

THE EFFECTS OF DIFFERENT LEVELS OF EXCHANGEABLE SODIUM ON SOIL HYDRAULIC CONDUCTIVITY

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Abstract

Permeability studies were undertaken on disturbed samples of five soil series which showed a wide range of physical properties. Hydraulic conductivity measurements taken during percolation of solutions of varying SAR (sodium adsorption ratio) and total salt levels showed the order of sensitivity of the soils to the effect of sodium to be Arcadia (most sensitive), Bonheim, Estcourt, Shortlands and Shorrocks series. Critical levels of sodium adsorption obtained from these data allow assessment of the degree of sodicity of soil from problem areas. The relationship between ESP (exchangeable sodium percentage) and SAR of the soil solution was determined for each of the soils.

Introduction

Salt-affected soils constitute a fairly serious problem in the dry irrigated regions of the South African sugar industry. In some instances the soils are naturally affected by salts and in others salt effects have been induced, primarily by inadequate soil drainage. This allows the development of water tables which may cause salinization of the rooting zone.

Sodium salts abound naturally in the soil environment in many of the semi-arid irrigated areas and such soils invariably have high exchangeable sodium levels. Soils are termed saline sodic where free salt levels are high (EC saturation extract more than 2,0 millimhos/cm at 25°C for sugarcane) and non-saline sodic where it is low. Excess exchangeable sodium adversely affects soil physical properties under conditions of relatively low total salt concentration in the soil solution (Rose¹⁰) causing swelling and dispersion of clay minerals which results in a deterioration in permeability of the soil to both water and air. Crop growth in turn suffers due to waterlogging and lack of aeration.

By original definition, sodic (alkali) soils are those which have an ESP (exchangeable sodium percentage) greater than 15 (USS Lab. Staff¹¹). Although this appears to be a sound average figure, more recent work has shown that the critical

ESP value differs markedly for different soil types (McNeal and Coleman,⁷ Hensley⁵). This is due largely to the clay mineralogy of the soil.

It is clear that there is a need for a better understanding of the critical sodium levels of soils of the industry to assess soil ameliorant requirements and the suitability of waters for irrigation. It was therefore decided to carry out a laboratory study on the effect of different levels of exchangeable sodium and total salt concentration on the hydraulic conductivity of a number of soils having a wide range of physical and clay mineralogical properties.

Materials and methods

Soil sampling

Five soil series were selected for sampling in virgin land in the Pongola/Mkuze region.

Shorrocks series

A deep red porous sandy clay loam with excellent internal drainage and derived from alluvial river terrace material.

Shortlands series

Red moderately structured blocky clay with moderate internal drainage, derived from basalt.

Estcourt series

Grey porous loamy sand A horizon (30 cm deep) abruptly overlying a dense strongly-structured prismatic sandy clay B horizon. The latter is sodic (Table 1) and drainage is very slow. By virtue of its duplex nature this soil is extremely prone to waterlogging. This is a solonetzic soil derived from Middle Eccla shale.

Bonheim series

A strongly-structured blocky clay with a black A and a dark yellowish-brown B horizon. This soil is derived from dolerite and was found to be saline sodic in the virgin state.

TABLE 1
Analyses of samples of the five soil series

Soil Series — Sample Depth cm	EC (mmhos/cm at 25°C)	pH (Sat. paste)	Total Cations (meq %)			CEC (meq %)	ESP	Texture (%)†					Montmorillonite Content (% of clay fraction)‡
			Na	Ca	Mg			Clay	Silt	FS	MS	CS	
Shorrocks 0- 30 30-120*	1,85	7,6	0,2	1,3	1,4	8,1	—	26	8	50	13	3	—
	2,18	6,7	0,4	3,4	4,2	7,2	2,3	31	12	46	8	2	10
Shortlands 0- 16 16- 85*	0,76	6,3	0,5	10,0	7,3	17,7	2,0	58	16	16	4	5	—
	0,62	6,3	0,8	9,8	7,2	17,3	3,8	68	18	11	2	0	45
Estcourt 0- 30 30- 60*	1,32	7,2	0,6	4,8	2,0	7,2	5,7	16	3	58	16	6	—
	3,38	7,7	5,7	5,5	8,1	15,1	21,3	44	9	37	7	2	15
Bonheim 0- 75 75-140*	9,80	7,3	8,3	18,7	15,9	33,6	14,7	61	20	12	3	3	—
	9,98	7,5	12,7	14,9	16,0	32,0	23,8	68	17	12	1	1	65
Arcadia 0- 20 20- 63 63- 95*	0,79	7,8	4,6	40,0	23,3	55,2	7,0	63	17	15	3	3	—
	1,62	8,0	9,6	35,2	29,4	57,5	13,1	73	13	12	1	0	—
	2,74	8,0	14,4	28,8	30,0	55,4	19,4	73	11	12	1	2	90

