CATENA vol. 15, p. 577–594 Braunschweig 1988

WATER, SALT AND SODIUM DYNAMICS IN A NATRAQUOLL IN ARGENTINA

R.S. **Lavado** & M.A. **Taboada**, Buenos Aires

Summary

The influence of soil and environmental factors on water and salt dynamics in a typic Natraquoll of the center of the Flooding Pampa (Argentina) was studied. In phreatimeters, the water table reached the soil surface during floods, but in the soil profile it was never above the bottom of the B31 horizon (0.65 m). This horizon and the over-laying B22 one showed a permanent unsaturation. The A1, B1 and B21 horizons, however, often became saturated with water.

The typical floods in the region are caused by the accumulation of rainwater on the previously saturated upper horizons. Simultaneously, phreatic water undergoes an abrupt increase in electrical conductivity (ECw). These saline peaks (ECw of up to 45.00 dS m^{-1}) caused the immediate salinization of the deep horizons, probably by diffusion. The arrival of salts at the soil surface was episodic and by convection. However, salt leaching prevailed in the course of time in the upper horizons. The soil saturation extracts showed a balanced proportion of anions, but among cations, Na^{+} prevailed over Mg^{++}, Ca^{++} and K^{+}. Soil alkalinity was low and with some significant variations in the surface horizons, that depended on episodic salt rises or salt leaching processes. In the deep horizons soil remained permanently natric.

This dynamic balance of water and salt showed that, in this part of the region, the soil profile exhibits two zones which are relatively independent of each other. Each represents different stages of the evolution as stated by Gedroiz's theory. The deep horizons undergo a continuous salinization and alkalinization process. The upper horizons tend to be similar to zonal soils. The slight halomorphism in this profile zone is due to the episodic salt rises.

1 Introduction

Among salt-affected soils, Solonetzes are characterized by their natric horizon (SZABOLCS 1969). Many ways of accumulation and transport of sodium salts, and consequently of clays, making up the B horizon have already been reported (MUNN & BOEHN 1983), but the traditional Gedroiz's theory, developed more than 60 years ago, is the one usually applied (FULLERTON & PAWLUK 1987, SZABOLCS 1969).

The above interpretation indicates that the origin of Solonetzes is due to the upward movement of salts from groundwater. In these profiles sodium displaces the divalent cations in the soil exchange complex, the soil colloids disperse and

ISSN 0341–8162

0341–8162/88/5011851/US$ 2.00 + 0.25

they are transported downward by percolating water. With time, the typical illuvial horizon of the solonetz is formed under the influence of wetting-drying cycles. This natric horizon is often characterized by a columnar structure and by being slowly permeable. Solonetzes thus formed show a different degree of development (morphology and chemical properties), usually connected with diverse topographic locations, with the properties of phreatic water (chemical composition, fluctuation in depth), and with climatic variations or parent material. The genesis of Solonetzes according to this model has been reviewed by several workers, for example SZABOLCS (1969). Some authors (FULLERTON & PAWLUK 1987, MACLEAN & PAWLUK 1975, SCHWARTZ et al. 1987), studied the flow of water and salts in the field but few quantitative studies have been completed.

The Flooding Pampa, located in the Province of Buenos Aires, is one of the areas in the world with extensive Solonetzes. The origin of these soils and the influence of environmental factors on their formation were the subject of many interpretations and controversies. Thus, different emphasis has been placed on a number of different factors such as floods, droughts, salts provided by rainfall, salts released by weathering of minerals, lack of regional slope, and so on (DURAN 1981, LAVADO 1983, LAVADO & TABOADA 1986, MIACZINSKI et al. 1984, MOSCATELLI & SCOPPA 1984, TRICART 1973). Currently, it is not clear what role these factors play in the salt-affected soils an what mechanisms operate. This lack of a clear model for their genesis has led to inappropriate reclamation methods of these soils.

This paper reports on the movement of water and salts from the water table, the mechanisms involved and their connection with environmental factors. The development of soil alkalinity is also considered.

2 Description of the area

The Flooding Pampa is a vast intrazonal area of about 90 000 km^2 located on the East of the Pampa region (fig.1). Most of its soils were developed from loess-like sediments which were transported from the Andes Mountain range on the West. Subsequently, during the climatic alternations of the Quaternary period, they were affected by different geomorphic processes: overflows due to the action of surface water, eolian action that gave way to deflation-accumulation land forms and littoral action connected with the interglacial sea ingressions. Soil profiles developed on sediments of different age and/or origin are common in the region (INSTITUTO NACIONAL DE TECNOLOGIA AGROPECUARIA 1977, TRICART 1973).

The present climate is temperate, subhumid on the West and humid near the Atlantic Ocean. Rainfall generally has a balanced monthly distribution, but the total yearly rainfall undergoes cyclic variations (SALA et al. 1984). The most frequent storms, occurring in winter, when water requirement by evapotranspiration is low, last for three to four days and may cause floods (CANZIANI et al. 1984). In summer, water losses are usually very high and drought periods occur.

Land-form is characterized by its exteme flatness and low relief above sea level (descending gently from around

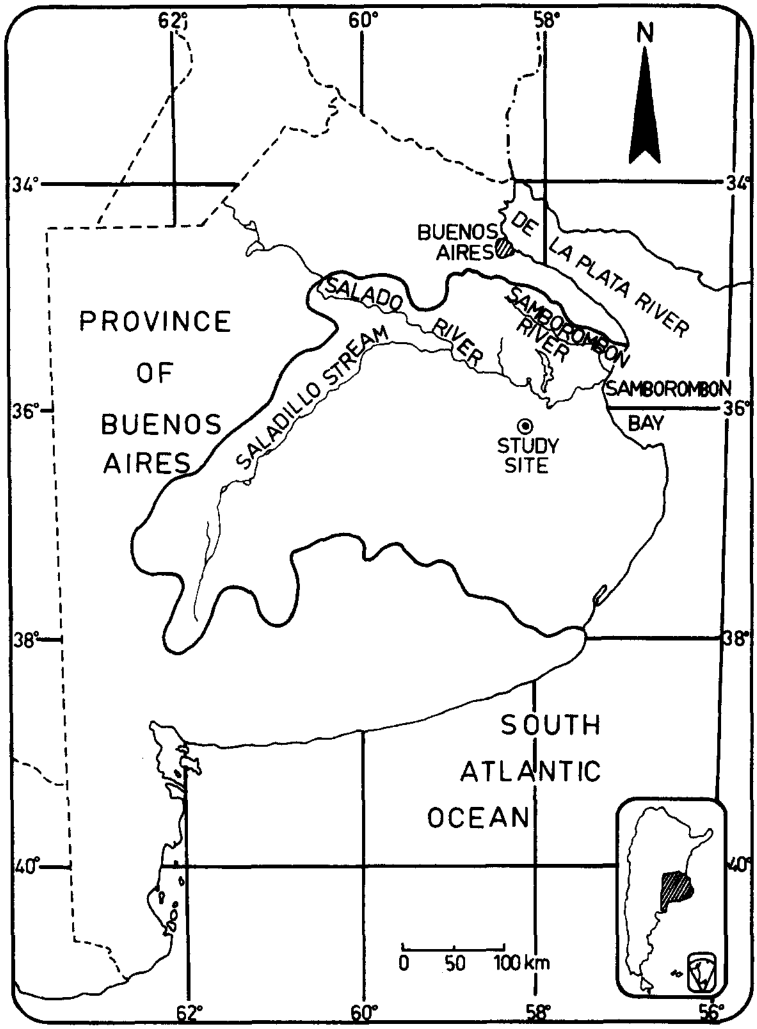

Fig. 1: *Geographic location of the site under study, and limits of the Flooding Pampa.*

