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Long-term salinity development in a lysimeter experiment

J.W. van Hoorn[1,*,a], N. Katerji[2], A. Hamdy[3]

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Abstract

Over a period of 6 years, various crops were grown in tanks, filled with loam and clay, and were irrigated with water of three different levels of salinity. A combination of soil water sampling, salt balance and salt model was used to study the change in the composition of the soil water and the development of soil salinity. After 3 years an equilibrium was attained in the exchange between soil water and adsorption complex. Precipitation of a mixture of calcium and magnesium carbonate occurred during the whole experimental period. During the last two cropping periods the average chloride concentration of the soil profile obtained from soil water sampling was about twice as low as that obtained from the salt balance, due to preferential flow through macropores attaining, the porous cups. Model calculation indicated a bypass fraction of about 0.15. The steady-state leaching model of USSL could be used to estimate the long-term chloride concentration of the soil profile.

Keywords: Soil salinity; Soil water sampling; Salt balance; Preferential flow

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1. Introduction

Use of saline water for irrigation is not a recent development. In areas where saline water is the only available water resource, it has been used already for a long time and the local population has learned, most probably by trial and error, the conditions and limits of its use.

In the Mediterranean area Tunisia is an example, where the fresh water resources for agricultural use are rather limited, and extension of irrigated agriculture is mainly possible by using saline water. For that reason extensive field research had been already carried out in the 1960s, within the framework of a UNESCO project, the results of which were published in 1970 (UNESCO, 1970).

Two factors contribute to the increasing interest in the use of saline water: the worldwide increasing water requirements and competition between human, industrial and agricultural use; and the disposal of drainage water through reuse.

In 1989 the Mediterranean Agronomic Institute at Bari, southern Italy, started a long-term lysimeter experiment to initiate students in the study of plant growth under soil and salinity conditions as may be encountered in practice. Therefore two soils, loam and clay, were chosen and three water qualities, fresh water as a control and two saline waters in the range still considered suitable for irrigation.

A lysimeter experiment presents, as with every method, advantages and disadvantages. Since it is easy to measure the amounts of irrigation and drainage water, an accurate salt balance can be obtained. However, frequent soil sampling for determining moisture and salt content is not possible and the number of plants available for physiological measurements is limited.

Previous papers (Katerji et al., 1992; Van Hoorn et al., 1993; Katerji et al., 1996) described the experimental procedure and the effect of soil salinity on water stress, growth and yield of various crops (broadbeans, wheat, potatoes, maize, sunflower), The second paper also presented soil salinity development during the first period 1990-1992. This paper is only concerned with soil salinity; it describes its development over a period of 6 years, and compares the methods used to determine soil salinity in this experiment.

2. Experimental procedure

2.1. Set-up

The set-up consisted of 30 tanks of reinforced fibre glass with a diameter of 1.20 m and a depth of 1.20 m. A layer of coarse sand and gravel, 0.10 m thick, was covered by a repacked soil profile of 1 m. At the bottom of the tank a pipe serving as drainage outlet connected the tank with a drainage reservoir. The set-up was covered at a height of 4 m by a sheet of transparent plastic to protect the assembly against precipitation.

One series of 15 tanks was filled with loam and a second series of 15 tanks with clay. Table I presents some properties of the soils.

Table I

Soil properties

Soil	Particle size in % of mineral parts			$CaC0_3$ (%)	% Water (v/v)		Bulk density (kg dm^3)
	<2ìm	2−50ìm	>50ìm		pF2.0	pF4.2	
Loam	19	49	32	25	363	20.4	1.45
Clay	47	37	16	5	410	24.0	1.45

2.2. Irrigation

The tanks were irrigated with waters of three different qualities: the control treatment with fresh water containing 3.7 mEq Cl l^{-1} and two saline treatments, obtained by adding equivalent amounts of NaCl and $CaCl_2$ to fresh water. During the first year the chloride concentrations of the saline treatments were 13.8 and 30 mEq l^{-1}; during the second year 10 and 20 mEq l^{-1}; during the third 15 and 30 meq on loam and 15 and 20 mEq l^{-1} on clay and afterwards 15 and 30 mEq l^{-1} on both soils. Table 2 presents the composition of the control treatment and the saline treatments, containing 15 and 30 mEq Cl l^{-1}.

