Salt-Balance Method As a Tool to Assess Solute Transfer in Soils. Case of Reclaimed Soils in Lower Casamance (Senegal).

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ABSTRACT

The salt balance is established by calculating the variation in salt reserves (Δms) bettween two given periods. We have applied this principle to a given soil profile.

Two cases, a bare soil and a tilled soil, were studied in simulated conditions after antisalt dam waters were evaporated during dry season. The experiment was carried out with three rainfalls (60 mm during 1 hour) spaced by a 24 hour drainage. The last rainfall was higher (120 mm) for the tilled soil. Before and after experiment, soil cores was sampled for salinity (soil solution extract method) and water content (gravimetric method) measurements.

Salt balances allowed to identify the processes leading to accumulate salts in the lowlands of Dijguinoum and to quantify the short-term impact of the antisalt dam.

The prevailing salt transfers at the soil surface are due to the alternate periods of soil moistening and desiccation. An impermeable salt crust is formed between rainfalls and the salt and water movements are governed by the soil surface feature before each rainfall. In ridgy soil, vertical and subvertical flows are the main process and salts can be remove from soil profile by drainage.

The soil physical development plays a significant role on the internal salt movements. Vertical transfers are stimulated by the crack netword. The space distribution of salts in the structural peds show that the crack netwrok conributes to the transverse movements of solutions, to their concentration and dilution.

Therefore, the quantification of salt transfers is an interesting approach to evaluating the influence exerted by agricultural developments and to accounting for the soil dynamics in time and space. However, the weighted salt contents remain indicators for the calculations do not take account of the variability of salinity and moisture within the soil volumes considered.

Key Words: Salt balance method, Solute transfer, Soil dynamics.

INTRODUCTION

In natural environment, saline soils cover large areas in all continents and under all climatic conditions. The worldwide growth of irrigated farming, especially in arid and semiarid regions, often lead to increase soil degradation linked to soil salinization (Carter 1975; Bresler et al., 1982; Robert 1992 and Cheverry 1995) by inadequate irrigation techniques like low-quality irrigation water (Rhoades 1972 and Ayers and Westcot, 1985), low salt leaching (Rhoades et al., 1974; Carter and Robbins 1978 and Oster 1984), or low drainage of shallow aquifer (Hassan and Ghaibeh 1977). However, methods are performed to assess the salinity of cultivated soils with sufficient accuracy so as to avoid its negative effects on food-production (Rhoades 1984; Szabolcs 1989; Ghassemi et al., 1995 and Chabra 1996).

Among these methods, salt balance concept was used in former studies (Wilcox and Resch 1963; Rhoades et al., 1974; Carter 1975; Carter and Robbins 1978 and Sposito et al., 1987). It accounted for all the processes which contribute to inflow, outflow and changes in salt storage in the soil profile, and was based on a mass conservative equation (Oster 1984). This concept is important for irrigation management, especially in steady state conditions (salt balance equal to zero), where the amount of salt added by irrigation must be equal to the amount drained. It implies that leaching must be performed during irrigation

Soil salinization by seawater occurs naturally in marshes and estuaries areas. In tropical coasts occupied by mangrove ecosystem, soils are daily flooded by seawater. For food-production, man have performed convenient agricultural practices like polder reclamation, small dam construction, furrowing (Dent 1986 and Van Breemen 1993). The existence of low-quality groundwater and a shallow watertable made it difficult water management of these soils.

In West african valleys managed by an antisalt dam, daily flooding was replaced by a seasonnal flooding In rainy season, dam reservoir was filled by watershed runoff water, whereas, in dry season, dam water concentrated by evaporation and soils dried Sulfur oxidization produced acidity in soils Salts precipitated at soil surface and were recycled with the next wet season

To gain practical experience in the reclamation of saline and acid sulphate soils, a large research program was carried out from 1989 to 1991 in the lowlands of Djiguinoum (Lower Casamance). Two rice-growing areas were constructed in these sterile soils in order to show that water management of an antisalt dam had a direct influence on their productivity. For this purpose, impounded waters were drained off so that their chemical quality should be consistent with an adequate rice growth. The agronomic results obtained in terms of yield were conclusive for several years (Montoroi et al , 1993)

However, these results raise a main question concerning the soil sustainability Even though human action carried out with the dam have proved to be effective on the general desalinization of lowlands, how salts were removed in soil profile, by runoff or by drainage? On other words, can we assess the efficiency of soil desalinization?

