Variation of average salinity of drainage water over the crop-growing season for different leaching levels (LF)

Table 2. Average salt balance for different irrigation treatments

Irrigation water salinity EC_{iw} (dS/m)	Leaching level LF (%)	Average salt in per irrigation (g)	Average salt out per irrigation (g)	Average salt accumulation per irrigation (g)	Average soil solution salinity EC_e (dS/m)
4	3	53.1	23.3	29.9	15.6
	20	70.2	95.9	–25.6	8.5
	29	93.6	141.8	–48.1	5.5
	37	121.2	195.7	–74.5	3.7
9	3	135.0	36.1	98.9	22.3
	20	171.5	118.5	53.0	17.1
	29	202.2	166.8	35.4	14.9
	37	265.9	270.8	–4.9	10.2
12	3	169.1	38.1	131	30.4
	20	213.3	125.5	87.8	23.5
	29	257.1	194.8	62.3	17.7
	37	315.8	282.9	32.9	15.4

All data are average values of all ten irrigation events

season for all treatments, except for the irrigation water salinity of 9 dS/m and the leaching level of 37% for which the salt accumulation was negative (–4.9 g). This means that with the leaching level of 37% the salt accumulation in soil can be avoided even at the high irrigation water salinity of 9 dS/m.

Na and Cl concentration balance

Table 3 shows that as the salinity of irrigation water and the leaching level increased, the amounts of Na^+ and Cl^- added to the soil with irrigation water and removed from the soil with drainage water increased. The application of leaching level of 37% with irrigation water salinity of 12 dS/m caused the greatest addition as well as removal of Na^+ and Cl^- in the soil. The amount of Na^+ and Cl^- remaining in soil depends on the quality of irrigation water and on its amount. For all treatments, Na^+ and Cl^- accumulated in soil over the crop growing season, except for the treatments with leaching levels of 20, 29 and 37% and irrigation water salinity of 4 dS/m and for the treatment with leaching level of 37% and irrigation water salinity of 9 dS/m. None of the applied leaching levels with irrigation water salinity of 12 dS/m was able to prevent accumulation of these elements in soil.

Figures 5 and 6 show the concentrations of Na^+ and Cl^- in drainage water, respectively, for different treatments in the middle and by the end of the crop-growing season. These figures show that both the salinity of irrigation water and the leaching level had significant effects on Na^+ and Cl^- concentrations in drainage water for both the middle and the end of the season. For the treatments with leaching levels of 20, 29 and 37% and irrigation water salinity of 4 dS/m, the Na^+ concentration in drainage water decreased between the middle and the end of the crop growing season both due to good quality and high quantity of leaching water. At higher irrigation water salinity and/or low leaching levels, the sodium concentration in drainage water was higher at the end of the season as compared to the middle of the season. As shown in Figure 6, when the salinity of irrigation water increases or the leaching level decreases, the Cl^- concentration in drainage water increases significantly. The highest Cl^- concentration in drainage water belongs to the irrigation water salinity of 12 dS/m with the leaching level of 3%, while the lowest Cl^- concentration in drainage water belongs to the irrigation water salinity of 4 dS/m with the leaching level of 37%.

Leaching was more effective in reduction of the soil Cl^- concentration than in reduction of the soil Na^+ concentration. Table 3 shows that, for all treatments, the soil accumulated more sodium than

Table 3. Average balance of Na^+ and Cl^- for different irrigation treatments

Irrigation water salinity EC_{iw} (dS/m)	Leaching level LF (%)	Na^+ (g)			Cl^- (g)		
		input per irrigation	output per irrigation	accumulation per irrigation	input per irrigation	output per irrigation	accumulation per irrigation
4	3	10.8	5.0	5.7	15.0	10.4	4.6
	20	18.5	18.9	–0.4	26.8	31.9	–5.1
	29	24.8	30.3	–5.5	36.0	46.7	–10.8
	37	31.0	38.0	–7.0	45.6	59.0	–13.4
9	3	25.1	7.7	17.4	35.0	20.7	14.3
	20	32.7	25.6	7.1	53.5	46.9	6.5
	29	38.8	36.0	2.9	63.6	61.3	2.3
	37	50.5	52.7	–2.2	82.7	91.7	–9.0
12	3	39.9	7.2	32.7	52.3	27.0	25.3
	20	51.6	28.0	23.6	67.6	47.8	19.8
	29	61.1	47.6	13.5	80.1	71.6	8.5
	37	77.4	58.0	19.4	101.5	97.8	3.7
Total of all treatments (g)		462.2	355.0	107.2	659.7	612.8	46.9

All data are average values of all ten irrigation events

chloride during the crop-growing season. In total, 462.2 g of sodium was applied to the soil in all the treatments together and 25.7% of this amount was accumulated in the soil during the crop-growing season. Of total amount of chloride (659.7 g) that was applied to the soil in all the treatments, only 7.1% accumulated in the soil during the season. As the study soil was a silty clay loam with a high content of clay particles, it was apt to hold more sodium than chloride in the leaching process.