30 m in the inland borders towards the coast). The general slope is very slight, which has prevented the development of a hydrologic network that is in a state of balance with the present humid climate. SALA et al. (1984) observed that a significant portion of the region has 0 km km^2 of drainage density, with permanent and temporary ponds generally connected with groundwater, and so the vertical movement components of the hydrologic cycle become more important (KOVACS 1984). Except for the Salado River, there are no other significant watercourses. The network of small streams and brooks that originate in the South disappear upon entering the region. From the beginning of this century, these large volumes of water have been conveyed to the Atlantic Ocean through

made-man channels. Groundwater remains near the soil surface for long periods. According to PARUELO (1984), the water table elevation generally fluctuates from a maximum at the end of winter-beginning of spring, to a minimum at the end of summer-beginning of autumn. It agrees respectively with the periods in which floods and droughts occur. Yet there also exist more erratic increases in phreatic heights corresponding to stormy seasons that occur over the whole region (CANZIANI et al. 1984). SALA et al. (1981) observed that water consumption by plants in grasslands within the region was not connected with phreatic water.

Most soils (60%) in the region under study are included in the aquic regime (INSTITUTO NACIONAL DE TECNOLOGIA AGROPECUARIA 1977, MOSCATELLI & SCOPPA 1984, MOSCATELLI et al. 1980); most of them show a natric horizon and excess of soluble salts, and they do not freeze in winter. The main Great Groups of Soil Taxonomy (SOIL SURVEY STAFF 1975) in this region are Natraquolls (28000 km^2) and Natraqualfs (11000 km^2). These soils do not occupy patches of different size, as in other regions in the world, but exist in large areas: the same soil series may cover a continuous area of a hundred thousand hectares (BERASATEGUI & BARBERIS 1982). Natralbolls, Argialbolls, etc. are also present, but only to a smaller extent. The climax soils of the Pampa region (Hapludolls, Argiudolls, and so on) are found in the highest places of the landscape. Most of the soils belong to loamy or loamy-fine texture families. They show a strong textural contrast between horizons, which is usually related to the presence of lithologic discontinuities (INSTITUTO NACIONAL DE TECNOLOGIA AGROPECUARIA 1977). The mineralogy of the fraction below 2μ (LAVADO & CAMILION 1984) does not differ from that found in the other soils of the Pampa region: there is a large amount of illite, a smaller amount of pure and interstratified smectite materials and a small amount of kaolinite. Volcanic ashes are also present.

The main portion of the region is devoted to cattle breeding on natural grasslands, which constitutes its main economic activity. This soil use was found to cause the increase of salt content in topsoil (LAVADO & TABOADA 1987). The highest lands are used for human settlement and for some agricultural use.

3 Materials and methods

The study site is located in the middle of the Flooding Pampa, in an area with areic drainage (SALA et al. 1984), geomorphologically identified by TRICART (1973) as the Subregion of the Fine Overflows. The study was carried out in a ranch near Casalins (Province of Buenos Aires), that has been engaged in cattle breeding since 1903. The natural grassland is made up of several plant communities (LEON 1975), closely related to the soil properties (BERASATEGUI & BARBERIS 1982). The soil is a General Guido Series typic Natraquoll (U.S. Soil Taxonomy, SOIL SURVEY STAFF 1975), moderately saline phase (MOSCATELLI et al. 1980), which covers about 200000 ha. This soil is widely representative of those of the center of the area (INSTITUTO NACIONAL DE TECNOLOGIA AGROPECUARIA 1977). The soil profile description and some of its

Horizon	A1	B1	B21t	B22t	B31cam	B32cam
Depth (m)	0–0.13	0.13–0.21	0.21–0.32	0.32–0.48	0.48–0.62	0.62–0.71
Colour (moist)	10YR 3/1	7.5YR 3/2	7.5YR 4/2	7.5YR 5/2	7.5YR 5/4	7.5YR 5/4
Texture*	l	sil	cl	c	c	l
Estructure*	2fsbk	2mabk	2cpr	2cpr	2mabk	2mabk
Consistence moist*	mfr	mfr	—	—	—	—
	wps-wss	wps-ws	wp-wvs	wvp-ws	wps-wss	wps-wso
Mottles*	fc	dc	dm	dm	dm	dm
Concretions*	—	—	consir	consir	consir-conca	consir-conca
Org C (g%)	3.53	1.62	0.46	0.48	0.27	0.06
Total N (g%)	0.28	0.15	0.07	0.05	0.03	—
Extr. P (mg Kg^{-1})	10.67	8.80	—	—	—	—
$CaCO_3$ (g%)	0.00	0.00	0.00	vest	12.35	9.50
CEC (cmol Kg^{-1})	13.57	12.69	23.06	29.12	28.80	—
Field Capacity (g%)	38.16	30.75	34.75	62.86	51.96	—

* The abbreviations follow the Soil Survey Handbook No. 18 (SOIL SURVEY STAFF 1951), 139–140

Tab. 1: *Morphological description and some properties of the studied soil.*

properties are shown in tab.1. Additional information may be found in previous reports on research performed in this site (TABOADA & LAVADO 1986) and nearby(BERASATEGUI & BARBERIS 1982, LAVADO & TABOADA 1985, 1987).

3.1 Soil and water sampling

The soil profile was sampled from February 1983 to February 1987 in all horizons down to the B31. In the A1 horizon, six samples were randomly taken 38 times. From the B1 horizon to the B31 horizon, three replicates were taken at random each time. Ten samples of all horizons up to the B31 were taken in May 1983, 1984, 1985 and 1986.

The water table depth was measured in 2 open wells (TRAFFORD 1986) down to a depth of 2 m, on the same dates, the A1 horizon was sampled. Whenever the water table approached the soil surface, its actual depth was checked in pits. Flood water was sampled every time a flood took place. All the samples were stored at low temperature and analyzed in the laboratory within 24 hours. Daily rainfall was measured by rain gauges.

3.2 Laboratory determinations

All soil samples were analyzed for gravimetric water content (GW) by oven drying, pH in paste and salinity through the electrical conductivity of saturation extracts (ECs). Water retention curves (pressure plate) of five replicated undisturbed soil samples from each horizon were obtained. These curves are expressed by the following linear functions:

Horizon A1:
$$ln\Psi m(MPa) = 3.19 - 0.18GW(g\%) \quad -0.93^{**} \quad (1)$$
Horizon B1:
$$ln\Psi m(MPa) = 5.95 - 0.30GW(g\%) \quad -0.85^{**} \quad (2)$$
Horizon B21:
$$ln\Psi m(MPa) = 7.33 - 0.30GW(g\%) \quad -0.99^{**} \quad (3)$$
Horizon B22:
$$ln\Psi m(MPa) = 13.30 - 0.28GW(g\%) \quad -0.90^{**} \quad (4)$$
Horizon B31:
$$ln\Psi m(MPa) = 11.56 - 0.27GW(g\%) \quad -0.98^{**} \quad (5)$$
** means highly significant correlation coefficient ($P \leq 0.01$).