Thus the aim of the present study was to focus on water and solute transfer through a soil profile using salt mass-balance. The experiment was designed to reproduce water supply conditions at the beginning of rainfall season when soils were not yet flooded.

MATERIALS AND METHODS

Soil and site preparation

Field rainfall simulation experiment was conducted on a saline and acid sulfate soil of Djiguinoum valley (Lower Casamance, Senegal) The soil is a Sulfaquept according to Soil Taxonomy (Fanning and Witty 1993) and is denoted in this study as STV. Mean annual rainfall in the area is about 1100 mm in the last 25 years. The soil was widely used for rice culture and were shown to undergo significant salinization which is linked to the climatic change occured in West Africa (Marius 1986; Montoroi 1996a and Fanning and Burch 1997).

Prior to rainfall simulation, the field site selected for this study was bare with a uniform soil surface. Salts were precipitated on the surface and were mixed with clay particles forming a 1 cm thick powdery layer (Montoroi 1995; 1996a, 1996b). The upper soil horizon was well-structured and 6 dm deep. Clay content (<2 mm) ranged from 60 to 80%, a silt fraction (<50 mm) 20%. Clay fraction was primarily of kaolinitic composition. Lower horizons (6-15 dm) were light textured with a sand content ranged from 59 to 75%. Soil was severely acid and pH value varied from about 5 in the upper part to 3 in depth. Groundwater level was present at 1.2-1.4 m with a pH of 4 and an electrical conductivity of 16 dS m^{-1}. Selected soil properties are shown in Table 1.

Table 1. Selected soil properties of the Djiguinoum saline acid sulfate soil used in the experiment

	Particle size distribution (g $100g^{-1}$)						1:5 soil solution extract	
Depth	Clay	Silt	Sand	D_s	H_p	H_v	pH	EC
(cm)	(<2 mm)	(2-50 mm)	(>50mm)	g cm^{-3})	(g $100g^{-1}$)	(cm^3 cm^{-3})		(dS m^{-1})
0-10	61.9	25.5	12.6	1.63	15.5	0.253	4.0	7.3
10-20	75.2	20.0	4.8	1.58	17.0	0.269	4.5	3.1
20-30	78.3	17.8	3.9	1.48	25.7	0.380	4.4	2.7
30-40	-	-	-	1.43	30.1	0.430	-	-
40-50	60.5	17.2	22.3	1.40	36.3	0.508	4.6	2.0
50-60	76.0	18.3	5.7	1.51	38.5	0.581	-	-
60-70	24.7	16.6	58.7	1.55	30.0	0.465	5.3	1.0
70-80	20.8	13.6	65.6	1.56	24.0	0.374	4.8	1.1
80-90	18.8	12.6	68.6	1.53	33.1	0.506	4.8	1.4
90-100	23.2	12.1	64.7	1.61	32.3	0.520	4.1	2.6
100-110	14.9	8.4	76.7	1.63	30.1	0.491	3.9	2.5
110-120	15.3	9.7	75.0	1.64	31.5	0.517	3.1	3.4
120-130	15.4	10.6	74.0	1.63	33.7	0.549	3.2	2.8
130-140	16.8	12.3	70.9	1.59	34.0	0.541	3.2	3.9
140-150	16.4	9.2	74.4	1.59	32.5	0.517	3.0	4.1

The plot device consisted of a 1 m^2 squarred frame (1 m x 1 m) inserted in the soil surface at few centimeters depth. The average slope was 1% and runoff water were collected in a 0.1 m^2 squarred section tank buried in the soil (Fig 1).

This layout was prepared to simulate the first rainfall events occurring annually in dried saline bottomland soils when antisalt dam waters were evaporated during dry season.

Rainfall simulation procedure

A programmable rainfall simulator based on the design of Casenave and Valentin (1989) was used. Raindrops were emitted through an oscillating V-jet spray nozzle. Rain fell from a height of 4 m above the soil surface

Well water supply with an EC of 0.8 dS m^{-1} was used. Wind effects were eliminated by the use of a wind-shield fixed on a tubular frame above and around the plot.