At each irrigation surplus water was added to provide a leaching fraction that generally fluctuated between 0.2 and 0.25.

During the winter periods 1993-1994 and 1995-1996 two leaching experiments were carried out on a non-cropped soil.

2.3. Soil salinity

Three methods were used to determine soil salinity: salt balance; soil water sampling with porous ceramic cups; and a model to calculate the salt distribution of the soil profile. Regular soil sampling could not be carried out, as it would have perforated the soil profile of the lysimeters. Soil samples were only taken twice, in autumn 1993 and autumn 1995 after harvest, to check the other methods.

The increase or decrease in the amount of salt present in the soil can be calculated by measuring the amounts of irrigation and drainage water and their salt concentrations at each application. Dividing the amount of salt by the volume of water at field capacity then gives the average salt concentration of the soil water. Since chloride does not react with the adsorption complex and does not precipitate at the prevailing concentrations, this ion primarily is used to express soil salinity; it was converted into EC of soil water by the equation $\ln EC = 0.824 \ln Cl - 1.42$, established in this experiment. The value was divided by two for the conversion into EC_e, the conductivity of the saturation extract.

The second method consists of taking soil water samples after each irrigation from porous ceramic cups, installed at depths of 0.125, 0.375, 0.625 and 0.875 m. The data are used to calculate the average concentration in the soil profile, from four replicates at four depths in five tanks per treatment. Due to high retention forces in the soil, it was not always possible to obtain samples front each cup.

Table 2

Composition of irrigation water (mEq l^{-1})

Treatment	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	SO_4^{2-}	EC (dSm^{-1})	SAR
Fresh	6.2	3.1	2.3	0.4	3.7	7.3	0.6	1.0	1.1
15 mEq Cl l^{-1}	10.8	3.1	8.7	0.4	15.0	6.6	0.8	2.3	3.3
30 mEq Cl l^{-1}	16.7	3.4	16.2	0.4	30.0	6.5	0.7	3.6	5.1

The third method consists of calculating the chloride distribution of the soil with a simple, numerical model, originally used for field leaching experiments in Tunisia (UNESCO, 1970) and later for leaching experiments in lysimeters (Van Hoorn, 1981). The model comprises four layers that contribute to the water uptake of the plant according to an extraction pattern of 50, 30, 15 and 5%, respectively. This pattern was derived by determining the soil water content before irrigation during the first year. The irrigation water follows a cascade system: irrigation water mixes with the soil water of the first layer, the excess percolates to the second layer and mixes with its soil water, and so on. Preferential or bypass flow can be simulated by introducing a leaching efficiency coefficient, that expresses the fraction of water participating in the mixing process, or a bypass fraction that expresses the fraction not participating in the mixing process. Since it was not possible to make systematic observations of soil water content or suction during the irrigation interval, capillary rise during the irrigation interval was ignored.

The following criteria can be used for the comparison between the three methods:

1. The average chloride concentration of the soil profile;
2. The chloride concentration of the drainage water, measured and calculated with the model;
3. The chloride distribution of the soil profile, measured in soil water samples and calculated with the model.

3. Results and discussion

3.1. Ionic composition

The change in the ionic composition of soil water, due to exchange reactions and precipitation or dissolution, is obtained from a comparison between the ionic concentration obtained by soil water sampling and the concentration calculated with the salt balance. For chloride, no reaction occurs, so the chloride concentrations obtained by both methods should be equal. If not, this can be attributed mainly to soil heterogeneity. Assuming that the salt-balance value is a better approximation of the real value and that the effect of heterogeneity is the same for all ions, the sampling values of the other ions can be corrected by multiplying with the ratio between the chloride concentration obtained from the salt balance and that of soil water sampling. This correction factor varied per year. Then the difference is calculated between the corrected ion concentration obtained from soil water sampling and the concentration calculated from the salt balance.

This difference is negative if adsorption or precipitation occurs and positive for adsorption or dissolution. The procedure has already been described in a previous publication (Van Hoorn et al., 1993).

Table 3 presents the cumulative differences between the ionic concentrations of soil water found by sampling and salt balance for the first 3 years 1990, 1990-1991 and 1990-1992, and for the second period 1993-1995. During the first 3 years the negative difference of Na^+ increases, due to the exchange between soil water and adsorption complex where Na^+ is replacing Ca^{2+} and Mg^{2+}. During the second period of 3 years the negative difference is very small. The other saline treatments showed a similar development; a negative difference increasing during the first 3 years, and a small difference, negative or positive, during the last 3 years. Apparently the exchange reaction is finished after about 3 years.

