

RECLAMATION OF SOME SODIC SOILS BY THE HIGH SALT WATER DILUTION METHOD

By

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Abstract

Results of the laboratory reclamation of four sodic soils by the high salt water dilution method are reported. The exchangeable sodium percentage (ESP) of all soils was decreased by leaching with solutions of decreasing sodium but constant calcium concentration. Although a final leaching with water of low electrolyte concentration ($EC_{25} < 100$ micromhos/cm) did not produce a rapid decrease in hydraulic conductivity, most soils did show an overall decrease in hydraulic conductivity during reclamation of up to 34%.

Introduction

Traditional methods of reclaiming sodic soils have included the application of chemical amendments such as gypsum or sulphur to soil followed by leaching with water of good quality. The inherent limitation of these methods has been the large and irreversible decreases in infiltration rate associated with the irrigation of sodic soils with water of low electrolyte concentration. Quirk and Schofield⁴ have indicated that the electrolyte concentration subtended by gypsum is generally too low to prevent large decreases in infiltration rate and consequently the time required to introduce the necessary amount of soluble calcium into the soil has often been excessive.

The problem in the reclamation of sodic soils is thus one of transport. The field infiltration rate must be sufficiently high for percolating water to convey sufficient divalent ions to the required depth, to replace a large proportion of the exchangeable sodium within a reasonable time.

Reeve and Doering⁵ showed that this was possible if the soil was leached with high salt water containing some divalent cations. By selection of an appropriate concentration for the initial leaching solution and by a sequential process of leaching to equilibration, followed by dilution of the high salt water, it was possible to achieve a stepwise reduction in ESP without severe decreases in soil permeability. Successful application of this technique requires a source of high salt water containing divalent cations. The greater the concentration of divalent cations, the more suitable the water for reclamation.

Three sodic soils from the Pongola Settlement

Irrigation Scheme and one from the Nkweleni Valley in Natal were selected for reclamation studies. A long history of injudicious irrigation has produced a saline profile and high ESPs with consequent deterioration of physical structure, which has caused yields on these soils to decline drastically. Reclamation is necessary before these soils can once more be cultivated.

The aim of this paper is to investigate the high salt water dilution method of reclamation on a laboratory scale as a means of establishing the concentration of initial leaching solutions, dilution rate, reduction in ESP and changes in hydraulic conductivity necessary to effect reclamation in a reasonable time. This information is required for the design of a suitable drainage system.

Theoretical basis

The United States Salinity Laboratory has found that the sodium adsorption ratio

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

(where Na, Ca and Mg are the concentrations of sodium, calcium and magnesium respectively in me/l), is highly correlated with the properties of exchangeable sodium on the exchange complex (U.S. Salinity Staff⁶).

Bower¹ first demonstrated the usefulness of a Gapon-type equation for relating the adsorbed cations to the cations in solution in the reclamation of sodic soils:

$$\frac{Na_{ad}}{CEC - Na_{ad}} = k_g \sqrt{\frac{Na}{(Ca + Mg)/2}} \quad (2)$$

where k_g is the Gapon constant $(me/l)^{-1/2}$,
 Na_{ad} is the exchangeable sodium (me%),
CEC is the cation exchange capacity (me%),
Na, Ca and Mg are the saturation extract concentrations of sodium, calcium and magnesium respectively (me/l).

The exchangeable sodium percentage is defined by

$$ESP = \frac{100 \text{ ESF}}{1} = \frac{100 Na_{ad}}{CEC} \quad (3)$$

where ESF is the exchangeable sodium fraction. From equations (1), (2) and (3) the equilibrium

exchangeable sodium fraction of a soil that has been equilibrated with water having a given SAR may be approximated by

$$ESF = \frac{SAR}{1/k_g + SAR} \quad (4)$$

The ratio R, of equivalent cation to total cation concentration (C_n) is defined as

$$R = \frac{Ca + Mg}{C_n} \quad (5)$$

where $C_n = Ca + Mg + Na$ (6) for the nth dilution step.

Consider a dynamic system such as a soil column undergoing leaching, in which exchangeable cations are in equilibrium with cations of unequal valence in the leaching solution. By the *valence-dilution* principle, exchangeable cations of lower valence are replaced by solution cations of higher valence when the solution is diluted, until equilibrium is again attained (Reeve and Doering⁵). Successive dilution and equilibration will ultimately reduce the exchangeable sodium on the exchange complex to a low value.

Each successive dilution step will require a certain depth of solution for equilibration and Reeve and Doering⁵ have demonstrated that it may be calculated from

$$\left(\frac{\Delta D_w}{\Delta D_s}\right)_n = \frac{10d_s \text{ CEC}}{d_w F} \frac{(\Delta ESF)_n}{\Delta(Ca + Mg)_n} \quad (7)$$

for the nth dilution step.

where $\left(\frac{\Delta D_w}{\Delta D_s}\right)_n$ is the depth of solution per unit depth of soil for the nth dilution step (cm),

d_s is the bulk density of the soil (g/cm^3),

d_w is the density of the solution (g/cm^3),

F is an efficiency factor (≤ 1) that accounts for inefficiencies of the dynamic system such as poor soil-solution content, leakage through large pores, etc.; it may be empirically determined or estimated,

and

$$(\Delta ESF)_n = ESF_{n-1} - ESF_n \quad (8)$$

$$\Delta(Ca + Mg)_n = (Ca + Mg)_n - (Ca + Mg)_x \quad (9)$$

$$(Ca + Mg)_x = \frac{1}{8} \{ (SAR_{n-1})^2 + 8C_n \}^{\frac{1}{2}} - SAR_{n-1} \}^2 \quad (10)$$

$(Ca + Mg)_n$ is the loss of divalent cation from the solution and is the difference between the divalent cation concentration of the nth dilution step and the divalent cation concentration of a solution of total cation concentration C_n but of $(SAR)_{n-1}$ corresponding to an equilibrium $(ESF)_{n-1}$ of the soil.