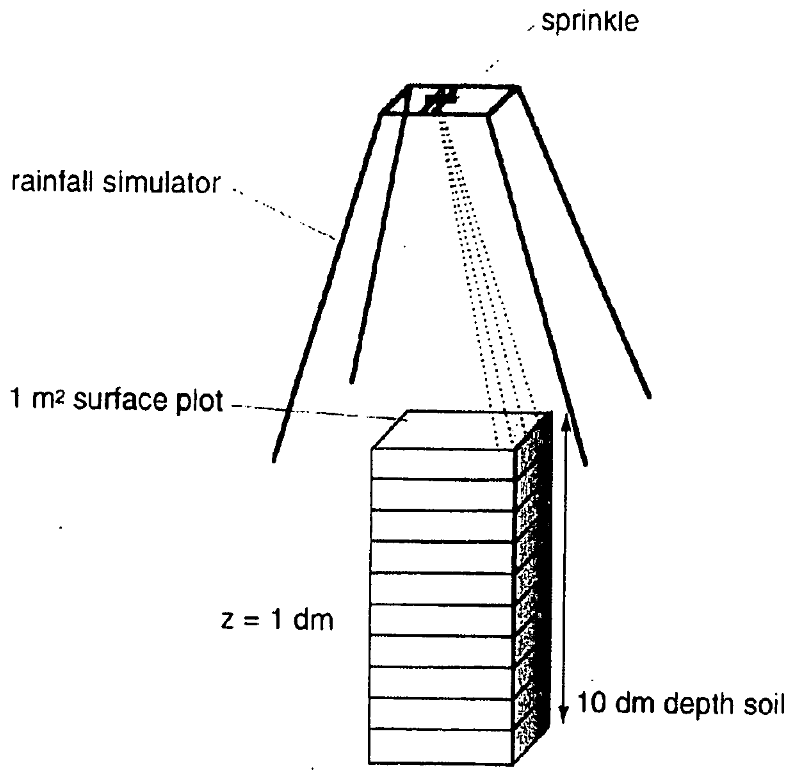

Fig. 1. Experiment device of rainfall simulation

Three successive rainfall events of 60 mm were applied with rainfall duration of 1 h The second event was carried out the following day to determine the influence of surface sealing on runoff rate and thus salt enrichment. The third event was applied one day after the second run

The rainfall intensity of 60 mm h^{-1} was consistent with the hydrological data recorded during the beginning of rainy season.

Before and after experiment, soil cores were sampled for salinity (1:5 soil solution extract method) and water content (gravimetric method) measurements.

Runoff and salinity measurements

For each simulated rainfall, runoff was volumetrically measured in tank with a water level recorder using a float gauge. The depth of surface runoff was calculated at 10-min intevalls Visual observations of particle distribution on soil surface were made and recorded both before and after simulation experiment

Runoff water salinity was measured with a portable conductivimeter, the cell being plunged in tank water. Electrical conductivity (EC) was regularly measured before and during each simulated rainfall.

Soil salinity was determined by 1:5 soil solution extract method (Richards 1954). Measures were converted to soil solution values compatible with field conditions. The conversion relationships were calculated by a former experiment carried out in the same site and published by Montoroi (1996a)

RESULTS AND DISCUSSION

Salt removal by runoff water

Salt mass-balance calculation

During rainfall simulation, salinity measurements of runoff water allow the calculation of salt mass-balance processed as following:

For a given time t, salt mass exported from 1 m^2 plot by runoff mass, salt content of runof water is denoted as $M_{E(t)}$. This parameter is equal to salt mass of water at time t ($M_{c(t)}$) minus salt mass of water at initial time ($M_{c(0)}$) and salt mass supplied by simulated rain water ($M_{p(t)}$). The equation is as follows :

$$M_{E(t)} = M_{c(t)} - (M_{c(0)} + M_{p(t)}) \qquad (1)$$

The different components of this equation are calculated from the following relations.

(i) The expression of $M_{c(t)}$, in g, is given by

$$M_{c(t)} = CD_{c(t)} \, V_{c(t)} \qquad (2)$$

where $CD_{c(t)}$ represents the salt concentration of tank water, expressed in g L^{-1}, and $Vc(t)$ the water volume in tank, in L.

At a given time t, water volume in tank Vc(t) is equal to the sum of runoff water volume Vr(t) and water volume at initial time Vc(0) Considering the plot surface (s, in m^2), and the depth of surface runoff ($L_{r(t)}$), directly measured on level hydrograph and expressed in mm or in L m^{-2}, we can write

$$V_{c(t)} = Vr(t) + V_{c(0)} = L_{r(t)} \, s + V_{c(0)}$$

Salt concentration of tank water ($CD_{c(t)}$) is determined with EC measurement according to the relationship (Montoroi 1996a)

$$CD_{c(t)} = 0.478 \, EC_{c(t)}^{1.104} \qquad (3)$$

where EC indicates electrical conductivity of water tank, in dS m^{-1}.