Table 3

Cumulative differences (in mEq l^{-1}) between the ion concentration of soil water found by sampling and salt balance. Loam, irrigation water of 15 mEq Cl l^{-1}

Period	Na^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}	HCO_3^-
1990	-17.2	17.0	-2.3	8.3	-11.2
1990 - 91	-29.1	20.0	-8.0	8.4	-26.6
1900 - 92	-41.0	8.4	-12.6	-2.7	-39.4
1993 - 95	-3.4	-47.9	-18.6	-20.9	-49.0

An exchange of 41.0 mEq Na l^{-1} corresponds to a volume of 410 l, contained at field capacity in the lysimeter, with an exchange of about 17000 mEq. Since the cation-exchange capacity of the loam equals 320 mEq kg^{-1} and the lysimeter contains about 1600 kg, the total amount of adsorbed ions amounts to 510000 mEq. The increase of Na^+ attains 3.3% and the calculated ESP 4.9, as the original value equalled 1.6. For the 30 mEq Cl l^{-1} treatment the increase of Na^+ attained 5.5% and the calculated ESP 7.1. Table 4 presents the adsorbed cations after 6 years. The ESP (%Na^+) of the fresh water treatment is almost the same as at the start of the experiment, when it equalled 1.3. The measured values of the ESP of the saline treatments are slightly higher than the calculated values.

The negative difference of Na^+ should be balanced by an equal positive difference of C^{2+} plus Mg^{2+}, if no precipitation of these ions occurs. A positive difference of SO_4^{2-} indicates dissolution of gypsum, present in traces in the soil, increasing Ca^{2+} by an equal amount, whereas a negative difference indicates precipitation. A negative difference of HCO_3^- indicates the precipitation of carbonate salts.

The difference of Ca^{2+} was indeed positive during the first 3 years, but it already declined during the third year and became negative during the second period 1993-1995. The difference of Mg^{2+} was always negative and steadily increased. From Table 3 the following calculation can be made for the deficit of Ca^{2+} plus Mg^{2+} due to their precipitation as carbonates, to be compared with the deficit of HCO_3^-. For the period 1990-1992 Ca^{2+} plus Mg^{2+}, not exchanged against Na^+, equal 41.0 - (8.4 - 12.6) = mEq l^{-1}. Ca^{2+}, precipitated as gypsum, equals 2.7 mEq l^{-1}. For Ca^{2+} plus Mg^{2+} the deficit equals 42.5 mEq l^{-1} against a deficit of 39.4 mEq l^{-1} for HCO_3^-.

Table 4

Adsorbed cations in % after 6 years on loam, average 0-100 cm

Irrigation water	Na^+	K^+	Ca^{2+}	Mg^{2+}
Fresh	1.6	2.5	87.7	8.2
15 mEq l^{-1}	5.3	2.7	85.3	6.7
30 mEq l^{-1}	7.5	2.8	83.7	6.0

Table 5

Cumulative deficits of calcium, magnesium and bicarbonate concentration (in mEq l^{-1}) in soil water

		Loam		Clay	
		15 mEq l^{-1}	30 mEq l^{-1}	15 mEq l^{-1}	30 mEq l^{-1}
1990-1992	Deficit of Ca^{2+} + Mg^{2+}	42.5	33.8	37.3	37.2
	Deficit of HCO_3^-	39.4	33.8	36.9	33.8
	Difference	3.1	0.0	0.4	3.4
1993-1995	Deficit of Ca^{2+} + Mg^{2+}	49.0	52.7	38.6	35.1
	Deficit of HCO_3^-	49.0	50.0	36.6	35.9
	Difference	0.0	2.7	2.0	-0.8

Table 5 presents the deficit of Ca^{2+} plus Mg^{2+} and HCO_3^- for the first and second period of 3 years. The deficit of Ca^{2+} plus Mg^{2+} is almost equal to the deficit of HCO_3^-, indicating the precipitation of a mixture of calcium and magnesium carbonate.