The overall efficiency of reclamation may be estimated from the ratio of calculated to observed depths of solution per unit change in ESF. The depth

of solution per unit change in ESF is defined by

$$B_n = \left(\frac{\Delta D_w}{\Delta D_s}\right)_n / (\Delta ESF)_n \quad (11)$$

for the nth dilution step. The efficiency of reclamation is then defined as

$$B^{c/e} = B^c/B^e$$

where superscripts c and e refer to calculated and experimental values respectively.

Materials and methods

The fine earth fraction (<2 mm) of the following soils were used in this study:

Bonheim	A1 horizon,	0-17 cm depth	} Pongola
Swartland	B horizon,	30-50 cm depth	
Shortlands	B horizon,	34-60 cm depth	
Nyoka	B horizon,	25-60 cm depth	Nkwaleni

Chemical extractions were performed on all soils before and after leaching in order to determine the soluble cation status and the proportion of the exchange complex occupied by sodium.

Soluble cations were determined by preparation of saturated soil pastes and extraction of the soil solution on a Buchner funnel. Total sodium was extracted with 0.2N NH_4Cl by centrifugation and decantation and exchangeable sodium was determined as the difference between total sodium and soluble sodium, both expressed as me%.

Gapon constants for the soils were determined equilibrating subsamples of the soils with various solutions of calcium and sodium and then extracting the total sodium with 0.2N NH_4Cl and determining the exchangeable sodium as the difference between total sodium and the sodium concentration of the equilibration solution. The Gapon constant was then calculated from equation (2).

Cations in the saturation extract and NH_4Cl solutions were determined by flame emission (sodium) and atomic absorption (calcium and magnesium).

The CEC of the original soil samples was obtained by leaching with 0.2N NH_4Cl , extraction of the NH_4 with 0.2N KNO_3 and distillation and titration of the extracted NH_4 . The chemical characteristics of the soils are shown in Table I.

Leaching studies were carried out on soil columns contained in double ring brass permeameters modified after McNeal and Reeve³. The soil columns were compacted to the same bulk density in a device described by Richard, Warneke and Weeks⁷ and CO_2 gas was passed through the soil columns for 30 minutes prior to leaching.

Leaching was done in a constant temperature laboratory ($\pm 1^\circ C$) using a constant head system to deliver solution to the soil column and maintain a constant depth of solution above the soil surface throughout leaching. Hydraulic conductivity was determined by timing the passage of successive 100 ml volumes of leachate through the soil columns. Each 100 ml of leachate was collected and analysed for sodium, calcium and magnesium in order to monitor changes during leaching. Only the inner core of soil in the column was characterised

TABLE I
Chemical characteristics of some sodic soils

Chemical characteristics	Soil series			
	Bonheim Al	Swartland	Shortlands	Nyoka
Saturation extract:				
SAR (me/l)‡	20,15	15,67	16,44	25,59
Ca	20,16	10,71	3,12	9,36
Mg	17,16	17,43	2,01	26,33
Na	86,80	59,34	26,65	108,75
Total C _n	124,12	87,48	31,78	144,44
R value	0,30	0,32	0,16	0,25
CEC (me%)	60,16	17,31	15,94	29,15
Exchangeable Na (me%)	11,73	4,20	5,54	5,09
ESP (%)	19,49	24,46	35,66	17,46
Gapon constant k _g (me/l)‡	1,433 × 10 ⁻²	1,880 × 10 ⁻²	2,467 × 10 ⁻²	1,233 × 10 ⁻²

with respect to hydraulic conductivity and leachate composition.

After solutions of the required dilutions had passed through the soil, the soil columns were removed, dried in a forced-draught oven and the inner core isolated and ground to pass a 2 mm sieve.

The leaching solutions were prepared from stock solution of NaCl and CaSO₄·2H₂O by dilution with tap water. The composition and concentration of these solutions are shown in Table II. All solutions contained 40 ppm HgCl₂ to prevent microbial growth during leaching. None of the solutions contained magnesium, but during leaching exchangeable magnesium, displaced by calcium, tended to assist in the removal of sodium from the exchange complex. The leaching solutions thus behaved as if they contained magnesium. Examination of the leachate data showed that magnesium concentration

in the leachate of the first two dilutions soon reached a steady state value. When this value was included in calculations requiring divalent ion concentration of the leaching solution, better agreement between calculated and experimental values was obtained. Corrected leaching solution concentrations are also shown in Table II.