(ii) With the former relationship (2), the expression of $M_{c(0)}$, in g, is given by

$$M_{c(0)} = CD_{c(0)} \, V_{c(0)}$$

where $CD_{c(0)}$ represents the initial salt concentration of tank water, calculated by (3) and expressed in g L^{-1}, and $Vc(0)$ the initial water volume in tank, in L

(iii) The expression of $M_{p(t)}$, in g, is given by

$$M_{p(t)} = CD_p \, V_{r(t)}$$

where CD_p represents the salt concentration of rainfall, expressed in g L^{-1}, and $Vr(t)$ the runoff water volume, in L.

Salt concentration of rainfall is considered constant during experiment. EC measurement is of 0 8 dS m^{-1} and CD_p is assessed by (3) to 0.37 g L^{-1}.

Finally, for each rainfall event, mass salt content of runoff water $M_{E(t)}$ is calculated at 10-min intervals and is cumulated to obtain the total amount after 60 mm of water supply. Salt mass-balance is determined by the variation of this total amount between two successive rainfalls and a bulk balance is made cumulating all the variations during experiment.

Results

For each rainfall, the characteristics of runoff water are given in Table 2.

For the three events, depth of surface runoff and thus runoff rate increased with time. For the first 60 mm water supply, depth of surface runoff was of 44.2 mm which corresponded to 73.7% runoff rate. For the second and third runs, runoff rate was higher and reached almost 100%. During the first rainfall event, a surface seal was developped reducing infiltration and increasing runoff. Fine particles were dispersed by freshwater supply and were moved downward. During the intervall between two successive rainfalls, surface seal dried and became a weak crust which was covered by white salt precipitate.

Table 2 Salt balance of runoff plot during rainfall simulation experiment[§]

Event	t	CE_c	CD_c	L_p	L_r	K_r	V_c	M_c	M_p	M_E
	(mn)	(dS m^{-1})	(g L^{-1})	(mm)		(%)	(L)		(g)	
1st rainfall	0	0.80	0.37	0	0	0	15.5	5.8	0	0
	10	10.90	6.68	10	2	20.0	17.5	116.9	0.7	110.4
	20	14.77	9.34	20	10.7	53.5	26.2	244.8	4.0	235.0
	30	14.18	8.93	30	18.5	61.7	34.0	303.6	6.9	290.9
	40	13.16	8.22	40	26.4	66.0	41.9	344.6	9.9	328.9
	50	12.50	7.77	50	34.2	68.4	49.7	386.2	12.8	367.6
	60	11.02	6.76	60	44.2	73.7	59.7	403.6	16.5	381.3
2nd rainfall	0	0.98	0.47	0	0	0	16.0	7.5	0	0
	10	7.09	4.15	10	7.2	72.0	23.2	96.4	2.7	86.2
	20	7.04	4.12	20	17.2	86.0	33.2	136.9	6.4	123.0
	30	6.76	3.94	30	27.2	91.0	43.2	170.3	10.2	152.6
	40	6.54	3.80	40	37.2	93.0	53.2	202.2	13.9	180.8
	50	6.45	3.74	50	47.2	94.4	63.2	236.5	17.6	211.4
	60	6.36	3.69	60	59.0	98.0	75.0	276.4	22.0	246.9
3rd rainfall	0	0.95	0.45	0	0	0	22.0	9.9	0	0
	10	7.41	4.36	10	7.4	74.0	29.4	128.2	2.8	115.5
	20	6.95	4.06	20	17.4	87.0	39.4	160.1	6.5	143.7
	30	6.32	3.66	30	27.4	91.3	49.4	180.8	10.2	160.7
	40	5.69	3.26	40	37.4	93.5	59.4	193.6	14.0	169.7
	50	5.22	2.96	50	47.4	94.8	69.4	205.6	17.7	178.0
	60	4.98	2.81	60	58.2	97.0	80.2	225.6	21.7	194.0

[§] The column headings are defined in the text.