*Samples used for permeability studies

† Bouyoucos hydrometer method (Bouyoucos⁸)

‡ Estimated from X-ray diffraction analysis

Arcadia series

Black strongly-structured cracking clay overlying weathering basalt. This is a vertisol and shows marked shrink/swell properties. Chemical analysis revealed that the soil is sodic (Table 1).

Large disturbed samples were taken from that zone of each profile which was judged to offer the greatest resistance to downward percolation of water. The soil was air dried and ground to pass through a 1 mm sieve.

Leaching procedure

Representative sub-samples of 400 g were placed in brass permeameters (see Figures 1 and 2) which were constructed to the design of Cass³ after McNeal and Reeve.⁷ An important feature of these is the concentric knife-edge brazed to the perforated bottom plate which eliminates boundary flow effects. Percolate from the inner core of soil is collected in the brass funnel which is set into the base upon which the upper cylinder rests.

Each permeameter was placed in a mechanical compactor (Richards, Waneke and Weeks⁹) and the soil compacted for 10 minutes in order to obtain reproducible bulk density. This yielded a sample thickness of approximately 4,5 cm. The permeameter was then placed on its base and subjected to CO₂ treatment for 90 minutes to expel air from the sample. Carbon dioxide being very soluble in water permitted a more effective saturation with the leaching solution than would an air saturated sample (Christiansen, Fireman and Allison⁴).

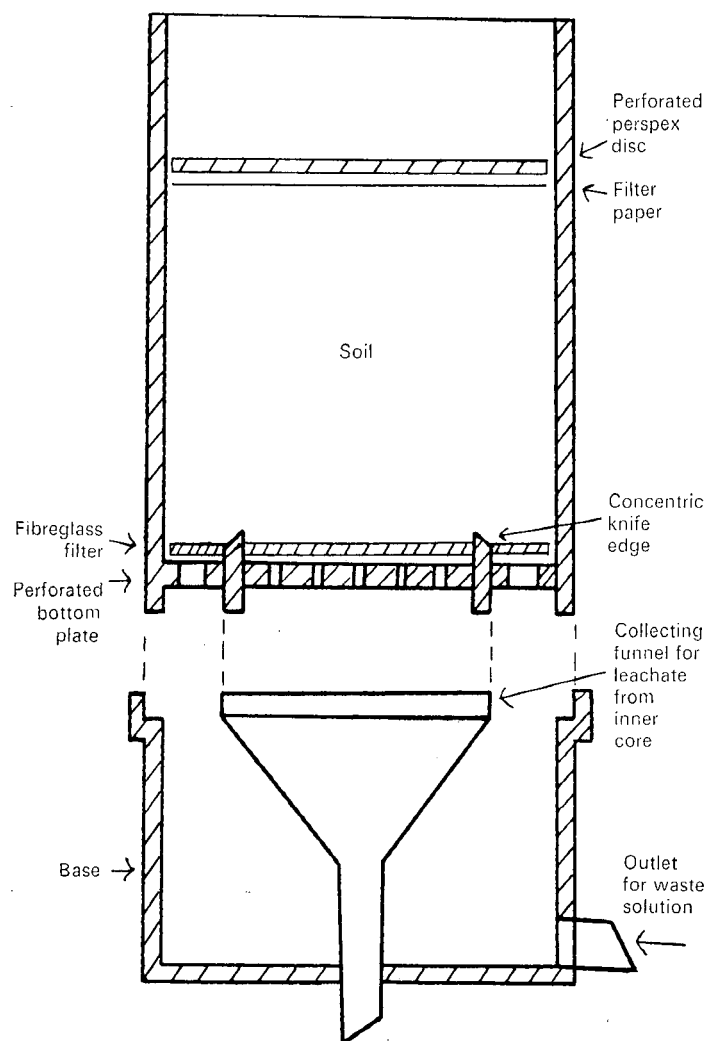


FIGURE 1 Diagram of permeameter (after Cass³).