Results

Changes in ESP during reclamation and depth of solution required for equilibration of each dilution step are presented in Table III. Two calculated depths of solution appear in Table III, one for the leaching solution as used and one for the leaching solution corrected for magnesium. These two depths of solution lead to two B^{c/e} ratios, reflecting the efficiency of reclamation in the presence and absence of magnesium. Where no magnesium was present the B^{c/e} ratios are approximately equal for both

TABLE II
Characteristics of original and corrected leaching solutions

Soil Series	Dilution n	Leaching Solution					Corrected Leaching Solution			
		Na	Ca	C _n	SAR	R	Ca+Mg	C _n	SAR	R
		me/l			(me/l)‡		me/l		(me/l)‡	
Bonheim Al	0	39,13	10,37	49,50	17,17	0,21	15,74	53,05	13,92	0,30
	1	17,69	10,27	27,96	7,80	0,37	14,96	32,65	6,46	0,46
	2	0,00	10,37	10,37	0,00	1,00	11,19	11,19	0,00	1,00
	3	0,00	0,00	0,00	—	—	0,08	0,08	—	—
Swartland	0	46,52	9,98	56,50	20,82	0,18	15,05	61,57	16,98	0,24
	1	24,78	10,32	35,10	10,90	0,29	10,51	35,19	10,82	0,30
	2	9,78	10,42	20,20	4,28	0,52	10,42	20,20	4,28	0,52
	3	0,00	9,88	9,88	0,00	1,00	9,88	9,88	0,00	1,00
	4	0,00	0,00	0,00	—	—	0,00	0,00	—	—
Nyoka	0	35,21	10,37	45,58	15,45	0,23	15,48	50,69	12,66	0,31
	1	17,30	10,37	27,67	7,59	0,38	11,35	28,65	7,27	0,40
	2	0,00	10,37	10,37	0,00	1,00	10,37	10,37	0,00	1,00
	3	0,00	0,00	0,00	—	—	0,00	0,00	—	—
Shortlands	0	35,21	10,12	45,33	15,64	0,22	16,78	51,99	12,14	0,32
	1	16,95	10,12	27,07	7,53	0,37	14,77	31,72	6,23	0,47
	2	0,00	10,12	10,12	0,00	1,00	13,24	13,24	0,00	1,00
	3	0,00	0,00	0,00	—	—	1,31	1,31	0,00	1,00

TABLE III

Calculated and experimental ESP changes, efficiency factors and depths of solution per unit depth of soil

Soil series	Dilution n	Experimental		Calculated					Reclamation time for 1m depth
		Δ ESP	$(\Delta D_w/\Delta D_s)$	Δ ESP	LS conc. $(\Delta D_w/\Delta D_s)$	Corr. LS $(\Delta D_w/\Delta D_s)$	LS conc. B ^{c/e}	Corr. LS B ^{c/e}	
		%	cm	%	cm	cm			days
Bonheim A1	0	6,66	4,96	5,78	12,84	4,15	2,98	0,96	5,8
	1	9,49	8,39	8,16	5,80	4,54	0,80	0,63	6,1
	2	6,90	6,18	8,47	4,68	4,35	0,62	0,57	3,7
	Total	23,05	19,53	22,41	23,32	13,04	—	—	15,6
Swartland	0	10,40	1,03	-1,44	—	—	—	—	1,4
	1	7,39	4,63	7,30	2,35	3,06	0,67	0,67	3,8
	2	3,24	3,60	9,45	2,97	2,97	0,28	0,28	5,7
	3	3,18	3,09	7,45	2,42	2,42	0,33	0,33	6,8
Total	24,21	12,35	24,20	7,74	8,45	—	—	17,7	
Nyoka	0	7,98	14,14	10,48	7,00	3,85	0,38	0,21	13,1
	1	7,44	11,64	5,27	2,93	3,37	0,36	0,41	9,3
	2	8,56	8,32	8,23	3,37	3,37	0,42	0,42	6,4
	Total	23,98	34,10	23,98	13,30	10,57	—	—	28,8
Shortlands	0	13,98	6,78	5,81	18,42	2,33	6,54	0,83	9,5
	1	10,66	5,71	9,72	3,20	2,70	0,61	0,52	8,9
	2	10,75	7,01	13,32	3,27	2,56	0,45	0,29	11,0
	Total	35,39	19,50	28,85	24,89	7,59	—	—	29,4

corrected and uncorrected values, but the latter is greater when magnesium was assisting in the removal of sodium. The difference between the B^{c/e} ratios is thus a quantitative evaluation of the favourable effect of magnesium on reclamation. The time for reclamation to a depth of one metre was estimated from the mean steady state hydraulic conductivity of each dilution step (Table III), but these values should not be related unconditionally to field conditions. They can serve only as a rough guide for the planning of reclamation work on a field scale.

The equilibrium ESP for each dilution step for calculated and experimentally estimated values, the ESP of unreclaimed soil and final ESP of reclaimed soil is shown in Fig. 1. The close correspondence between the curves of Fig. 1 indicate the prognostic value of the theory, and the large and progressive decrease in ESP confirms the value of the method in reclaiming sodic soils. In each case ESP was reduced to a low value. Most soils had ESPs of less than 1% at the end of leaching and this is considerably below the critical figure of 15% accepted by the U.S. Salinity Laboratory Staff as the upper limit for non-sodic soils.