Fig. 2 shows the variations in depth of surface runoff L_r with time for the three rainfalls. At a given time t, runoff rate $K_{r(t)}$, expressed in percent, is calculated by

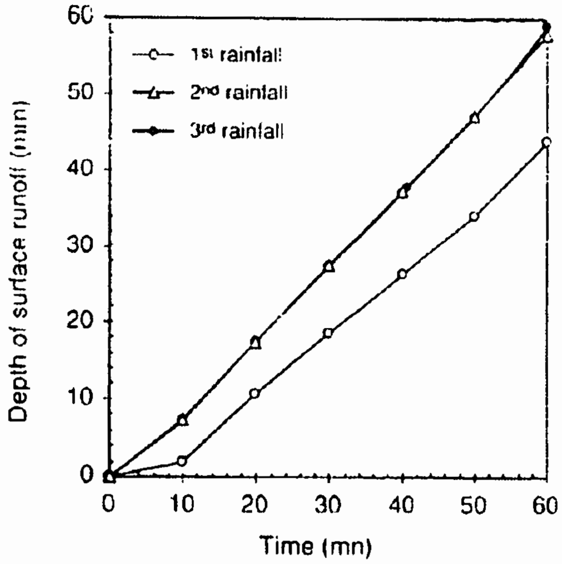

Fig. 2. Depth of surface runoff during experiment, as a function of time. For each rainfall, water supply is equal to 60 mm.

$$K_{r(t)} = 100\,(L_{r(t)} / L_{p(t)})$$

where $L_{p(t)}$ represents the depth of supplied water by simulated rain in mm. The change in runoff rate with time can be seen in Fig. 3.

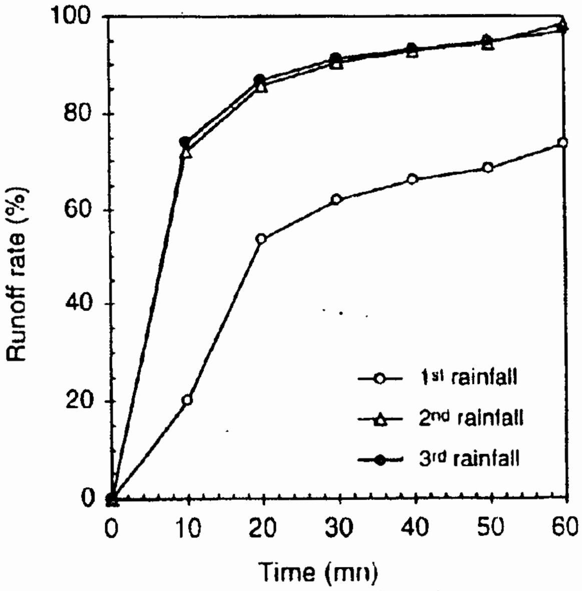

Fig. 3. Runoff rate during experiment, as a function of time.

Fig. 4 shows the temporal variations in the salt concentration of runoff water (CD_c). For each event, this parameter increased with time, reached a maximum level and decreased slowly. For the first run, runoff water was more concentrated than for the both following runs, with a CD_c maximum value of 9.34 g L^{-1} instead of 4.15 and 4.36 g L^{-1}. This maximum was reached more rapidly for the second and the third runs. after about 10 mn rainfall duration instead of 20 mn for the first run For the second run, CD_C decrease was less accentuated

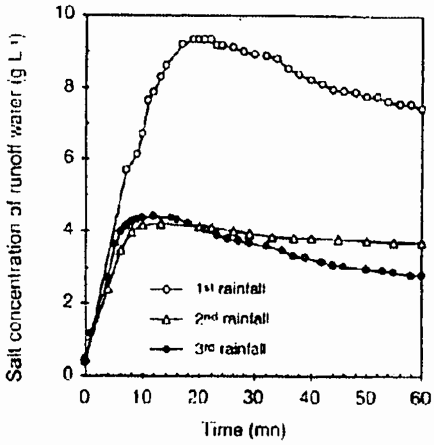

Fig. 4 Salt concentration of runoff water during experiment. as a function of time

The change in salt mass (M_E) removed from runoff plot with time is shown in Fig. 5. For the first rainfall, salt removal was high and curve slope, denote that salt mass rate was quivalent to the amount of salt removed per time unit. then decreased with time and ranged from 11 to 1.4 g mn^{-1} However. for the following event. salt mass rate was less pronounced approaching steady state at about 10 mn after runoff initiation with a mean amount of 3 2 g mn^{-1}. For the last rain, steady state was rather reached after about 20 mn runoff and salt mass rate was of 1.3 g mn^{-1}