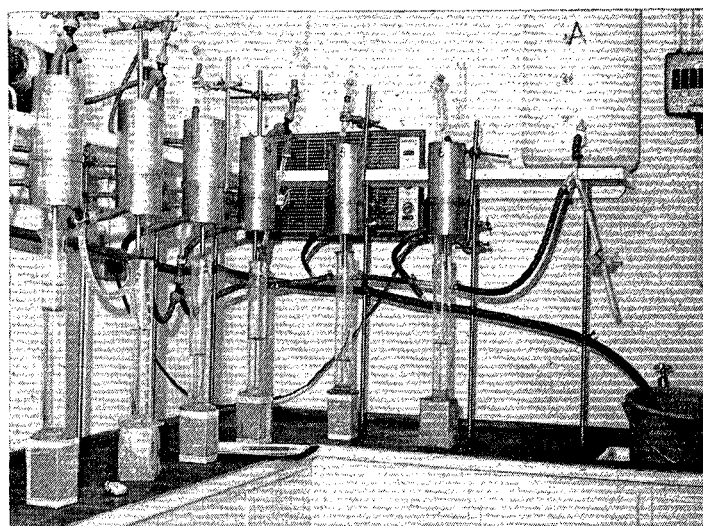


FIGURE 2 Arrangement of permeameters with reservoir and measuring cylinders used in measuring soil hydraulic conductivity.

The first of the series of leaching solutions at a particular SAR was then introduced. For each SAR level the total salt concentration declined via 8 solutions from an initial total cation concentration of 800 meq/l through 100, 20, 10, 5, 3, 1 meq/l and solution 8 consisted of de-ionized water. Divalent cations consisted of calcium and magnesium in equivalent amounts and each solution contained 40 ppm HgCl₂ in order to control microbial activity (McNeal and Coleman⁶). The SAR levels considered were 2, 5, 10, 25 and 50, but only for the Bonheim series were all these levels used (see Table 2). During percolation of the solutions a constant head was maintained at a hydraulic gradient ($\frac{\Delta H}{\Delta L}$, see Equation 1) of approximately 2, by means of a Mariotte bottle reservoir of 50 litres capacity (see Figure 2). The first solution was allowed to percolate until the hydraulic conductivity was constant from one day to the next. This required up to 10 days to accomplish and it often needed a considerable volume of solution to pass through the sample before all remaining entrapped air had been displaced. The hydraulic conductivity (see Equation 1) was obtained by measuring the volume of solution that percolated during a given period (usually 1 hour). Once equilibrium hydraulic conductivity had been reached the solution was removed from the delivery system and the next solution of the series introduced and allowed to percolate until a constant hydraulic conductivity was recorded. These measurements were made for the whole leaching series or until the hydraulic conductivity fell below 0,1 of that of the first leaching solution. With some samples the first leaching solution was re-introduced at this stage in order to see if a recovery in hydraulic conductivity could be achieved by means of a high salt concentration. Leaching was performed in this way for a range of SAR values for each soil. Soil depth measurements were always taken before changing to the next solution and the percolate examined for signs of clay dispersion (see Table 2).

Hydraulic conductivity was calculated according to Darcy's law:

$$K = \frac{Q \Delta L}{A t \Delta H} \quad (\text{Equation 1})$$

- where K = hydraulic conductivity (cm/hour)
- Q = volume (cm³) of solution passing through the soil in t hours.
- A = cross sectional area of core (cm²)
- Δ L = depth (cm) of soil
- Δ H = depth (cm) of solution, i.e.: from the surface to the filter paper on the bottom plate.

Relationship between ESP and SAR (soil solution)

To establish this relationship duplicate 10 g samples of each soil were equilibrated with 5×40 ml aliquots of 8 solutions, 4 of which contained total cation concentrations of 10 meq/l and SAR levels of 2, 10, 25 and 50, and the other 4 contained 100 meq/l total cations and the same SAR levels.

Each sample was shaken for 10 minutes on a reciprocating shaker with the equilibrating solution and then centrifuged. After shaking with the fifth 40 ml aliquot the sample was allowed to stand overnight and then centrifuged the next day. This solution was kept for analysis and the weight of solution occluded in the soil recorded to determine exchangeable cations. Cations were then extracted by shaking and centrifuging with 5×40 ml aliquots of 0,2N, NH_4Cl and the volume then made up to 250 ml with the NH_4Cl solution. Cation concentrations were determined by atomic absorption.