The GW data were transformed into matric potentials (Ψm) through the fitted relationships.

Anion (Cl^- by titration with $AgNO_3$ and $CO_3^=$ by titration with H_2SO_4, and $SO_4^=$ by gravimetric analysis) and cation (Na^+, K^+, Ca^{++} and Mg^{++} by atomic absorption spectrophotometry) concentrations in the saturation extracts were measured in all the samples taken in May, as well as on other dates when necessary. The Sodium Adsorption Ratio (SAR) = $[Na^+]/[Ca^{++} + Mg^{++}]^{1/2}$ (mmol L^{-1}) of each sample was calculated. Procedures followed in all the laboratory analyses were those described in BLACK (1965) and PAGE et al. (1982). The ion concentration in the phreatic water, sampled from December 1983 to June 1985, and in the flood water samples was determined by the same methods. Salinity (by means of electrical conductivity (ECw)) and pH was measured in all water samples.

Daily evaporation rates on May, June and December 1986 were measured using ten microlysimeters (BOAST & ROBERTSON 1982) placed at random or bare soil surfaces. Soil temperature at a depth of 4 cm and air temperatures were measured throughout the day. Ambient relative humidity was calculated from temperature differences between wet-bulb and dry-bulb thermometers.

4 Results and discussion

4.1 Soil water regime

Weekly rainfall, flood periods, the Ψm of all horizons down to the B31 and the water table depth during the period under study are shown in fig.2.

Fluctuations of water table depth generally agreed with total yearly rainfall: in the relatively dry 1983 (835 mm) the water table generally remained well below the soil surface, but it was generally near the surface throughout the wetter 1984 (1180 mm), 1985 (1300 mm) and 1986 (1012 mm). In these years floods occurred: in 1984, from the beginning of July to the middle of September and from mid-October to the beginning of November; in 1985, from the end of July to the end of August and from the beginning of October to the beginning of December; in 1986, over almost all of April and from the beginning of August to the middle of October. Flood water height above the soil was never higher than 0.20 m. Periods with water deficit occurred during the first half of 1983 and during summer in 1984/85. At those times the water table was deeper than 2 m.

The aquifer response to rainfall varied according to the season. Whereas 8.7 mm of rain was required in summer to raise the water table by 1 cm, only 1.7, 2.2 and 2.6 mm were necessary in autumn, winter and spring respectively. Some swift responses of the aquifer, equivalent to the ones observed by VISWANATHAN (1984) in Australia, occurred in October 1983, March and July 1984, June 1985 and April 1986, when a heavy rain (about 80 mm) or a succession of showers caused rapid water table rises. As shown by the Ψm value (fig.2), at those times, the soil had low water contents. This recharge can be explained by the action of some complementary mechanisms: deep percolation through macropores before the soil attains field capacity (THOMAS & PHILLIPS 1979), unstable water flow in the soil (HILLEL 1987) and direct downwards flow of water through cracks (HILLEL 1987,

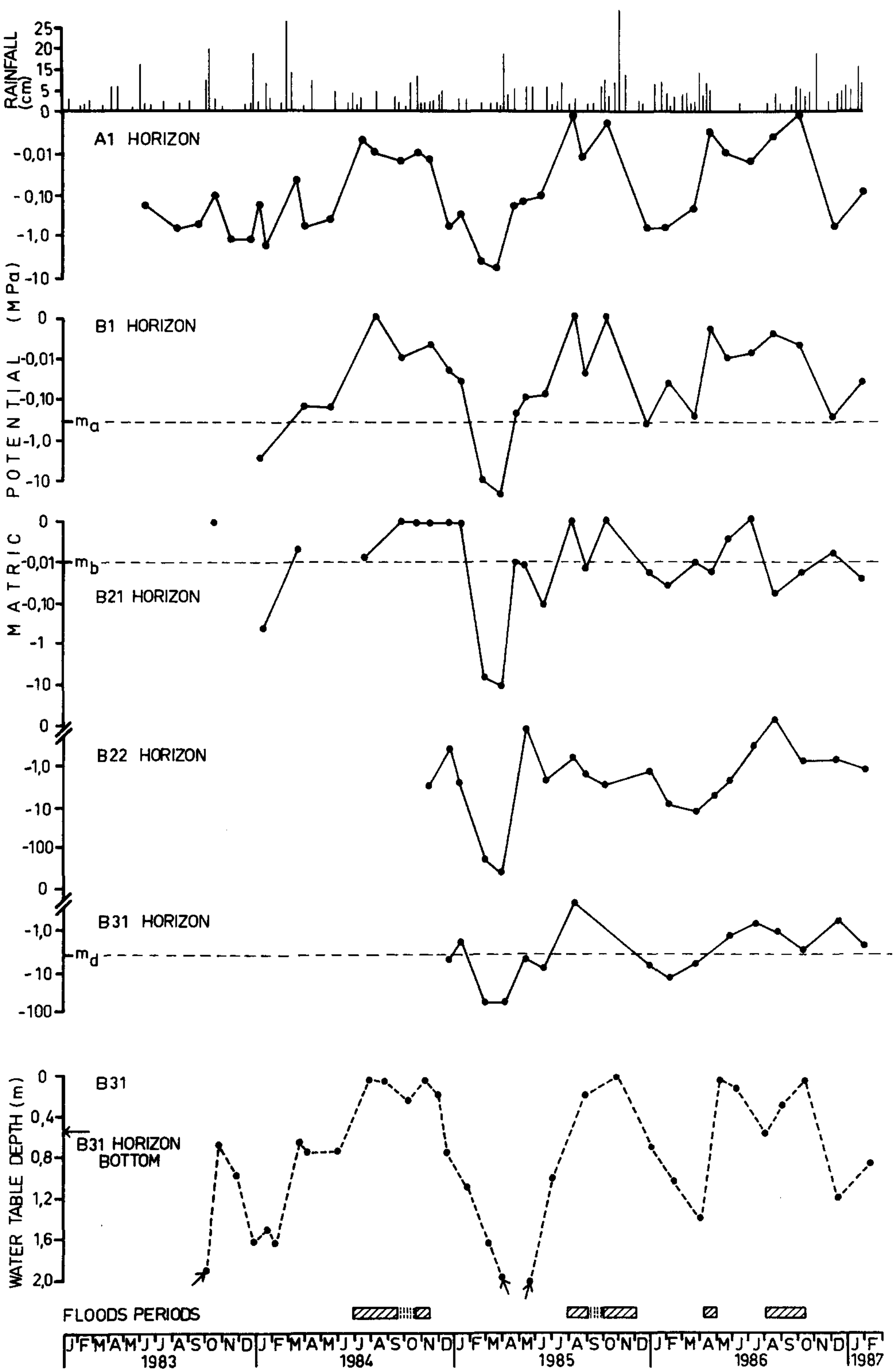

Fig. 2: *Weekly rainfall, matric potential in soil horizons, water-table depth in phreatimeters, and flood periods during the study period.* m_a, m_b *and* m_d *are the calculated points of equal matric potentials between adjacent horizons.*

NIELSEN et al. 1984). The latter mechanism can be important for these soils for, although they are not Vertisols, they have high swell-shrink potential (TABOADA et al. 1988).