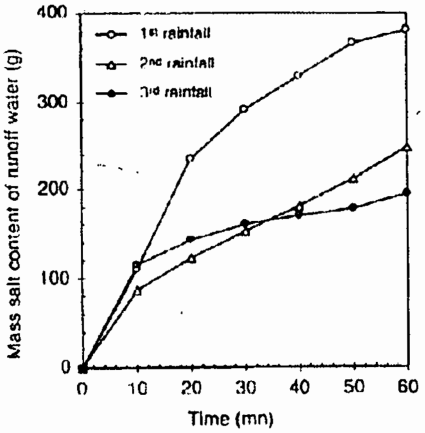

Fig 5. Mass salt content of runoff water during experiment. as a function of time

The amount of salt removed by surface runoff decreased with the successive rainfalls It was twice less considerable between the first rainfall with an amount of 381.3 g and the third one with an amount of 194 g At the end of experiment. the total amount of salt removed by runoff from 1 m^2 plot reached 822.2 g (Table 2)

Salt leaching in soil profile

Salt mass-balance calculation

Given a soil volume V (expressed in dm^3), the mass salt content Ms (expressed in g) this volume V is calculated by the relationship :

$$Ms = CD_{ss} V_e = CD_{ss} H_v V \qquad (4)$$

where CD_{ss} is the dissolved salt content of the soil solution (in g L^{-1}),

V_e is the volume of water (in dm^3) contained in soil volume V (in dm^3).

H_v is the volumetric water content (in dm^3 dm^{-3}) of soil volume which is related mass water content H_p (in g per 100 g dried soil) and dry bulk density D_s (in g cm^{-3}) by t relation $H_v = H_p D_s / 100$.

Given the sizes of the volume V, namely the thickness z (dm) and the area s (dm^2), t relationship (4) becomes :

$$Ms = CD_{ss} H_v z s$$

Considering a cubic volume (z = 1 dm, s = 1 dm^2), we have applied this principle. F a given soil profile of 1 m in depth (z = 10 dm) which is thus equivalent to 10 cubic volum the total mass salt content Mst is calculated by cumulative method. Considering a s volume k, which can be assumed to an horizontal soil layer with a mass salt content Ms(k the cumulated mass salt content Msc(k) for a soil profile forming by the k upper layers, calculated by the following relationship:

$$Msc(k) = Msc(k-1) + Ms(k)$$

In the surface layer, salt contents of runoff water is added to salt content in s volume.

The salt mass-balance is established by calculating the variation in mass salt conte (DMs) between two given periods.

In the same way, water reserve was determined for each layer (S) and for the who soil profile by cumulative method (Sc). Considering a z dm thick layer k, parameter expressed in mm or L m^{-2} is given by:

$$S(k) = 100\, Hv\, z$$

and parameter Sc(k) is equal to the following realtion:

$$Sc(k) = Sc(k-1) + S(k)$$

Results

Before and after rainfall simulation experiment, the water and salt contents of STV soi are given in Table 3. Fig. 6 shows the variations in volumetric water content Hv with dept and the change in mass salt content with depth can be seen in Fig. 7.

Water content increased of about 20 mm in the first 35 cm in depth This value was consistent with the 18 6 mm total depth of infiltrated water which was equal to the 161 4 mm total depth of surface water minus of the 180 mm total depth of rain water It is assumed that there was no water loss by evaporation during the two drainage intervals between successive rainfall because of the formation of salt crust.

In soil profile, given an area of 1 dm^2, a decrease of 18.5 g salt was observed at the upper layer, while it increased by 8.1 g in the two underlying layers (Table 4) Therefore, salts transferred downward.

The amount of upper layer was obtained in adding the salt balance as referred in table 4 and the amount of salt release by runoff water was calculated for the 1/100 of surface plot (1 m^2).

In the first 35 cm in depth, the cumulative salt balance showed a salt loss amounting to 2.3 g. This negative balance hardly varied in depth