Results

Soil hydraulic conductivities in Figures 3-7 are expressed as a fraction of the hydraulic conductivity of the solution of most rapid permeability. This generally does, and theoretically should, refer to the solution of highest salt concentration. In some instances (see Table 3, e.g. Shortlands SAR 10) the relative hydraulic conductivity was initially less than 1,0 at the highest salt concentration but increased to 1,0 at a lower salt

concentration before decreasing again as swelling and/or dispersion influenced soil permeability. This increase is believed to be caused by the release of entrapped air but is not considered to have adversely affected the quality of the results to any great extent.

The relative hydraulic conductivity has been used in order to simplify the comparison of the effect of different SAR levels on soil hydraulic conductivity. Since disturbed samples were used the absolute hydraulic conductivity values generally have minor significance and little is lost by using relative values.

Threshold concentration curves (see Figure 8) relate points of 15% reduction in hydraulic conductivity (from Figures 3-7) to SAR and total cation concentration. This level of decline in hydraulic conductivity was proposed by Quirk and Schofield⁸ to represent the boundary between favourable and unfavourable physical condition.

In order to relate the threshold concentration curves to the ESP of the soil instead of the SAR of the soil solution, the relationship between SAR and ESP has been established for the five soils (see Table 3). Expressed graphically these relationships are generally linear at 10 meq/l total cations, but appear to be curvilinear at 100 meq/l. The regression line for the data is given in Figure 9 for all five soil series over the range of SAR 2 to SAR 30 and a total cation concentration of 10

TABLE 2
Summary of results of permeability tests

SAR	SOLUTION NUMBER																	
	1		2		3		4		5		6		7		8		1* or 2*	
	RHC	D of S	RHC	D of S	RHC	D of S	RHC	D of S	RHC	D of S	RHC	D of S	RHC	D of S	RHC	D of S	RHC	D of S
SHORROCKS																		
10	0,87	0,96	0	1,00	0	1,00	0	0,98	0	0,97	0	0,95	0	-	-	-	-	
25	0,83	0,85	0	1,00	0	0,99	0	0,97	0	0,93	0	0,90	0	-	-	0,83	0	
50	0,89	1,00	0	0,92	0	0,77	0	0,74	0	0,73	0	0,69	0 D	-	-	-	-	
SHORTLANDS																		
10	0,95	1,00	0	0,99	0	0,96	0	0,92	0	0,89	0	0,88	0	-	-	-	-	
† 25	1,00	1,00	0	0,93	0	0,87	0	0,80	0	0,75	0	0,59	0	-	-	-	-	
50	0,96	1,00	2	0,78	4	0,45	4	0,05	6 D	0,01	7 D	-	-	-	-	0,01	-	
ESTCOURT																		
2	-	0,68	-	0,77	0	0,92	0	1,00	-	0,97	1	0,94	1	0,82	1	-	-	
5	-	1,00	-	0,83	0	0,72	0	0,63	0	0,59	0	0,50	0	0,39	1 SD	0,45	0	
† 25	1,00	0,97	0	0,72	1	0,46	1 SD	0,05	1 D	-	-	-	-	-	-	-	-	
50	1,00	0,92	3	0,10	7 D	0,00	9 D	-	-	-	-	-	-	-	-	0,00	-	
BONHEIM																		
2	-	0,87	-	0,94	0	0,95	-	1,00	-	0,99	2	0,91	2	0,55	3	0,40	3	
5	-	1,00	0	0,90	0	0,79	0	0,66	0	0,56	1	0,40	1	0,09	1 D	0,11	0	
10	1,00	0,97	0	0,81	0	0,67	0	0,46	0	0,33	0	0,07	0 SD	0,02	0 SD	0,04	0	
25	0,96	1,00	0	0,40	8	0,12	14	-	-	-	-	-	-	-	-	0,29	4	
50	1,00	0,80	2	0,02	22	-	-	-	-	-	-	-	-	-	-	0,58	20	
ARCADIA																		
25	1,00	0,85	2	0,19	12	0,05	15	-	-	-	-	-	-	-	-	-	-	
50	1,00	0,61	6	0,03	41	-	-	-	-	-	-	-	-	-	-	0,95	29	

* = Either solution 1 or 2 was used depending on soil type and SAR level.

D of S = Degree of swelling as percentage increase in soil depth.

RHC = Relative hydraulic conductivity.

† = With the exception of these leaching series, all hydraulic conductivity measurements represent the mean of duplicate determinations.

SD = Slight dispersion.