Progressive changes in calcium concentration and SAR of the leachate, and relative hydraulic conductivity of the soils during reclamation, are presented in Figs. 2 to 5. Relative hydraulic conductivity (RHC) is the hydraulic conductivity expressed as a percentage of the maximum hydraulic conductivity observed during leaching. The calcium concentration and SAR of the dilution steps are indicated in Figs. 2 to 5, as Ca LS and SAR LS respectively. The net change in relative hydraulic conductivity and steady state hydraulic conductivity (cm/hr) for the last dilution are shown on the

right of each figure. The known relationship between soil ESP and its equilibrium solution SAR permits one to interpret the steady decrease in leachate SAR in Figs. 2 to 5 as a decrease in the exchangeable sodium status of the soil. In each case leachate SAR approached zero at the last dilution step.

Discussion

The value of the high salt water dilution method as an economical means of reclaiming sodic soils has been demonstrated. However, some Bonheim subsoils, the data for which have not been included in this paper, were susceptible to irreversible decreases in hydraulic conductivity if the ESP was increased during the initial stages of leaching. The other soils did not appear to be as susceptible, possibly due to the fact that even when the ESP increased, interlayer clay swelling was not as great as in Bonheim series and they were reclaimed without serious loss of hydraulic conductivity. At this time, then, the reclaimability of the Bonheim series must be accepted with some reservation.

An advantage of the high salt water method of reclamation is that the course of reclamation may be predicted from the extensive theoretical basis of the method. The agreement obtained between observed and calculated parameters confirms this, but where magnesium participated in exchange reaction, it was necessary to take account of its effect in predicting ESP values and depths of solution. The favourable effect of magnesium in reclamation is illustrated in the first dilution step of the Bonheim and Shortlands soils as the very large B^{c/e} ratio for the uncorrected leaching solution in comparison with the smaller value for the corrected leaching solution. According to the calculated values in Fig. 1 and Table III there should have been an

TABLE IV

Proposed initial solution concentrations for formulating suitable dilution series and the expected change in field intake rate during reclamation

soil series	Expected change in infiltration rate	Initial leaching solution				
		Na	Ca	C _n	SAR	R
		me/l			(me/l) [‡]	
Bonheim Al	+16%	40,00	10,00	50,00	17,89	0,20
Swartland	-25%	35,00	10,00	45,00	15,65	0,22
Nyoka	-34%					
Shortlands	-27%					

increase in ESP for Swartland on leaching in the first dilution. However, there was in fact a large ESP decrease (10,40%) due to the effect of exchangeable magnesium. This cannot be shown as a $B^{c/e}$ value since the theoretical depth of solution for an increase in ESP has no meaning and thus a $B^{c/e}$ value cannot be calculated.

The object of this research was to formulate suitable initial solution concentrations and dilution rates for reclamation and to determine the effect of the leaching solutions on the hydraulic conductivity of the soil. This information is presented in Table IV. It is important to accept that laboratory hydraulic conductivity of fragmented soil samples cannot be directly related to solution intake rates in the field. However, it is likely that the relative decrease in hydraulic conductivity observed during leaching in the laboratory will be of the same order of magnitude as that in the field, provided solution compositions are similar.

In conclusion an important feature of the leaching solutions used in this investigation was the constant calcium concentration of all but the last dilution step where it was zero. This implies a source of calcium independent of the high salt water. The most feasible method of achieving this in the field will probably be to apply gypsum to the soil prior to leaching. The amount of gypsum required will depend on the calcium concentration of the diluted high salt water. Reclamation is possible with high salt water only, provided the R value is greater than 0,3 (Doering and Reeve²), but since water of such favourable calcium status is seldom available, addition of gypsum to the soil is usually necessary.

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Discussion

Dr. Thompson (in the chair): Were all the sites from which the sodic samples taken small areas, or were they large enough to be reclaimed by irrigation?

Mr. Fitzpatrick: The areas were two or three acres in extent and there was virtually no grass growing on them.

Mr. Johnston: In Table I the S.A.R. of the saturation extract and exchangeable sodium percentages (E.S.P. %) of the various soils show poor agreement. Is this sufficient evidence to disprove the relationship given by the U.S.D.A. Salinity Handbook?

Professor Sumner: The nomogram relating S.A.R. and E.S.P. was determined over a large number of American soils and there will be discrepancies and variations for certain soils.

Mr. Long: Is there a simple method for determining cation exchange capacity accurately?

Mr. Fitzpatrick: It is a laborious process. We have just purchased new distillation equipment to assist us but are using basically the same procedure. We determined C.E.C. by two different methods for all the soils and used these to calculate the constant, K_g .

Dr. Gosnell: Is it possible to use a low sodium but high magnesium water in the first instance for leaching?

Mr. Fitzpatrick: It is possible and we found that magnesium helped to reclaim the soils.

Professor Sumner: Any divalent or trivalent cation will be beneficial. The only source of divalent cations available in agriculture is gypsum and this has a limited solubility.

Dr. Thompson: If you used river water for the soils would you make up by adding a saturated solution of calcium sulphate?

Mr. Fitzpatrick: We would not normally use that method for reclamation but where it was used in California a saturated solution of gypsum was made up and applied.

magnesium has a bad effect on soil permeability?

Mr. Johnston: Has there not been a suggestion that magnesium has a bad effect on soil permeability?