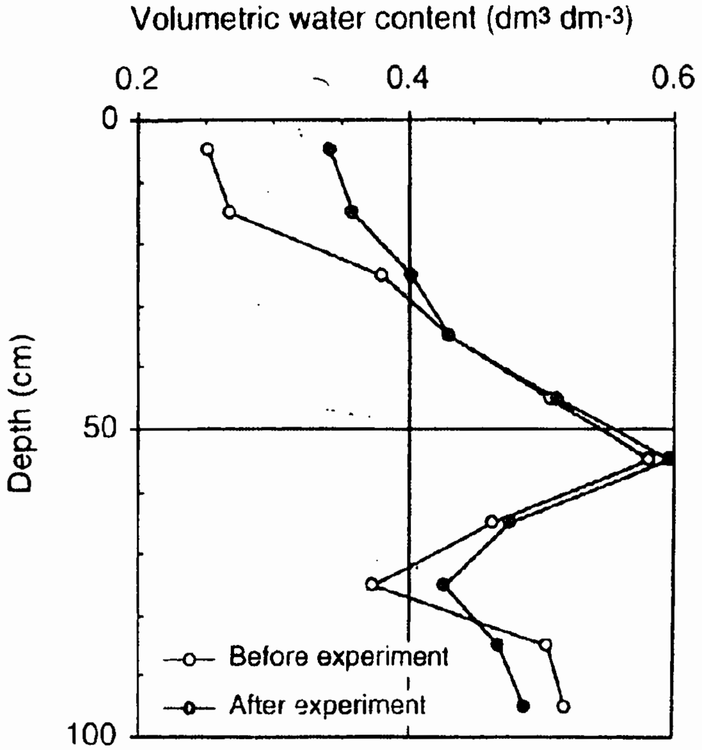

Fig. 6. Distribution profiles of volumetric water content before and after experiment.

Table 3. Water and salt contents of STV soil before and after rainfall simulation experiment‡

	Depth	D_s	H_p	H_v	S	S_c	$CE_{1/5}$	CE_{ss}	CD_{ss}	M_s	M_{sc}
	(cm)	(g cm^{-3})	(g/100g)	(dm^{3}dm^{-3})	(mm)		(dS m^{-1})		(gl.$^{-1}$)	(g)	
Before 1st rainfall	5	1.63	15.5	0.253	25.3	25.3	4.0	124.3	98.1	24.8	24.8
	15	1.58	17.0	0.269	26.9	52.1	1.9	62.5	45.9	12.3	37.1
	25	1.48	25.7	38.0	38.0	90.2	2.4	48.8	35.0	13.3	50.4
	35	1.43	30.1	0.430	43.0	133.2	1.8	32.9	22.7	9.8	60.2
	45	1.40	36.3	0.508	50.8	184.0	1.5	23.4	15.6	7.9	68.1
	55	1.51	38.5	0.581	58.1	242.2	1.7	24.3	16.2	9.4	77.5
	65	1.55	30.0	0.465	46.5	288.7	0.9	19.1	12.4	5.8	83.3
	75	1.56	24.0	0.374	37.4	326.1	1.2	30.3	20.6	7.7	91.0
	85	1.53	33.1	0.506	50.6	376.7	1.5	25.8	17.3	8.8	99.8
	95	1.61	32.3	0.520	52.0	428.7	1.4	25.1	16.8	8.7	108.5
After 3rd rainfall	5	1.48	23.1	0.342	34.2	34.2	2.6	58.2	42.4	14.5	14.5
	15	1.36	26.4	0.359	35.9	70.1	3.3	61.1	44.8	16.1	30.6
	25	1.30	31.0	0.403	40.3	110.4	4.0	60.2	44.1	17.8	48.3
	35	1.26	34.3	0.431	43.1	153.5	2.1	32.5	22.3	9.6	58.0
	45	1.20	42.7	0.512	51.2	204.7	1.9	23.9	15.9	8.1	66.1
	55	1.51	39.5	0.596	59.6	264.3	1.6	22.6	14.9	8.9	75.0
	65	1.55	30.8	0.477	47.7	312.1	0.9	18.6	12.0	5.7	80.7
	75	1.56	27.4	0.427	42.7	354.8	1.2	26.4	17.7	7.6	88.3
	85	1.53	30.7	0.470	47.0	401.8	1.4	26.4	17.8	8.3	96.6
	95	1.61	30.4	0.489	48.9	450.7	1.6	29.7	20.2	9.9	106.5

‡ The column headings are defined in the text.