D = Dispersion (clearly observed).

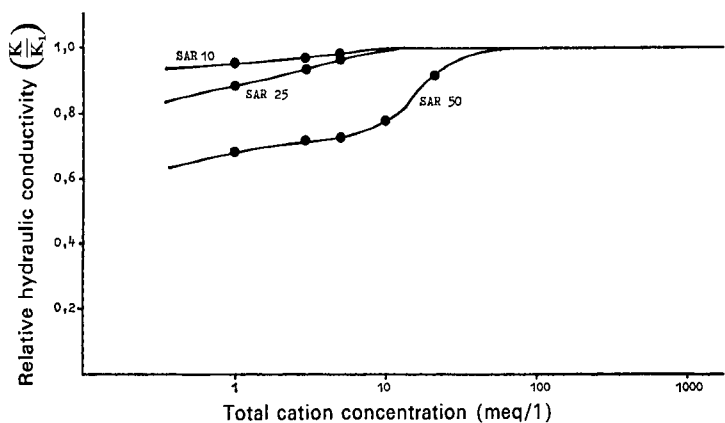


FIGURE 3 Effect of solution composition on the hydraulic conductivity of the Shorrocks series.

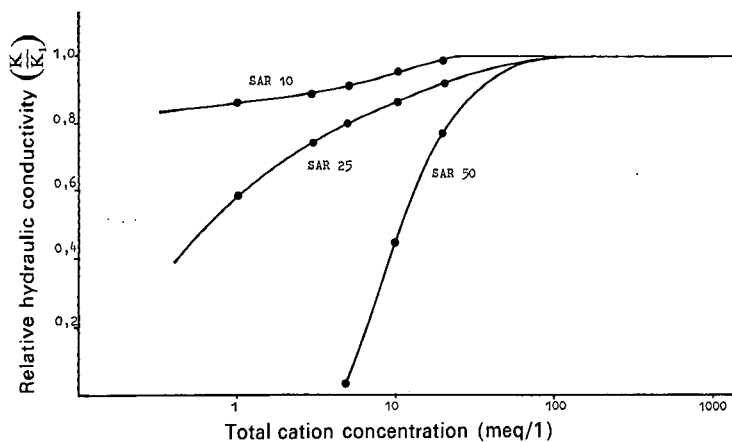


FIGURE 4 Effect of solution composition on the hydraulic conductivity of the Shortlands series.

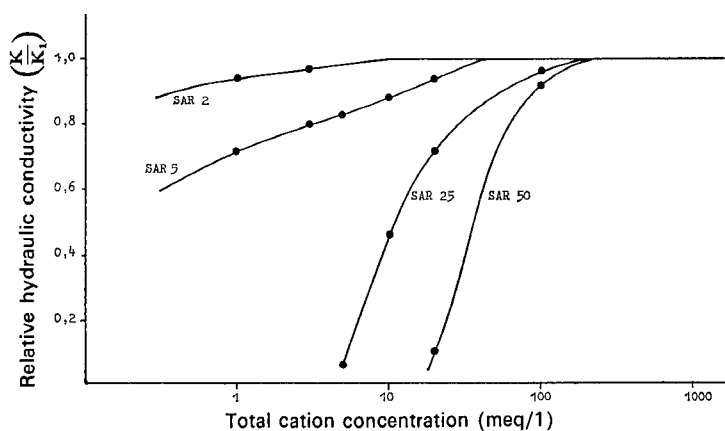


FIGURE 5 Effect of solution composition on the hydraulic conductivity of the Estcourt series.

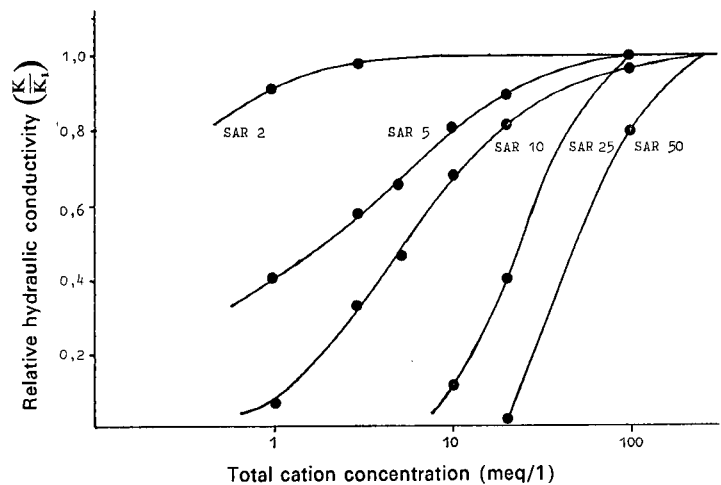


FIGURE 6 Effect of solution composition on the hydraulic conductivity of the Bonheim series.