When floods occurred, the water table in phreatimeters reached the soil surface. Despite these rises, its actual level in the soil was never above the B31 horizon depth (fig.2). Cemented calcium carbonate accumulates at this depth. This accumulation was ascribed (TRICART 1973) to the **in situ** crystallization of phreatic waters oversaturated with $CaCO_3$. Both this horizon and the overlaying B22, are characterized by being natric, extremely clayey and having a very low permeability. In the B22 horizon, the saturated hydraulic conductivity is 0.23 cm day^{-1} (Perelman, personal communication). The water content in the topsoil and the water table level showed a parallel increase until the water table reaches 0.65 m, usually at the end of autumn-beginning of winter. Subsequent rainfall rapidly saturates the soil from the B21 horizon to the surface, causing a temporary perched water on the impermeable B22 horizon. When rains continue, water accumulates on the soil surface and causes a flood. The short time required by perched water to reach the soil surface, would agree with the results of FAYER & HILLEL (1987) concering the effect of entrapped air in the soil. From 35 to 53% of the total porosity of the upper horizons remained filled with trapped air during floods (TABOADA et al. 1988), thus causing a decrease in their water storage capacity.

The Ψm values of each horizon show how the soil water dynamics in the upper profile is controlled by the water table depth. During the summer drought in 1985, the water content remarkably decreased in all the profile, with Ψm as low as -5.16, -21.74, -10.54, -403,60 and -63.75 MPa in the A1, B1, B21, B22 and B31 horizons, respectively. Over the remaining periods, the Ψm behaviour varied in the different layers. Thus in the upper three horizons the field capacity value (tab.1) was exceeded many times. The Ψm values fluctuated from 0 MPa to -2.03 MPa in the A1 horizon, -2.74 MPa in the B1 and -0.10 MPa in the B21. The B22 and B31 horizons, on the other hand, never reached their field capacity (tab.1). The Ψm values showed their permanent unsaturation, as they fluctuated from -0.08 to -14.11 MPa in the B22 horizon and from -0.22 to -16.33 MPa in the B31. It would appear that during flood periods these middle horizons contained trapped air, whereas above and below, they were saturated with water. The effect of this air layer (SHIRMOHAMMADI & SKAGGS 1984) would further decrease their low permeability, maintaining the separation of the deep water coming from the water table, and the surface one coming from rain. This fact would explain that observed earlier (SALA et al. 1981) from the viewpoint of plants, that the soil water regime is regulated by the natric horizons.

The Ψm data from adjacent horizons were linearly related; logarithmic projections of the fitted functions are shown in fig.3. Soil water fluctuations took place simultaneously in all the horizons, though at a different Ψm range in each one. This was shown by the very high and statistically significant correlation coefficients. Bearing in mind that the unsaturated flow in the soil takes place through water potential gradients (HILLEL 1971), the possibility of upward water movement could be determined by the point "m" at which the Ψm of ad-

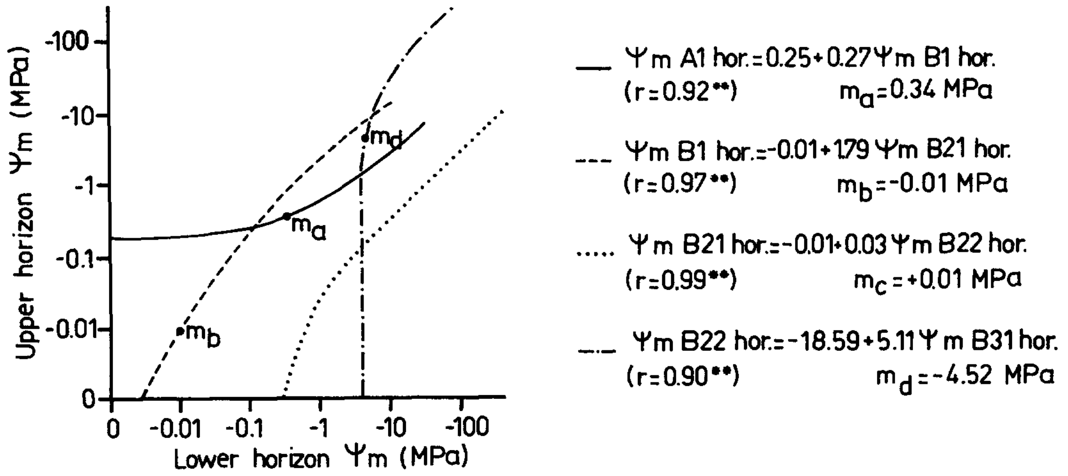

Fig. 3: *Logarithmic projections of the straight lines fitted between the matric potentials of adjacent horizons. m_a; m_b; m_c and m_d are the points of equal matric potential, calculated from the fitted linear function..*

jacent horizons become equal. In the fitted linear functions (y = a + bx), "m" is estimated when "y" (Ψm of the overlaying horizon) equals "x" (Ψm of the underlaying horizon). Then:

$$m(MPa) = a/1 - b \qquad (6)$$

For the B1 and A1 horizons m_a was -0.34 MPa and this suction was attained in the B1 horizon on some dates (fig.2). In a similar way m_b was -0.01 MPa between the B21 and B1 horizons, a low water retention value often being attained in the B21 horizon (fig.2). But between the B22 and B21 horizons, m_c was +0.01 MPa, and from this it becomes evident that the upward water movement from this depth was not possible. The point m_d between the B31 and B22 horizons was -4.52 MPa. Though this Ψm was sometimes attained in the B31 horizon, the unsaturated flow tends to disappear at such high water retention (HILLEL 1971). Thus, there was no upward movement of water from the B31 to the B21 horizon. Rising water gradients occurred quite often between the B21 and B1 horizon, but the upward flow of water above them was only possible whenever the soil surface underwent considerable desiccation. The occurrence of continuous gradients between the B21 and the A1 horizon was observed in March and May 1984, from September 1984 to January 1985, and in December 1986. On these dates, and following Ψm gradients, the flux of water to the soil surface could be observed.

Upward gradients are established when moisture requirement by the atmosphere is high, causing soil water losses as vapor (HILLEL 1971). Evapotranspiration losses show a remarkable seasonal distribution in the region (SCHLICHTER & PERELMAN 1985). According to a model developed by the latter authors, potential evapotranspiration is 9 mm day^{-1} in summer, with 1/3 of this corresponding to evapora-

		May	June	December
Temp. air (°C)	min	7.2	13.0	24.0
	max	16.0	17.9	26.8
Temp. soil (°C)	min	5.9	9.0	23.1
	max	10.8	12.8	30.6
mRH (%)		52.00	65.00	30.00
VW (v%)		36.28*	37.27*	21.11
Ev (mm day^{-1})		1.71	1.30	3.16*

* differences between dates are significant at 5% level

Tab. 2: *Daily temperatures range in air and soil, minimum ambient relative humidity (mRH), volumetric soil water content (VW), and evaporation rate (Ev), on different dates during 1986.*

tion. The daily evaporation rates, air and topsoil temperatures, minimum daily ambient relative humidity and soil water content are shown in tab.2.