Professor Sumner: Magnesium is considerably

better than sodium. In Holland some soils are very high in magnesium and have poor physical properties but the same soils saturated with sodium are very much worse.

Dr. Thompson: What is the extent of sodic soils in the Eastern Transvaal.

Professor Sumner: This is not known but the University of Natal is at present carrying out a survey of the Pongola area.

Dr. Macvicar: There are not many very badly affected areas.

Most of our salinity problems in the sugar industry are due to saline alkaine conditions.

Where such conditions exist reclamation can be carried out by draining.

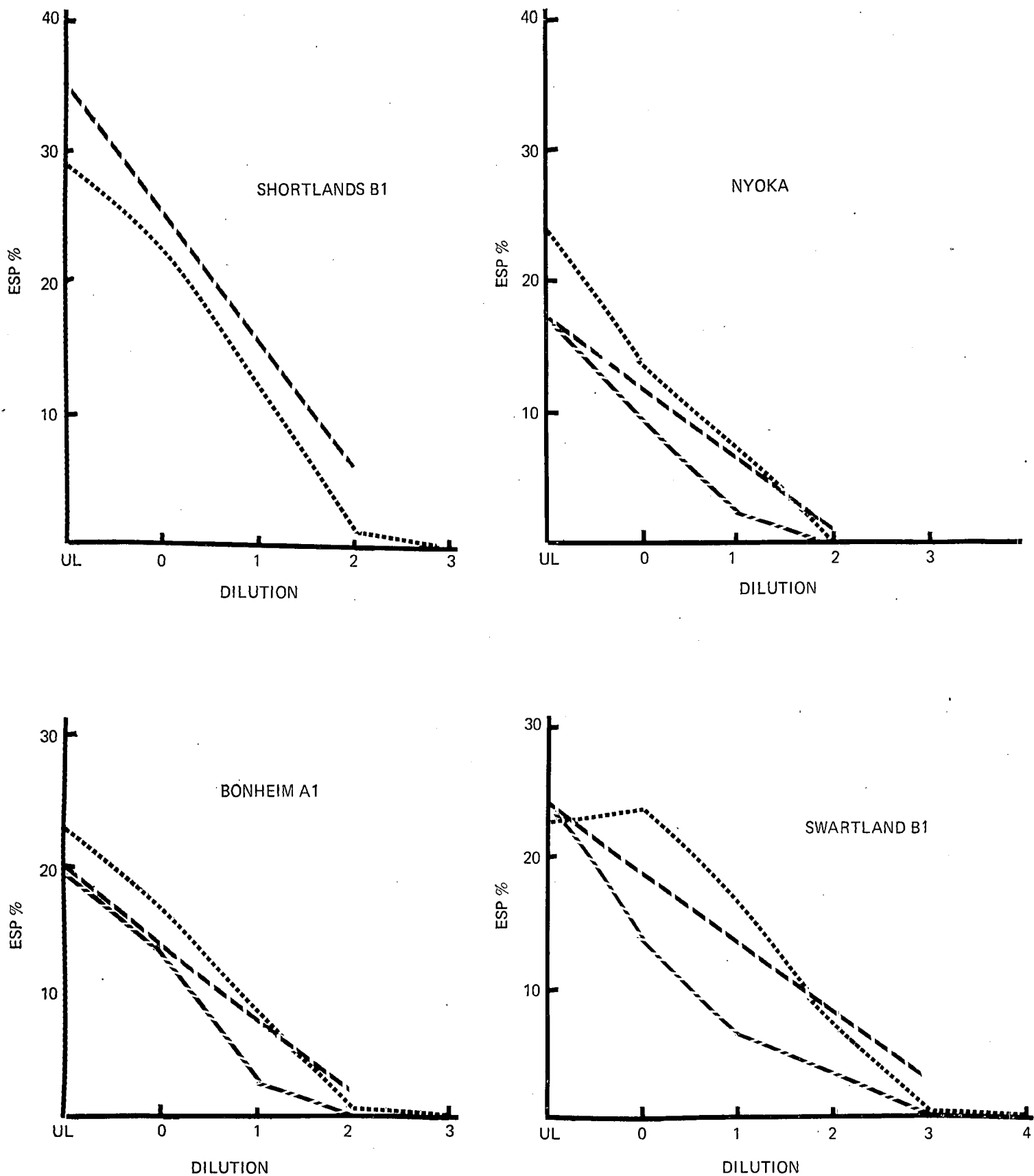


FIGURE 1: The predicted and observed ESP changes as a function of solution composition (dilution step) for four soils:

- ESP determined from the soil, before and after leaching;
 - - - ESP determined from the measured loss of calcium from the leaching solution;
 - ESP calculated from the corrected leaching solution concentration.
- UL unleashed soil.