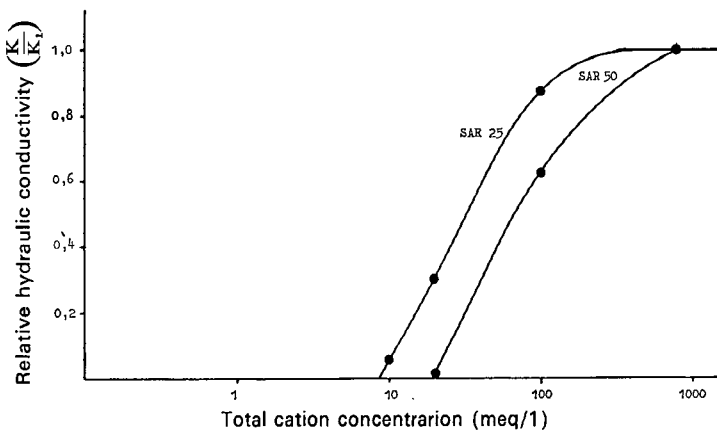


FIGURE 7 Effect of solution composition on the hydraulic conductivity of the Arcadia series.

TABLE 3

ESP measurements on soil samples equilibrated with solutions at two different total cation concentrations and four different SAR levels

Soil series	Total cation concentration (meq/l)	SAR*	ESP*
Shorrocks	100	2,1	3,5
		10,0	13,1
		24,7	28,9
		49,2	45,2
	10	2,2	3,6
		10,2	10,8
		17,3	18,0
		19,3	19,6
Shortlands	100	2,2	2,4
		9,9	10,9
		24,5	27,0
		47,1	42,6
	10	2,1	2,9
		9,4	10,3
		13,8	14,3
		14,4	15,2
Estcourt	100	2,1	4,2
		9,9	14,0
		24,5	30,6
		48,5	48,9
	20	5,4	7,8
		10,5	13,5
		22,2	27,7
		29,3	36,3
Bonheim	100	2,1	3,5
		10,0	13,6
		24,6	28,6
		44,3	48,8
	10	3,2	4,5
		14,9	16,2
		19,1	20,5
		20,7	21,6
Arcadia	100	2,0	2,8
		9,4	12,4
		23,7	26,3
		40,3	41,9
	10	3,3	3,9
		11,0	11,3
		13,3	14,0
		13,7	14,8

* Each figure represents the mean of duplicate determinations

to 100 meq/l. The data show that one can be 95% confident that the ESP estimated is within approximately three units of the true value over the abovementioned range.

These SAR/ESP relationships are useful for estimating ESP from the more easily determined SAR of the saturation extract of soil samples when assessing the degree of sodicity. Where the soil series is known, graphs constructed for each soil series from Table 3 should be used, but where it is not known or does not correspond with those considered, then use can be made of the regression line in Figure 9 without incurring an unreasonable amount of error.