The daily evaporation rates agreed with the trends predicted by the Schlichter and Perelman model and they were almost three times higher in summer than in winter. From these data and others obtained in previous years (data not shown), it was observed that water loss from soil (Ev) was linearly related to the minimum daily ambient relative humidity (mRH):

$$Ev(mmday^{-1}) = 4.3 - 0.05mRH(\%) \qquad r = -0.95** \tag{7}$$

These evaporation losses were also related, though not so closely, with water content and soil surface temperature. The decrease in water content in the A1 horizon takes place in summer together with the deepening of the water table. The simultaneous occurrence of the two phenomena led to the generalization that the water table decreases by evaporation losses (SALA et al. 1984). However, the fact that the B21 horizon remained saturated with water at those times, while both the B22 and B31 horizons are dry (fig.2), shows that the water table elevation mainly decreases as a result of the regional drainage rather than by evaporation through the soil.

4.2 Saline content of phreatic water

Phreatic water had low ECw values from the beginning of the study to May 1984. However, the remaining period, its salinity showed important changes: whenever there was a flood and a water table rise, abrupt increases in its ECw occurred (fig.4). After each of these saline peaks, the ECw decreased at a slower rate attaining values similar to the initial ones. The ECw showed a significant correlation with water table depth (Wd):

$$ECw(dSm^{-1}) = 17.73 - 8.55Wd(m) \qquad r = -0.56** \tag{8}$$

The ion composition of phreatic water is shown in tab.3. Before and after the saline peak, anions exhibited similar HCO_3^- and Cl^- concentrations, the former slightly prevailing over the latter, and $SO_4^=$ was present in a smaller concentration. During the saline peak, only Cl^- and $SO_4^=$ increased their concentration, while the converse was the case for HCO_3^-. $CO_3^=$ was not recorded at any time. Among cations, Na^+ always

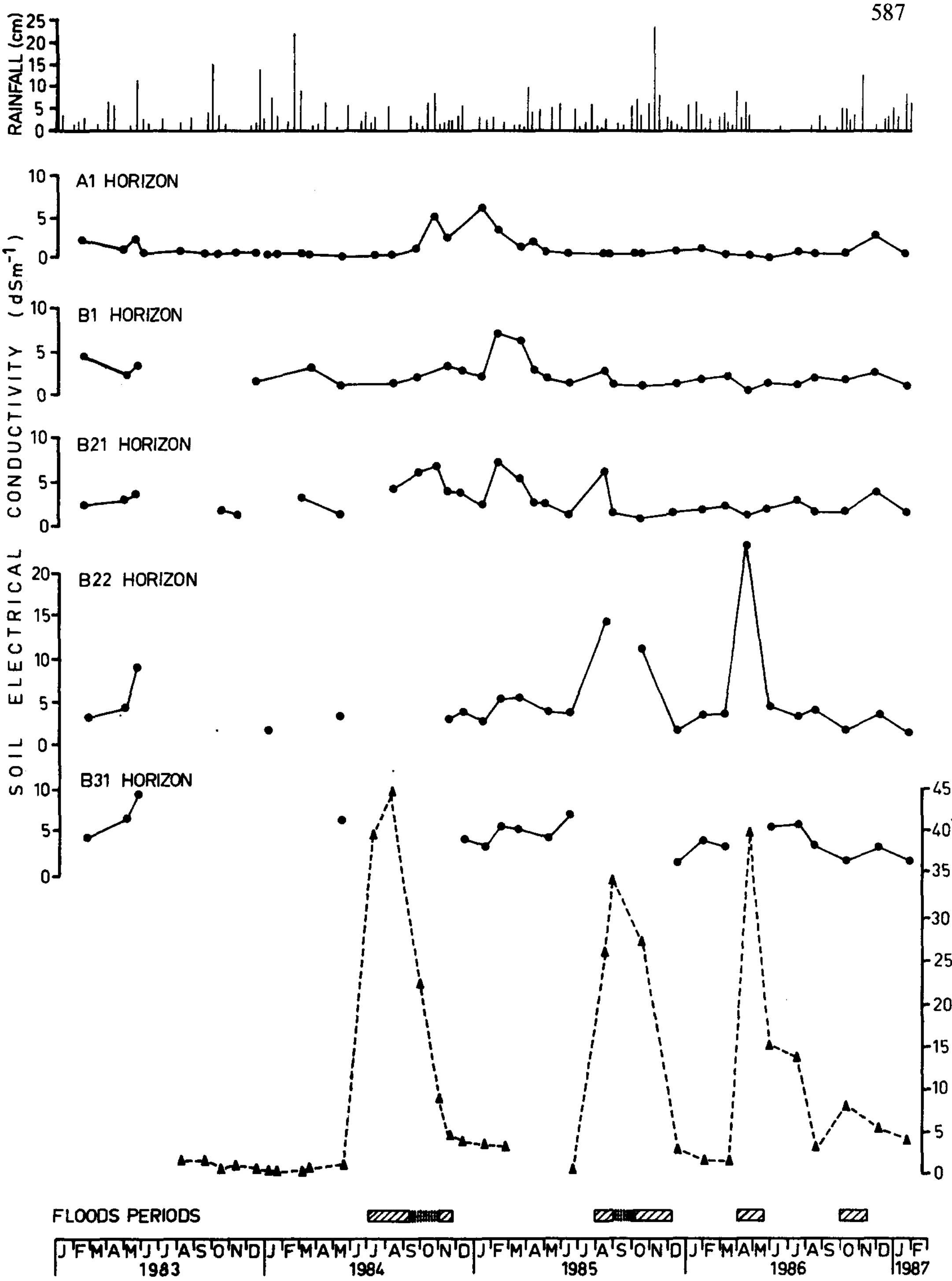

Fig. 4: *Weekly rainfall, flood periods, soil salinity measured as electrical conductivity (ECs) of saturation extracts, and phreatic water electrical conductivity (ECw) along the study period.*

	1983	1984						1985
	Dec	May	July	Aug	Sept	Nov	Dec	June
ECw (dS m^{-1})	0.70	1.40	39.50	45.00	22.20	4.90	6.00	7.51
anions (mmol L^{-1})								
Cl^-	3.78	7.70	247.56	309.45	121.00	54.60	3.91	4.87
HCO_3^-	8.40	6.19	8.33	5.84	5.94	8.95	5.80	6.21
$CO_3^=$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$SO_4^=$	2.75	4.99	94.74	122.56	47.95	20.03	1.92	1.44
cations (mmol L^{-1})								
Ca^{++}	1.35	1.50	37.98	35.32	9.12	7.10	1.48	1.25
Mg^{++}	1.39	2.81	80.89	71.56	36.06	17.14	1.69	1.66
Na^+	10.84	14.50	237.50	350.00	126.93	53.29	7.57	9.09
K^{++}	0.11	0.11	0.59	0.60	0.47	0.19	0.40	0.42
SAR	9.26	9.86	30.80	47.88	26.72	15.31	4.30	7.54

Tab. 3: *Electrical conductivity (ECw), ionic composition, and Sodium Adsorption Ratio (SAR) in phreatic water samples taken before, during and after the saline peak of 1984.*

prevailed over the remaining ones and showed the highest increase in concentration during the saline peak, as shown by the changes in the SAR value. On the other hand, Mg^{++} always prevailed over Ca^{++}, and K^+ was always in low concentration.