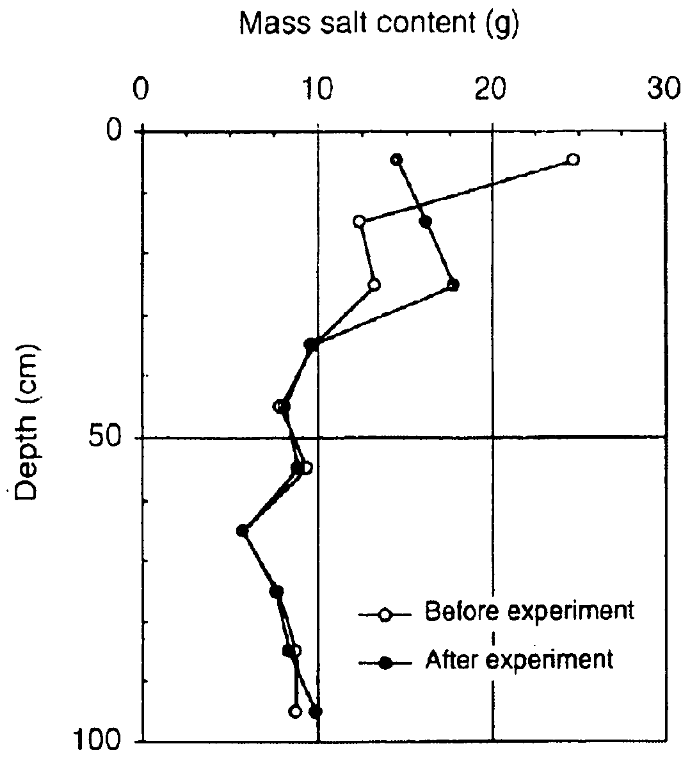

Fig 7 Distribution profiles of mass salt content before and after experiment

Table 4. Water and salt balances of STV soil before and after rainfall simulation experiment

Depth	ΔS	ΔS_c	ΔM_S	ΔM_{Sc}
(cm)	(mm)		(g)	
5	+8.9	+8.9	-10.3	-10.3
15	+9.0	+17.9	+3.7	-6.6
25	+2.3	+20.2	+4.4	-2.2
35	+0.0	+20.2	-0.1	-2.3
45	+0.4	+20.6	+0.2	-2.1
55	+1.5	+22.1	-0.5	-2.6
65	+1.2	+23.3	0.0	-2.6
75	+5.3	+28.6	-0.2	-2.8
85	-3.7	+24.9	-0.4	-3.2
95	-3.1	+21.8	+1.2	-2.0

CONCLUSION

A rainfal simulator experiment involving soil of known salinity led to the following conclusions.

- Runoff rate measurements pointed out the predominance of this process. For the first rainfall, runoff rate was less high than the two following rainfalls. For these later rainfalls, the amont was equal to almost 100%.
- Runoff water was highly saline, the mass salt content decreased with the successive rainfalls.
- The prevailing salt transfer at soil surface was due to the alternate periods of soil moistening and soil desiccation favoring the formation of an impermeable salt crust between rainfalls. Thus salt and water flows were governed by the soil surface feature before each rainfall.
- On the opposite, salt leaching was a secondary process and was promoted by the cracks present under the formed salt crust.
- Salt balance method allowed to quantify the processes leading to accumulate salts in soils. For a $1m^2$ squarred area and 1m deep soil, the salt release by runoff water was four times higher than by infiltrated water.

Therefore, this calculation method is an interesting approach to account for the soil dynamics in time and space, and to assessing the influence exerted by agricultural practices. However, mass salt content remains a bulk parameter because calculation do not take account of the variability of salinity and moisture within the considered soil volume.

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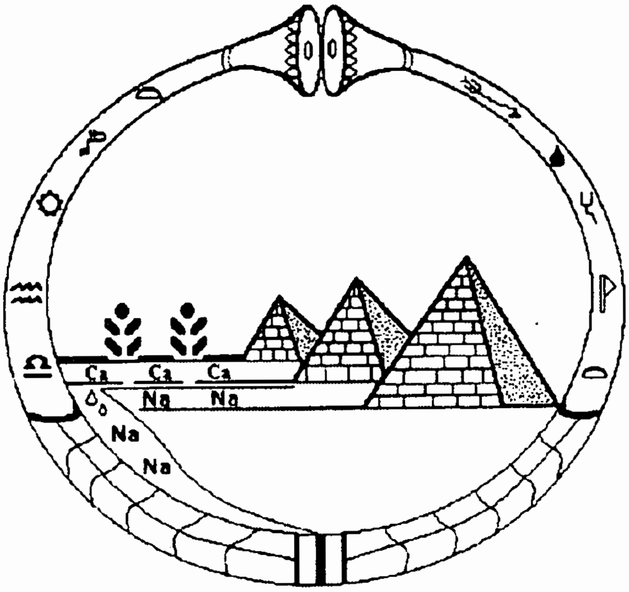

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