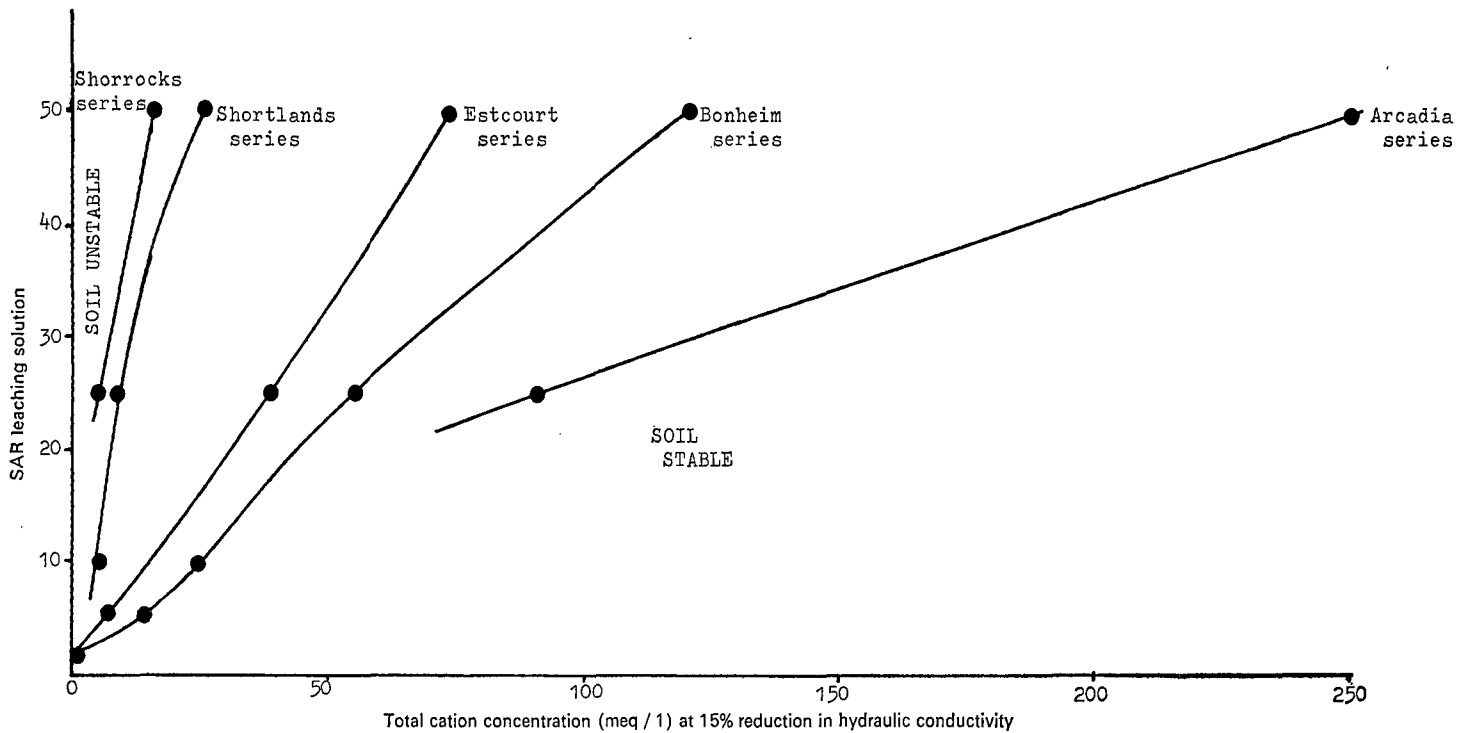


FIGURE 8 Threshold concentration curves for the five soil series.

Discussion

Sensitivity of different soil series to sodium

The order of sensitivity of the soils to sodium is clearly shown in Figure 8 as being Arcadia (most sensitive), Bonheim, Estcourt, Shortlands, Shorrocks. As expected the order is positively associated with the montmorillonite clay content (Table 1). The structure of this clay mineral allows a high degree of expansion of the constituent layers when relatively high levels of exchangeable sodium are present. There is one anomaly in the sodium sensitivity-montmorillonite relationship in that the Shortlands series has a higher content of montmorillonite than the Estcourt series. The greater sensitivity of the Estcourt to sodium is possibly explained by the fact that this soil showed a marked tendency to disperse during the permeability tests.

Swelling and dispersion effects

Soil swelling is clearly a function of montmorillonite content (see Tables 1 and 2) and the Arcadia and Bonheim series showed 41 and 22% increases in sample thickness respectively due to swelling at SAR 50 and 20 meq/l total cation concentration. On the other hand, swelling in the Shorrocks series was insignificant, while the Estcourt and Shortlands series show an intermediate degree of swelling. At SAR levels of 10 or less swelling is generally insignificant for all soils even though the hydraulic conductivity in some instances decreased to a very low level (e.g. Bonheim series, SAR 10, Table 2). Where the hydraulic conductivity declines without any observed swelling or dispersion, there presumably occurs a disorientation of clay particles or a small degree of dispersion or swelling that is difficult to detect. It should be mentioned that the permeability results obtained for the Arcadia series at SAR 10 have been excluded from Table 2 as these were considered to be unsatisfactory. However, 4 replications at this SAR level showed neither swelling nor dispersion.

The only soils showing a notable recovery in permeability on re-applying a concentrated salt solution (either the first or second leaching solution) were those of the Arcadia and Bonheim series (Table 2). This was achieved only under conditions of high SAR where marked swelling had occurred previously.