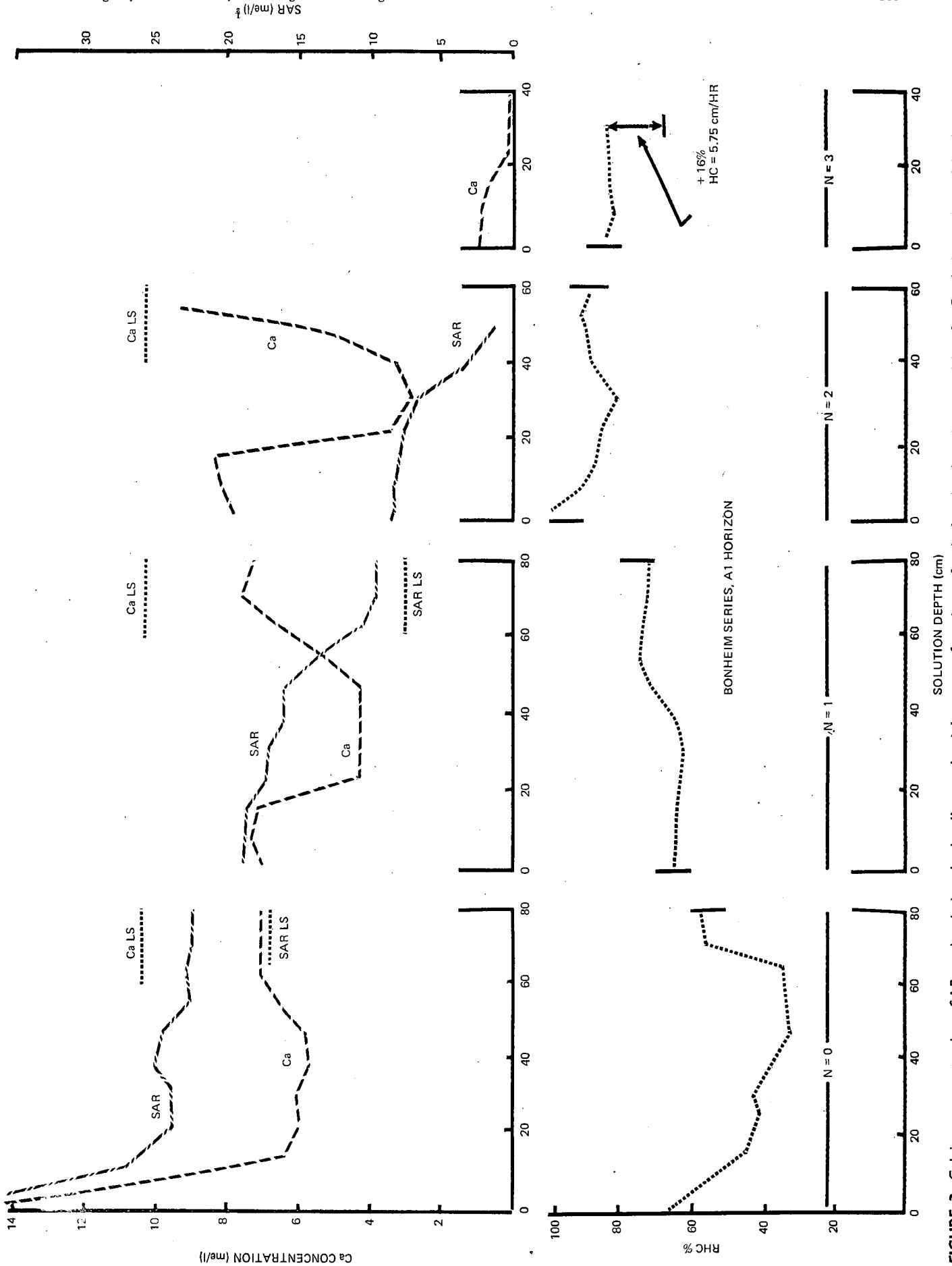


FIGURE 2: Calcium concentration, SAR and relative hydraulic conductivity as a function of solution depth and composition for Bonheim series, A1 horizon.