Comparison of the actual soil salinity parameters with the calculated steady-state balance

Four hypothetical steady-state drainage water salinity parameters, namely the average volume of drainage water V_{dw}, the average salinity of drainage water EC_{dw}, the average sodium ion concentration in drainage water Na^+_{dw} and the average chloride ion concentration in drainage water Cl^-_{dw}, were

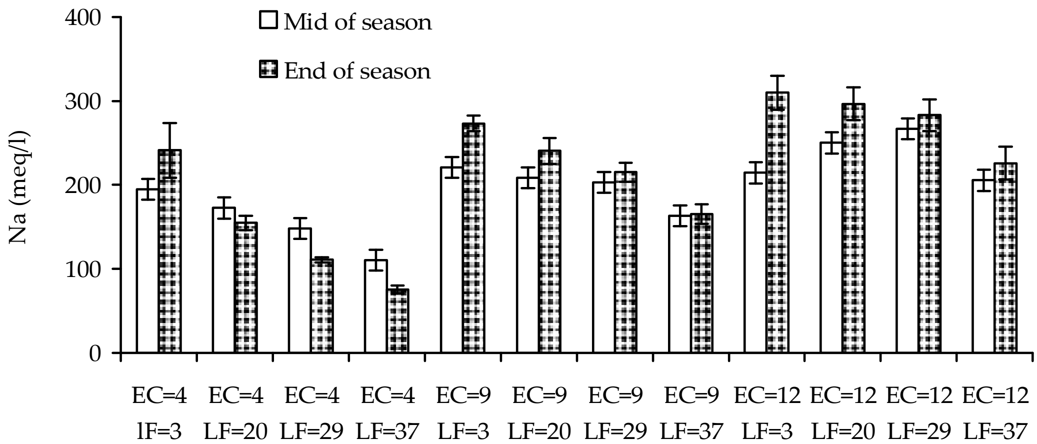

Figure 5. The average concentration of Na^+ in drainage water of individual treatments in the middle of the season and by the end of it. The columns indicate particular average values of parallel pots; vertical intercepts indicate their standard errors

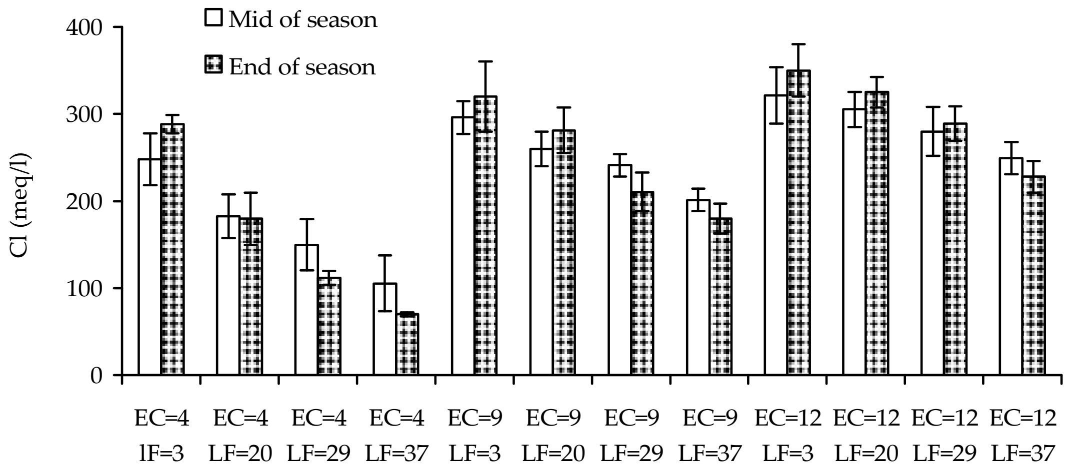

Figure 6. The average concentration of Cl^- in drainage water of individual treatments in the middle of the season and by the end of it. The columns indicate particular average values of parallel pots; vertical intercepts indicate their standard errors