Salinity increases in phreatic water during floods were also observed at other places in the area (RUBIO 1987), but so far there is not a clear concept as to the origin of these changes. Soil samples taken down to a depth of 3 m in February 1986 showed that they are not salts deposited at the bottom of the profile when the water table recedes and which are then redissolved during its upward movement. At that time ECs varied from 0.80 to 2.10 dS m^{-1} (top and bottom of profile, respectively) and phreatic water at 1.02 m depth had an ECw of 1.63 dS m^{-1}. Two months later during a flood and with the water table at 0.65 m, it reached an ECw of 40.60 dS m^{-1}. It could be hypothesized that salts from deep saline aquifers were carried upward at flooding. The occurrence of saline groundwaters in the area are probably associated with the underlying marine deposits from the Quaternary period (TRICART 1973).

4.3 Soil salinization

Soil salinity in each horizon (ECs) is shown in fig.4. It can be seen that the abrupt increases in phreatic water salinity during the floods in 1985 and 1986 caused corresponding ECs increases in the B22 horizon. Both salinities were closely related by a curvilinear function:

$$ECs(dSm^{-1}) = 3.07 - 0.06ECw(dSm^{-1}) + 0.01ECw^2(dSm^{-1}) \quad r = 0.98{**} \qquad (9)$$

The B22 horizon ECs also showed a highly significant dependence on water table depth (Wd):

$$ECs(dSm^{-1}) = 10.91 - 16.16Wd(m) + 7.35Wd^2(m) \quad r = 0.60** \tag{10}$$

Data from the B31 horizon are fragmentary but, as its salinity was significantly related to that of the B22 horizon by (11), it can be assumed that it was also influenced by phreatic water.

$$ECsB22(dSm^{-1}) = 0.88 + 0.64ECsB31(dSm^{-1}) \quad r = 0.77** \tag{11}$$

These changes in the salinity at the bottom of the profile are likely also to have occurred during 1984 flood.

When there was free water below the highly unsaturated B31 horizon, steep water gradients were no doubt established. However, despite the fact that phreatic water was confined under pressure at that time, it could not imbibe the soil above it (fig.2). This allows the exclusion of water flow as a vehicle of salts at the bottom of the profile, and suggests that diffusion was the most probable mechanism in the salinization of the B31 horizon. Furthermore, it would have been widely favored by the large difference in salt concentration between phreatic water and soil during floods. The translocation of salts was high since both, ECw and ECs in the B31 horizon, were equivalent (considering the dilution of saturation extracts). Diffusion might be also the mechanism that salinized the B22 horizon, since the permanently high moisture retention in it and in the B31 horizon (fig.2) minimizes water flow (HILLEL 1971, NIELSEN et al. 1986, VARALLYAY 1979) in this profile zone. In other saline soils, salts move upward mainly by convection (FULLERTON & PAWLUK 1987) and diffusion is only limited to narrow strips of the profile (WILLIAMSON 1986). In this soil, however, diffusion would have turned out to be more important, because it would be the only mechanism acting in a vast zone of the profile charactrized by its impermeability.

The lack of upward water gradients between both the B22 and B21 horizons (fig.3) causes diffusion to be the mechanism most likely involved in salt movement between them. The salinization of the B21 horizon did not always follow that of the B22, as there was no correlation (r = 0.08) between both ECs. In October 1985 and April 1986, for example, despite the fact that the B22 horizon became salinized, the salts did not rise to the B21. This could probably be related to the abrupt increase in clay content from 34% in the B21 horizon to 60% in the B22 (TABOADA et al. 1988). This lithologic discontinuity caused the accumulation of perched water above it. Salts were leached following steep water gradients toward the B22 horizon, thus counteracting upward diffusion from it. Latter, the water table descended and a larger free water flow transported the salts downwards.

The mechanism of salt rising from the B21 to the B1 horizon and thence to the A1 horizon was by convection, as can be clearly seen from the Ψm relationship (fig.3). Correlations between the ECs of these adjacent horizons (equations (12) and (13)) were all significant, showing that salt passage was direct.

$$ECsB1(dSm^{-1}) = 0.70 + 0.55ECsB21(dSm^{-1}) \quad r = 0.68** \tag{12}$$

$$ECsA1(dSm^{-1}) = 0.67 + 0.44ECsB1(dSm^{-1})$$

$$r = 0.52* \quad (13)$$

As previously mentioned, continuous gradients from the B21 horizon to the topsoil took place in March and May 1984, from September 1984 to January 1985 and in December 1986. The low saline concentration and the depth of the water table in March and May 1984 gave way to the total absence of salts at the bottom of the profile, and there were no ECs increases on topsoil. On the remaining dates, significant ECs increases in the A1 horizon were observed. An ordinary fact previous to this was the occurrence of abrupt increases in the salt content of phreatic water at the beginning of floods.

Salinity increases on topsoil had their maximum pulse in summer 1985, when the highest continuous water gradient (-6.38 MPa m^{-1}) occurred. As a consequence, the saline profile reversed and became of the ascendant type. The lower ECs increases on topsoil in December 1986 can be ascribed to both the smaller gradient observed at that time (-3.46 MPa m^{-1}) and the previous lower salt content which both the phreatic water and deep horizons previously had. Relatively high ECs values on topsoil were also observed at the beginning of the present study. Those high salinities could be thought of as the remainder of a previous salinization process that started with a flood in winter-spring 1982. Most of these salts were leached during 1983 and part of 1984. Since topsoil salinization would not have taken place before the introduction of livestock into the region (LAVADO & TABOADA 1987), the halomorphic features in the upper horizons would be the result of a relatively recent anthropic effect. The most usual condition of this soil is to have descedent saline profiles, as shown by the slopes of equations (11), (12) and (13). Salt leaching develops very rapidly, e.g. between January and March 1985 with a rainfall of 256 mm (fig.4). This process represents an interesting example of "cascade depletion" of the salt content from the topsoil to the B21 horizon.

The ion composition of the saturation extracts of soil horizons is presented in tab.4. Unlike other salt-affected soils in which an only anion—chlorides (WILLIAMSON 1986) or sulfates (TIMPSON et al. 1986)—absolutely prevails, there was a balanced proportion of Cl^-, HCO_3^- and $SO_4^=$ (the latter estimated by difference) in the A1 horizon. In the other horizons, however, chlorides tended to dominate. Na^+ prevailed among cations, and according to the ECs increase, it showed an increasing trend in depth. The concentrations of K^+, Mg^{++} and Ca^{++} showed a similar behavior to that observed in phreatic water. Flood water always showed low salinity thus reflecting its pluvial origin, and its ion composition was similar to that of the A1 horizon because of its close contact with it.