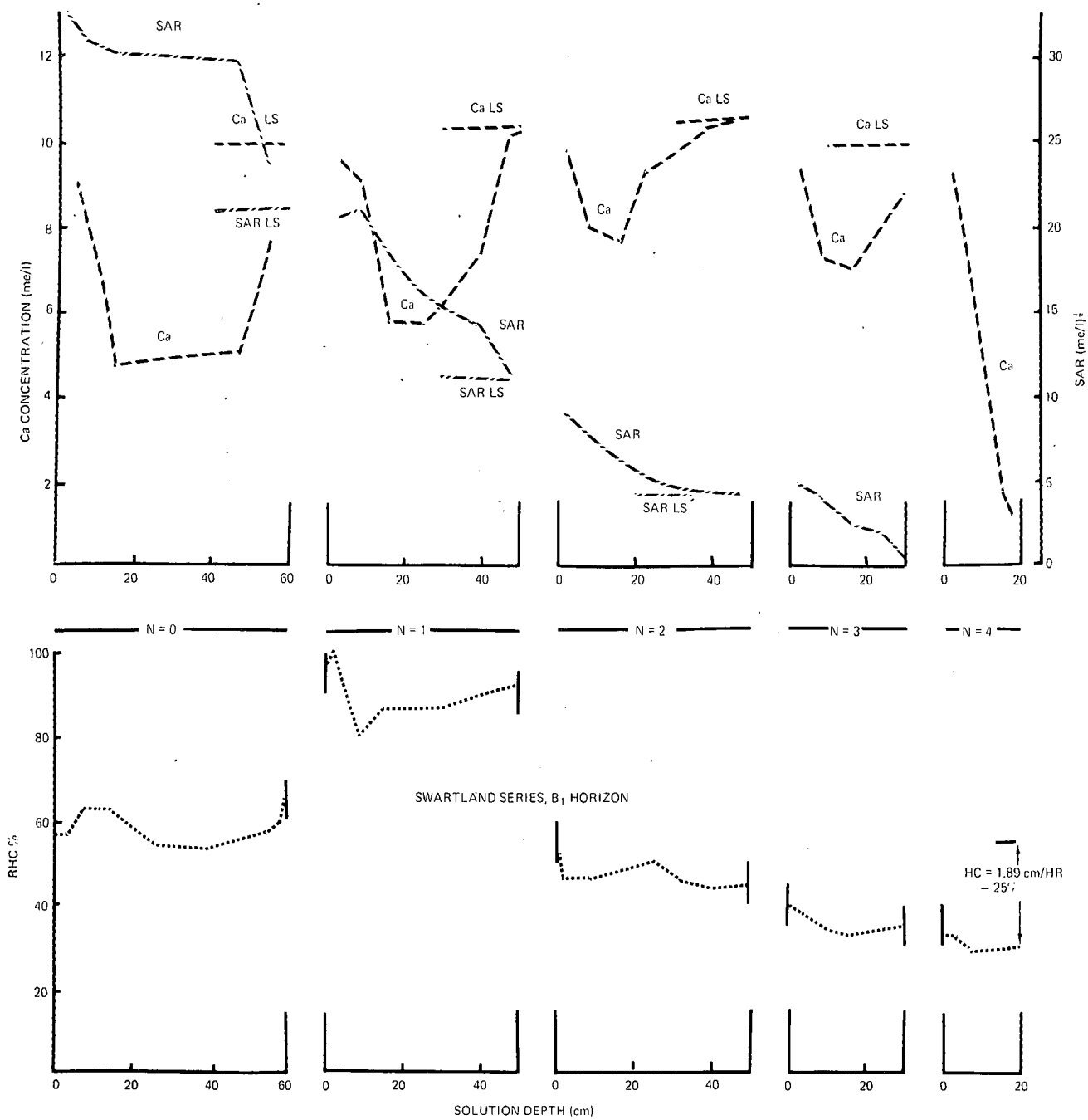


FIGURE 3: Calcium concentration, SAR and relative hydraulic conductivity as a function of solution depth and composition for Swartland series, B1 horizon.