calculated from equation (8) and compared with the actual values of V_{dw}, EC_{dw}, Na^+_{dw} and Cl^-_{dw} (Table 4). The calculated V_{dw} are lower than the corresponding actual values for all four leaching levels. The other calculated parameters are higher than the actual ones and the differences, both absolute and relative, decrease considerably with the increase of the leaching level. The highest difference between the actual and the calculated parameters EC_{dw}, Na^+_{dw} and Cl^-_{dw} was found at the leaching level of 3%, while the lowest difference occurred at the leaching level of 37%. These results are consistent with those obtained by Hoffman et al. (1979), Miyamoto et al. (1996) and El-Haddad and Noaman (2001). As the leaching level increases, the steady-state mass balance of salt, sodium and chloride is more closely approached. The differences in terms of sodium and chloride concentrations and drainage water salinities are especially large for the 3% leaching level. This indicates that the soil cannot be leached properly at this leaching level, when the salt in the drainage water comes mainly from the soil itself and not from the irrigation water. As the leaching levels become higher, the mass balance of salt, sodium and chloride becomes more similar to the volume balance between irrigation and drainage water. The highest relative difference between the calculated and the actual parameters belongs to EC_{dw} (Figure 7). The calculated and the actual values of Cl^-_{dw} at the high leaching levels of 29 and 37% are almost the same. At these two leaching levels, the ratio of chloride concentrations in irrigation and drainage water closely follows the ratio of volumes of drainage and irrigation water according to equation (8). Chloride approaches the steady-state mass balance more easily than sodium because, as mentioned earlier, the soil holds chloride less strongly than sodium. The applied leaching fractions in terms of water volume are close to the leaching fractions in terms of Cl_{iw}/Cl_{dw}.

The leaching of salts from the soil profile is more efficient at the beginning of the crop growth stages and thereafter becomes less efficient. The drainage

Table 4. Average actual and calculated steady-state hypothetical drainage water volumes V_{dw}, electrical conductivities EC_{dw} and sodium (Na^+_{dw}) and chloride (Cl^-_{dw}) concentrations for different leaching levels

Leaching level LF (%)	V_{dw} (l per pot)		EC_{dw} (dS/m)		Na_{dw} (meq/l)		Cl_{dw} (meq/l)	
	actual	calculated	actual	calculated	actual	calculated	actual	calculated
3	0.07	0.05	39.6	288.3	275	2200	319.3	2022.2
20	0.54	0.51	29.5	43.2	230	330	262.1	303.3
29	1.01	0.97	23.4	29.8	203	228	203.9	209.2
37	1.60	1.55	19.5	23.4	155	170	159.3	162.0

Data are averages of three irrigation water salinities and ten irrigation events

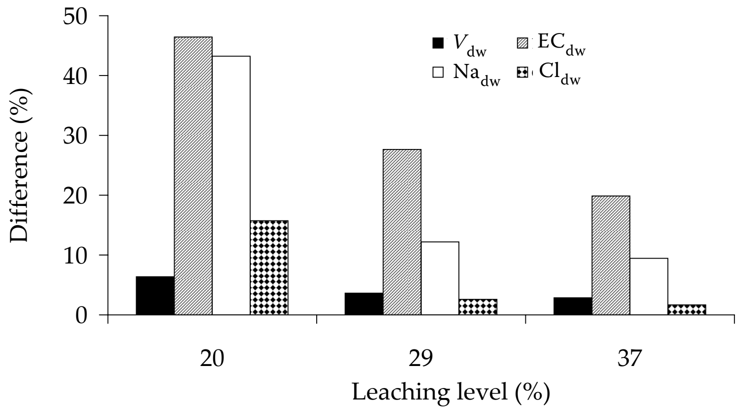

Figure 7. Absolute values of relative differences between hypothetical (steady-state) and actual average drainage water volume (V_{dw}), drainage water electrical conductivity (EC_d) and sodium (Na_{dw}) and chloride (Cl_{dw}) ion concentration in drainage water for different leaching levels. The 3% leaching level is not shown

water is most saline at the beginning of the growing season due to the lack of equilibrium between the soil and irrigation water and due to high initial soil salinity. The drainage water salinity becomes nearly constant after several irrigations. When the leaching level increases, the salinity of drainage water and the rate of change of drainage water salinity decrease with respect both to time and to leaching level. The comparison of measurements and a hypothetical steady-state mass balance of salt, sodium and chloride showed that the irrigation water salinity of 4 dS/m with 37% leaching level is the best treatment for desalinization of the soil. Even the treatment with high irrigation water salinity (9 dS/m) and with the 37% leaching level can prevent soil salt accumulation. The differences between the actual and the calculated chloride concentrations of drainage water at high leaching levels (29 and 37%) are only about 2–3%. Hence, the simple ratio Cl_{iw}/Cl_{dw} can be used to estimate the actual leaching fraction with high accuracy. For saline soils, special attention should be paid to the computation of leaching requirement, taking into account that soil water is less available to the crop.

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