4.4 Soil alkalinization

The soil is characterized by not having high alkalinity, as shown by the pH and the SAR values (tab.5.). Both parameters increased with depth and they became highest at the B22 horizon. The variations in the SAR among years showed that the increase in the saline content of the topsoil from the end of 1984 to the beginning of 1985 also caused its alkalinization. The SAR in the A1 and B1 horizons was significantly higher in 1985. These differences were maintained in the B1 horizon in 1986. The high SAR value observed in this horizon in

Horizon		Cations (mmol L^{-1}) Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Anions (mmol L^{-1}) Cl^{-}	HCO_3^{-}	$CO_3^{=}$	$SO_4^{=}$
A1	m	0.94	1.21	8.56	0.49	3.45	4.05	0	—
	sd	0.53	0.52	1.34	0.12	2.82	1.59	0	—
B1	m	0.87	2.43	10.65	0.46	7.70	6.03	0	—
	sd	0.26	1.35	5.50	0.04	4.56	1.46	0	—
B21	m	0.88	1.78	14.96	0.39	9.02	4.78	0	—
	sd	0.48	1.50	4.28	0.06	2.13	1.23	0	—
B22	m	1.51	2.51	23.80	0.42	12.20	3.96	0	—
	sd	0.63	1.20	9.55	0.10	4.48	1.29	0	—
B31	m	3.41	4.84	43.67	0.51	21.96	3.64	0	—
	sd	1.66	2.86	19.17	0.08	3.24	1.64	0	—
Flood	m	0.35	0.59	3.45	0.07	1.87	1.08	0	1.80
water	sd	0.07	0.17	1.01	0.01	0.69	0.27	0	0.29

(1) samples corresponding to salinization peaks were excluded.

Tab. 4: *Mean (m) and standard deviation (sd) of ion concentration in the soil saturation extracts (1) and in flood water.*

Horizon	pH (paste) min	max	SAR 1983	1984	1985	1986
A1	6.4	7.1	9.03	6.73	13.45*	8.23
B1	7.3	7.9	14.60*	9.74	20.13*	15.99*
B21	7.7	8.1	22.94	16.16	23.02	19.81
B22	8.1	8.6	27.91	23.53	24.55	27.62
B31	8.2	8.6	28.92	22.95	24.19	20.70

* differences in SAR value between dates are significant at 5% level.

Tab. 5: *Range of pH and mean SAR values in soil, in May 1983, 1984, 1985 and 1986.*

1983 was probably due to the remainder of the assumed soil salinization in 1982. All the profile had low SAR values in May 1984 showing, in turn, the preeminence of salt leaching before that time. The B21, B22 and B31 horizons showed no significant variations in SAR values among years. Therefore, even over periods of noticeable preeminence of salt leaching the soil always had a natric horizon.

Fluctuations in soil alkalinity, when salts rised or were leached, were not so noticeable as fluctuations in soil salinity. For example, on January 1985 salinization of the A1 horizon was 10 times larger than the minimum ECs measured. Nevertheless, the SAR was 15.41, that is, about twice the minimum value observed. This lack of equivalence between salinity and alkalinity fluctuations can probably be ascribed to the buffering capacity of the soil cation exchange complex.

The SAR value of top horizons showed the preeminence of salt leaching and it was characterized by variations in time. The SAR of the deep horizons, on the other hand, was higher and stable in the course of time, showing that at that depth the alkalinity was not dependent on salt leaching or salt rise, but was determined by the frequent contact with the water table. Then, also as regarded salinity, soil alkalinity behaves in a different way in topsoil as compared to deep horizons. The SAR of the phreatic water had variations related to its salinity: most times, it was lower or equal to 10, and its pH ranged from 7.2 to 7.4, over the period under study. Flood water had SAR values similar to those of the A1 horizon and pH averaged 7.40.

5 Conclusions

Soil salinization in the centre of the Flooding Pampa takes place after saline peaks in phreatic water at flooding periods. At the bottom of the profile, salts would probably move by diffusion, but in the upper horizons they move by convection. This upward flux occurs episodically in summer when water requirement by the atmosphere is high. Each of the five horizons above the salinized water table acts as a link with its own characteristics. Any of them stoping or delaying salt movement causes salts not to reach the surface the soil. This successive sequence starting with the rise and salinization of the phreatic water, does not permit a concept of a "critical depth" of groundwater, as occurs in other instances (PECK 1978, WILLIAMSON 1986).

Gedroiz stated that the genesis of salt-affected soils is a result of an evolution in the course of time from the Solomchak. It can be stated that this soil might be an example of evolutive differentiation at a vertical level. The distribution of salts and sodium in its profile, mainly depend on two salinization regimes acting at different depths. The B22 and B31 horizons, that are often salinized by groundwater, are at an initial evolutionary stage and maintain a relatively high salinity and alkalinity. Since salt leaching prevails on the surface horizons, they tend to be similar to zonal soils. Halomorphism in topsoil only occurs to a small extent and is due to episodic salt rises.

The characteristics of the salinization and alkalinization processes clarify understanding of the occurrence of salt-affected soils in the center of the region. These soils result from the interaction of several factors (climate, geomorphology, hydrology and land use) and from the proper soil-water and salt-dynamics.

References

BERASATEGUI, L.A. & BARBERIS, L.A. (1982): Los suelos de las comunidades vegetales de la región Castelli-Pila, Depresión del Salado (Provincia de Buenos Aires). Revista de la Facultad de Agronomia **3**, 13–25.

BLACK, C.A. (Ed.) (1965): Methods of Soil Analysis, Part 1. Agronomy No. **9**, Madison, Wisconsin.

BOAST, C.W. & ROBERTSON, T.M. (1982): A "microlysimeter" method for determining evaporation from bare soil: description and laboratory evaluation. Soil Science Society of America Journal **46**, 689–696.

CANZIANI, O.F., FORTE LAY, J.A., QUINTELA, R.A. & TROHA, A. (1984): Estudio de grandes tormentas en la Pampa Deprimida de la Provincia de Buenos Aires (Argentina) y su incidencia en al balance hidrológico. In: Hydrology on Large Flatlands, Proceedings of the Olavarría Symposium II, 899–922.

DURAN, D. (1981): La Pampa Deprimida. Balance Geográfico. Oikeos, Buenos Aires.

FAYER, M.J. & HILLEL, D. (1986): Air encapsulation: II. Profile water storage and shallow water table. Soil Science Society of America Journal **50**, 572–578.

FULLERTON, S. & PAWLUK, S. (1987): The role of seasonal salt and water fluxes in the genesis of solonetzic B horizons. Canadian Journal of Soil Science **67**, 719–730.

HILLEL, D. (1971): Soil and Water, Physical Principles and Processes. Academic Press, New York.

HILLEL, D. (1987): Unstable flow in layered soils: a review. Hydrological Processes **1**, 143–147.

INSTITUTO NACIONAL DE TECNOLOGIA AGROPECUARIA (1977): La Pampa Deprimida, Condiciones de Drenaje de sus Suelos. INTA, Departamento de Suelos, Publicación No. **154**, Castelar, Buenos Aires.