Treatment of the "swollen" soil with the concentrated salt solution resulted in partial shrinkage of the sample with a recovery from 2 to 95% of the original permeability in the case of the Arcadia soil, and from 2 to 58% for the Bonheim. At the lower SAR levels virtually no recovery in hydraulic conductivity was obtained. This observation suggests that the Bonheim and Arcadia series, under conditions of high sodium saturation, lend themselves to reclamation by the high salt water dilution technique. This is not to imply that the other three soils are unreclaimable. Under field conditions drying and cracking of soil would tend to promote movement of water through the profile.

Implications of the threshold concentration curves

Stable soil structure exists under conditions of a low ESP and a high total cation concentration in the soil solution (see Figure 8). The threshold concentration curve thus provides a maximum level of SAR and a minimum level of total cation concentration to aim for when reclaiming a sodic soil; since it provides a guide as to the amount of sodium the soil can tolerate before structure will be adversely affected. An ameliorant such as gypsum can be applied to either the irrigation water or the soil to counteract the effect of sodium.

If it is accepted that it is desirable to reduce the total cation concentration of the saturation extract of a saline sodic soil to 15 meq/l (approximately 1.5 millimhos/cm) in reclaiming it, then the critical SAR (soil solution) and ESP levels for the five soils are as follows:

Soil series	SAR	ESP*
Shorrocks	50	approx. 45
Shortlands	37	approx. 37
Estcourt	10	13
Bonheim	6	7
Arcadia	< 6	< 6

* Estimated using data in Table 3.

More precise data for the Arcadia series is not available because of the difficulty of obtaining satisfactory results at low SAR levels for this soil.

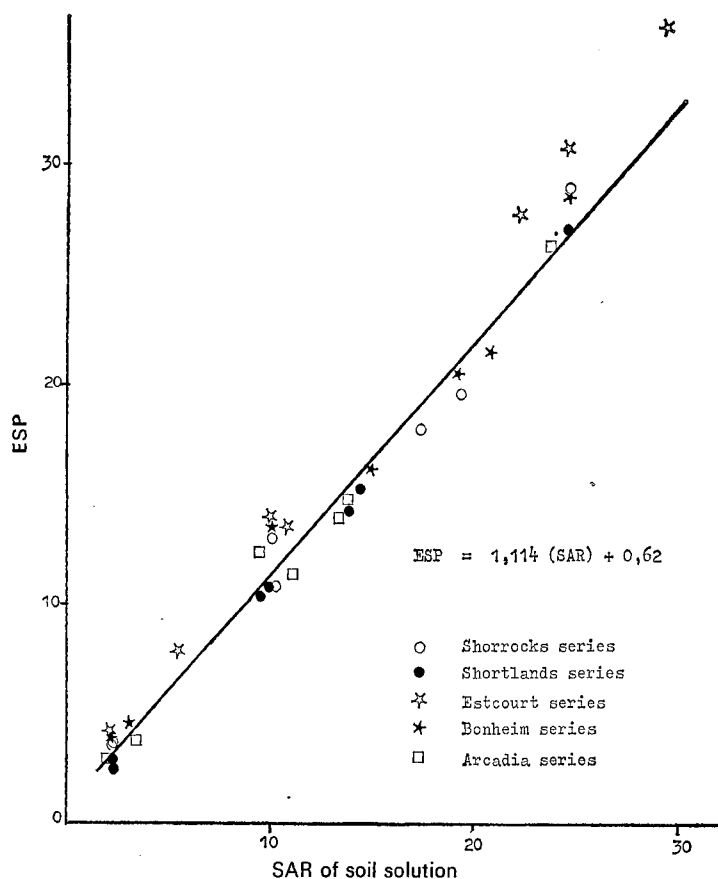


FIGURE 9 Relationship between ESP and SAR of the soil solution.

The approach which has been adopted in this experiment was to study the effect of sodium on soil physical properties rather than on cane growth. It is possible in certain soils that sodium toxicity effects will influence the crop at lower sodium levels than those harmful to soil physical properties. It has also been suggested (Abedine, Robinson and Tyego¹) that moderately high levels of exchangeable sodium can have a desirable effect

on crop production in vertisols, (cracking clay, e.g. Arcadia series) enhancing cracking and thereby improving water acceptance during furrow irrigation. However, local experience of these soils when sodic generally shows that patchy growth associated with waterlogged conditions develops under irrigation. It therefore seems wise to regard the threshold concentration curves as guides to critical sodium levels and to supplement this information with results from field trials and observations.

Acknowledgement

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