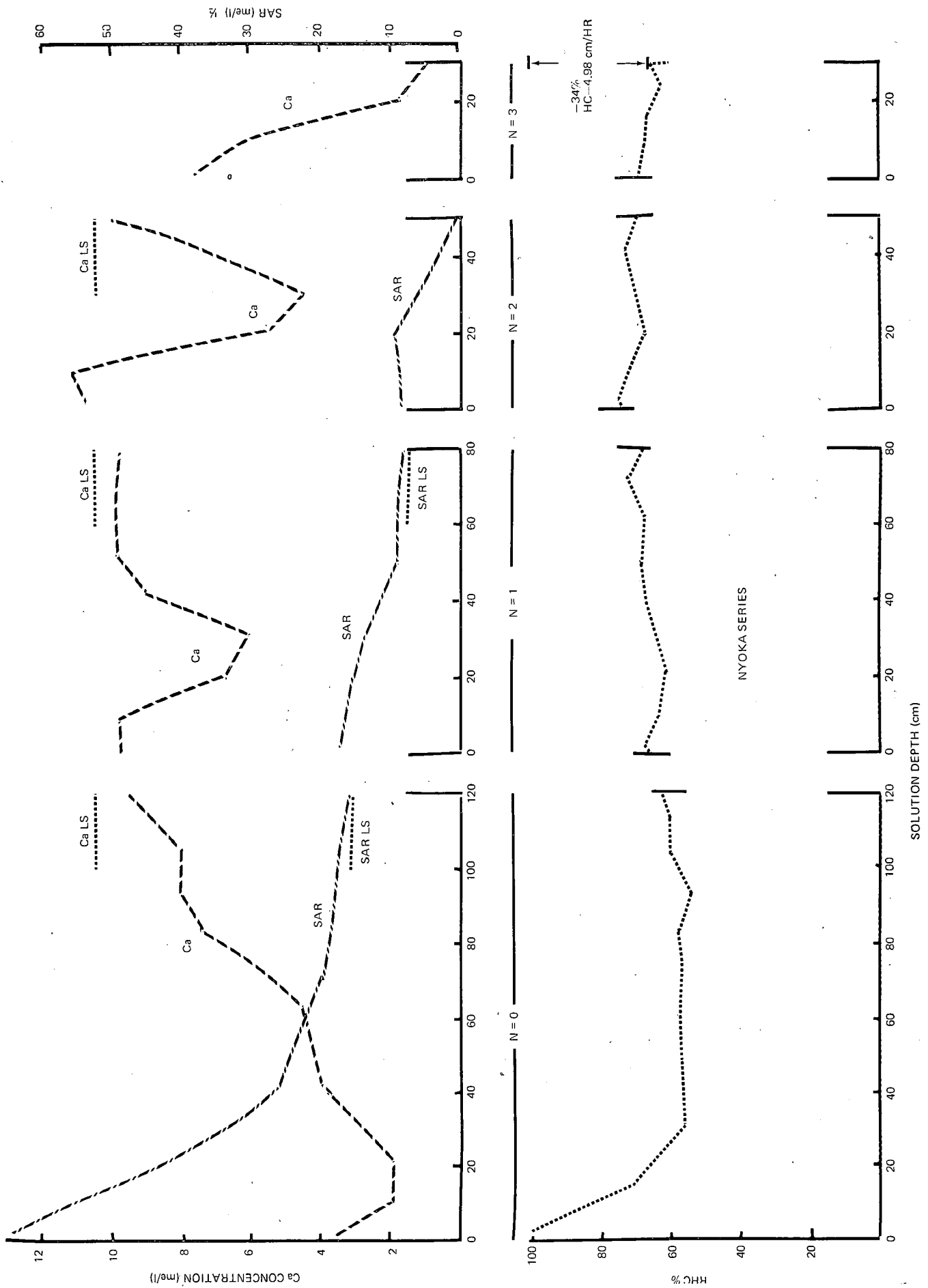


FIGURE 4: Calcium concentration, SAR and relative hydraulic conductivity as a function of solution depth and composition for Nyoka series, B horizon.

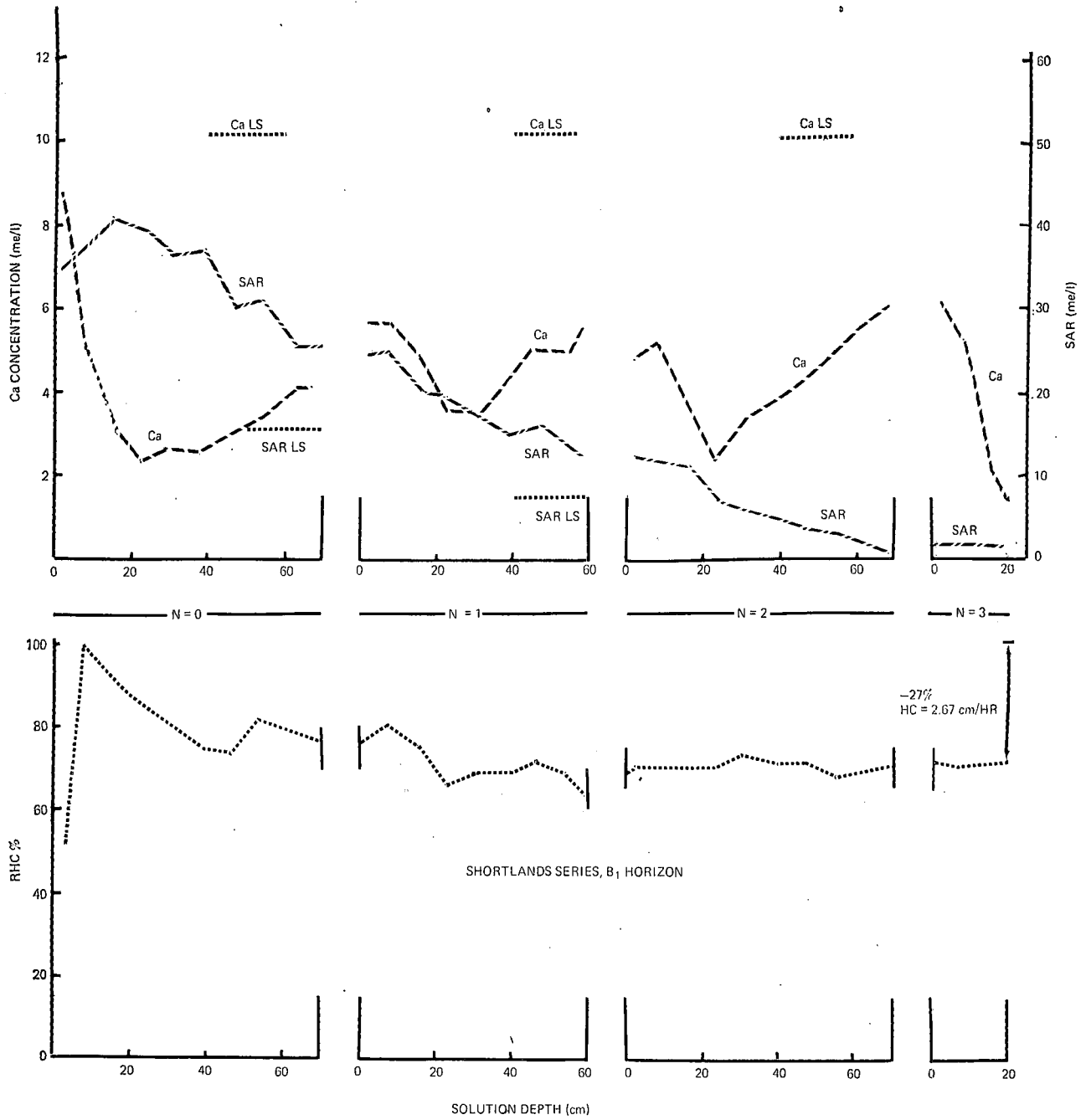


FIGURE 5: Calcium concentration, SAR and relative hydraulic conductivity as a function of solution depth and composition for Shortlands series, B₁ horizon.