KOVACS, G. (1984): General principles of flatland hydrology. In: Hydrology on Large Flatlands, Proceedings of the Olavarría Symposium I, 297–355.

LAVADO, R.S. (1983): Evaluación de la relación entre la composición química del agua de lluvia y el distinto grado de salinidad y sodicidad de distintos suelos. Revista de la Facultad de Agronomía **4**, 135–139.

LAVADO, R.S. & CAMILION, M.C. (1984): Clay minerals in Argentine salt-affected soils. Clay Research **3**, 68–74.

LAVADO, R.S. & TABOADA, M.A. (1985): Influencia del pastoreo sobre algunas propiedades químicas de un Natracuol de la Pampa Deprimida. Ciencia del Suelo **3**, 102–108.

LAVADO, R.S. & TABOADA, M.A. (1986): Influencia de las inundaciones sobre la salinidad de un Natracuol de la cuenca del río Salado. In: Actas XI Congreso Argentino de la Ciencia del Suelo, Neuquén 135–136.

LAVADO, R.S. & TABOADA, M.A. (1987): Soil salinization as an effect of grazing in a native grassland soil in the Flooding Pampa of Argentina. Soil Use and Management **3**, 143–148.

LEON, R.J.C. (1975): Las comunidades herbáceas de la región Castelli-Pila. Comisión de Investigaciones Científicas de la Provincia de Buenos Aires, Monografías **5**, 73–109.

MACLEAN, A.H. & PAWLUK, S. (1975): Soil genesis in relation to groundwater and soil moisture regimes near Vegreville, Alberta. Journal of Soil Science **26**, 278–293.

MIACZINSKI, C., SANTANATOGLIA, O.A., COLLANTES, M.B. & KADE, M. (1984): Incidencia de las inundaciones sobre los suelos y la vegetación en el área de Chascomús (Depresión del río Salado). Talk presented in "X Jornadas Cienfíficas de la Asociación Argentina contra la Contaminación Ambiental", Buenos Aires.

MOSCATELLI, G.M. & SCOPPA, C.O. (1984): Características hidroedáficas de la Pampa Deprimida. In: Hydrology on Large Flatlands, Proceedings of the Olavarría Symposium II, 1069–1087.

MOSCATELLI, G.M., SALAZAR LEA PLAZA, J.C., GODAGNONE, R., GRINBERG, H., FERRAO, J. & CUENCA, M. (1980): Mapa de Suelos de la Provincia de Buenos Aires, escala 1:500 000. In: Actas IX Reunión Argentina de la Ciencia del Suelo, Paraná III, 1079–1089.

MUNN, L.C. & BOEHN, M.N. (1983): Soil genesis in a Natrargid-Haplargid Complex in Northern Montana. Soil Science Society of America Journal **47**, 1186–1192.

NIELSEN, D.R., VAN GENUCHTEN, M.T. & BIGGAR, J.W. (1986): Water flow and solute transport processes in the unsaturated zone. Water Resources Research **22**, Suppl., 89–108.

PAGE, A.L., MILLER, R.H. & KENNEY, D.R. (Eds.) (1982): Methods of Soil Analysis, Part 2. Agronomy No. **9**, 2nd Edition, Madison, Wisconsin.

PARUELO, J.M. (1984): Caracterización de las inundaciones en la Depresión del Salado, Buenos Aires, Argentina: dinámica de la capa freática. Undergraduate Thesis, Facultad de Agronomía, Universidad de Buenos Aires.

PECK, A.J. (1978): Note on the role of a shallow aquifer in dryland salinity. Australian Journal of Soil Research **16**, 237–240.

RUBIO, G. (1987): Relación entre aguas subterráneas y suelos en un área del centro de la Pampa Deprimida. boletín Informativo de la Asociación Argentina de la Ciencia del Suelo **54**, 3–6.

SALA, O.E., SORIANO, A. & PERELMAN, S.B. (1981): Relaciones hídricas de algunos componentes de un pastizal de la Depresión del Salado. Revista Facultad de Agronomía **2**, 1–10.

SALA, J.M., GONZALEZ, N. & KRUSE, E. (1984): Generalización hidrológica de la provincia de Buenos Aires, Argentina. In: Hydrology on Large Flatlands, Proceedings of The Olavarría Symposium II, 973–1009.

SCHLICHTER, T.M. & PERELMAN, S.B. (1985): Aplicación de principios de la física del suelo a la simulación de la circulación de agua en ecosistemas de bosque y de pastizal natural. Ciencia del Suelo **3**, 8–16.

SCHWARTZ, F.W., CROWE, A.S., HENDRY, M.J. & CHORLEY, D.W. (1987): A case study to assess the potential for saline soil development due to irrigation. Journal of Hydrology **91**, 1–27.

SHIRMOHAMMADI, A. & SKAGGS, R.W. (1984): Effect of soil surface conditions on infiltration for shallow water-table soils. Transactions of the ASAE 27, 1780–1787.

SOIL SURVEY STAFF (1951): Soil Survey Manual. United States Department of Agriculture, Soil Conservation Service, Agricultural Handbook No. **18**, Washington D.C.

SOIL SURVEY STAFF (1975): Soil Taxonomy. United States Department of Agriculture, Agricultural Handbook No. **436**. U.S. Government Printing Office, Washington D.C.

SZABOLCS, I. (1969): The influence of sodium carbonate on soil forming processes and on soil properties. Agrokemia Es Talajtan **18**, Suppl., 37–68.

TABOADA, M.A. & LAVADO, R.S. (1986): Características del régimen ácuico de un Natracuol de la Pampa Deprimida. Ciencia del Suelo **4**, 66–71.

TABOADA, M.A., LAVADO, R.S. & CAMILION, M.C. (1988): Cambios volumétricos en un Natracuol típico. Ciencia del Suelo (accepted for publication).

THOMAS, G.W. & PHILLIPS, R.E. (1979): Consequences of water movements in macropores. Journal of Environmental Quality **8**, 149–152.

TIMPSON, M.E., RICHARDSON, J.L., KELLER, L.P. & MC CARTHY, G.J. (1986): Evaporite mineralogy associated with saline seeps in Southwestern North Dakota. Soil Science Society of America Journal **50**, 490–493.

TRAFFORD, B.D. (1986): The measurement of water-tables. FDEU Technical Bulletin, **72/B**.

TRICART, J.F.L. (1973): Geomorfología de la Pampa Deprimida. INTA, XII Colección Científica, Buenos Aires.

VARALLYAY, G. (1981): Extreme moisture regime as the main limiting factor of the fertility of salt-affected soils. Agrokemia Es Talajtan **30**, Suppl., 73–96.

VISWANATHAN, M.N. (1984): Recharge characteristics of an unconfined aquifer from the rainfall - water table relationship. Journal of Hydrology **70**, 233–250.

WILLIAMSON, D.R. (1986): The hydrology of salt affected soils in Australia. Reclamation and Revegetation Research **5**, 181–196.

Address of authors:
R.S. Lavado, M.A. Taboada
Departamento de Ecología
Facultad de Agronomía
Universidad de Buenos Aires
Avenida San Martín 4453
1417 Buenos Aires, Argentina