3.2. Preferential flow

During the period 1990-1994, the chloride concentration obtained from the salt balance was sometimes higher and sometimes lower than the concentration measured in soil water samples, without a systematic trend in the ratio between both values. The difference can be attributed to heterogeneity in the salt distribution. Table 6, however, shows a clear change for the last two cropping periods, where the chloride concentration obtained from the salt balance is always much higher than that measured in soil water samples. The chloride concentration obtained from soil samples in autumn 1995 after the soybean harvest, confirmed the values obtained from the salt balance.

The difference between both methods during the last two cropping periods can be attributed to a change in the soil water flow, which apparently passes by preference along the porous cups.

The preferential flow is confirmed by the calculation with the model. During the first 4 years complete mixing between irrigation water and soil water without bypass flow yielded a good agreement between the values obtained from the model and those obtained from the chloride balance. The leaching experiment on non-cropped soil during the winter 1993-1994 yielded a bypass fraction between 0 and 0.1. For the last year, however, a good agreement was obtained for a bypass fraction of about 0.15. During the leaching experiment on non-cropped soil in the winter 1995-1996, the bypass fraction increased from 0 at the start to 0.6 at the end. The soil water samples yielded at the end an average chloride concentration of the soil profile of about 10 mEq l^{-1} against 100 mEq l^{-1}, indicated by the chloride balance, confirming the strong bypass flow along the porous cups.

Table 6

Ratio between the chloride concentration of the soil profile, obtained from the salt balance and that obtained from soil water sampling. Average values during the growing season

Year	Crop	Loam		Clay		Average
		15 mEq l^{-1}	30 mEq l^{-1}	15 mEq l^{-1}	30 mEq l^{-1}	
1990	Broadbeans	1.06	1.17	0.99	1.09	1.00
1990-1991	Wheat	0.93	1.39	0.69	0.88	0.97
1992	Potatoes	1.24	1.78	1.04	1.23	1.32
1993	Maize	0.90	0.98	0.77	0.83	0.87
1994	Sunflower	1.04	0.90	0.71	0.83	0.87
1994-1995	Sugarbeet	1.80	1.80	1.36	1.42	1.60
1995	Soybean	2.23	2.20	1.91	1.84	2.05

Field experiments in Tunisia on a silty clay loam showed a bypass fraction of about 0.15 under good irrigation management and that the fraction varied with irrigation regime and soil structure (UNESCO, 1970).

A change in the irrigation regime did not occur during the lysimeter experiment and cannot explain the change in soil water flow. Preferential flow can occur along the wall of lysimeters in case of soil shrinkage. In this experiment, no visible shrinkage appeared between the soil and the wall of the lysimeters and no visible difference in this respect was observed between the first leaching experiment in the winter 1993-1994 and the second one in the winter 1995-1996. Moreover, the soil water samplers are situated about 25 cm from the wall of the lysimeter. Apparently the preferential flow should be attributed to a change in soil structure and an increase of the volume of macropores, which may be due to the effect of the deep root development of sugar beets in 1995 and the root residues.

3.3. Chloride concentration

During the last crop but one (sugar beet) the average chloride concentration of the soil profile increased only slightly and during the last crop (soybean) it remained constant, as is shown in Table 7.

The leaching fraction LF can be expressed as the ratio between the amount of irrigation water I and the amount of drainage water D:

$$LF = D/I \tag{1}$$

If we assume the root zone being one unit of average chloride concentration, in which no capillary rise of saline groundwater occurs, and also assume complete mixing of irrigation water with concentration Cl_i and soil water with concentration Cl_{sw}, we can use the steady-state leaching model of USSL (Richards, 1954) and write for the leaching fraction that maintains long-term equilibrium:

$$LF = Cl_i/Cl_{sw} \tag{2}$$

Table 7

Development of the chloride concentration of the soil profile, obtained from) the salt balance in mEq l^{-1}, at five sampling dates during the growing season of soybean in 1995

Soil	Water	29-7	12-8	1-9	18-9	19-10	Average	EC_e (dS m^{-1})
Loam	15 mEq l^{-1}	71.6	72.3	72.9	74.6	76.2	73.5	4.2
	30 mEq l^{-1}	137.1	136.1	137.0	138.7	141.3	138.0	7.0
Clay	15 mEq l^{-1}	63.8	64.4	64.7	66.0	66.3	65.0	3.8
	30 mEq l^{-1}	121.1	120.2	121.3	121.1	120.7	120.9	6.3

Table 8

Comparison between the leaching fraction calculated as D/I and the leaching fraction calculated as Cl_i/Cl_{sw}

Crop	LF	Loam		Clay		Average
		15 mEq l^{-1}	30 mEq $l^{-1'}$	15 mEq l^{-1}	30 mEq l^{-1}	
Sugarbeet	D/I	0.21	0.19	0.20	0.19	0.20
	Cl_i/Cl_{sw}	0.24	0.24	0.26	0.27	0.25
Soybean	D/I	0.25	0.26	0.26	0.28	0.26
	Cl_i/Cl_{sw}	0.20	0.22	0.23	0.25	0.23

Table 8 presents for the last two crops a comparison between both expressions of the leaching fraction. It shows for both crops a good correspondence, but the ratio Cl_i/Cl_{sw} is higher than the ratio D/I for sugar beet and lower for the last crop of soybean. For soybean the chloride concentration of soil water is higher than for sugar beet, notwithstanding more leaching water. This reflects the increase of bypass flow, which also appears from a comparison between both crops in Table 5.

The steady-state leaching model of USSL is based on complete mixing between irrigation and soil water in a one-layered root zone. In reality mixing is almost never complete and, due to the decreasing water uptake with depth by plant roots, the salt distribution is not homogeneous, but increases with depth. In an earlier publication (Van Hoorn, 1981) it was shown that the simple steady-state model for non-reactive solutes leads to the same long-term salinity of the soil profile as a model that takes into account decreasing water uptake and bypass flow, if the latter is about 0.15, a value that may be expected on medium-textured soils under good irrigation management. Thorburn et al. (1990) also concluded after their field studies in Australia that the steady-state model was useful for a long-term prediction of the chloride concentration.

4. Conclusion

A comparison between the ionic composition of soil water, obtained front sampling with porous cups, and the composition calculated with the salt balance shows during the first years a deficit of Na^+ in soil water, due to the exchange with the adsorption complex, which attains an equilibrium after 3 years. From the first year onwards the deficit of Ca^{2+} plus Mg^{2+} remains almost equal to that of HCO_3^-, owing to precipitation of a mixture of calcium and magnesium carbonate.

During the first years preferential flow almost did not occur. Differences between the average chloride concentration of the soil profile obtained from soil water sampling and that obtained from the salt balance can be attributed to heterogeneity in salt distribution. During the last two crops the difference became large and systematic, soil water samples yielding much lower values. The phenomenon can be attributed to preferential flow through macropores that apparently attain the porous cups. Preferential flow with a bypass fraction of about 0.15 also resulted from a comparison between the chloride concentration of the soil profile obtained from the salt balance and that calculated with a mixing model.

Although the assumptions of the steady-state leaching model of USSL, complete mixing and homogeneous salt distribution, do not exist in reality, this simple model can be used to estimate the long-term average chloride concentration of the soil profile.

References

Katerji, N., van Hoom, JW., Hanidy, A., Bouzid, N., El-Sayed Marous, S. and Mastrorilli, M., 1992. Effect of salinity on water stress, growth, and yield of broadbeans. Agric. Water Manage., 21: 107-117.

Katerji, N., van Hoorn, JW., Hamdy, A., Karam, F. and Mastrorilli, M., 1996. Effect of salinity on water stress, growth, and yield of maize and sunflower. Agric. Water Manage., 30: 237-249.

Richards, L.A. (Editor), 1954. Diagnosis and improvement of saline and alkali soils. USDA Agric. Handbook 60. Washington, 160 pp.

Thornburn, P.J., Rose, CW., Shaw, R.J. and Yule, D.F., 1990. Interpretation of solute profile dynamics in irrigated soils. IFrig. Sci., 11: 99-207.

UNESCO, 1970. Research and training on irrigation with saline water. Tech. Report of UNDP Project, Tunisia 5. UNESCO, Paris, 256 pp.

Van Hoorn, J.W., 198 1. Salt movement leaching efficiency, and leaching requirement. Agi ic. Water Manage., 4: 409-428.

Van Hoorn, J.W., Katerji, N., Hamdy, A. and Mastrorilli, M., 1993. Effect of saline water on soil salinity and on water stress, growth and yield of wheat and potatoes. Agric. Water Manage., 23: 247-265.