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Notes on the reclamation of salt-affected soils in the Indus Plain of West Pakistan[1]

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Summary

About 5.5 million acres of cultivable land in the Indus Plain of West Pakistan are to various degrees damaged by salinity and alkalinity, which are caused by waterlogging and under-irrigation practices under prevailing conditions of an arid climate. Practically all of the juvenile, sedimentary soils of the Indus Plain are calcareous. Part of the salt-affected soils, particularly in the southern areas, are easily reclaimed because of their high content of divalent cations. In the northern areas, however, it was found that a large proportion of salt-affected soils are difficult to reclaim because of alkalinity.

These soils are characterized by very low contents of divalent cations, Ca/Mg-carbonates being the only source of these cations.

It is concluded that a rapid and efficient reclamation of these soils can be achieved only with the aid of soil amendments.

Introduction

In the vast expanses of level, alluvial land along the Indus River and its tributaries, increasing salinization of the land presents a major restraint to agricultural cropping and to the national production of food for the 60 million people and the livestock of West Pakistan.

In the greater part of the Indus Plain, which extends from the Potwar Plateau in the north some 600 miles southwards to the Arabian Sea, an arid and continental climate prevails with very high summer temperatures and a total rainfall of less than 10 inches per annum. In the central section of this long-stretched plain the annual rainfall is even less than 5 inches, most of which accompanies the summer monsoon. Towards the north, in the former Punjab directly south of the Potwar Plateau, the rainfall increases gradually from 10 to 20 inches per annum and the climate becomes semi-arid.

Throughout the Indus Plain agriculture depends almost entirely on irrigation, though rain-dependent 'barani-cropping' is practised to a limited extent in the semi-arid zone of the Punjab.

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[1] Data collected during our 'Indus Special Study' in West Pakistan, which was commissioned by the International Bank for Reconstruction and Development.

The tremendous expansion of canal irrigation during this century, that commands a gross area of 38 million acres and annually serves some 24 million acres of land, has induced a hazardous rise in ground-water tables. This rise is due to an increased recharge, caused by canal leakage and widespread infiltration of applied irrigation water. Consequently, shallow ground-water tables at depths of less than 10, and even less than 5 ft., prevail nowadays in extensive zones of the Indus Plain. In these zones the salinization of the soil is further accelerated by inadequate drainage.

Due to rapid growth of the population and increasing pressure on the land for food production, the cultivated acreage and cropping intensities have been steadily on the increase and have outgrown available water supplies. The common practicce of farmers arising from this chronic water shortage is to under-irrigate their fields. Under-irrigation presents another major cause of salinization.

Annual surveys of all canal-commanded land throughout West Pakistan indicate that, on an average, 15% of the land is visibly affected by salt and another ½% by waterlogging. The actual incidence of salinity and alkalinity must be worse than indicated by this percentage which is based on visible salt symptoms of surface soils and of crop failure.

By allocating additional water supplies per canal circle to a limited number of farmers for a period of 3–5 years, an annual effort is made to reclaim temporarily a contingent of cultivated land which is worst affected by salt. This increased water supply, amounting to 45 acres per cusec, enables these farmers to leach the salts in their fields down to a depth of 5 ft. or more and to keep on cropping.

However, this type of reclamation is not a lasting one, as the salts are bound to reappear after some years, once the farmer is put back on the usual water supply of 300 acres per cusec of water (Asghar and Hafeez Khan, 1961).

Although in this way, on an average, about 29,000 acres of cultivated land are reclaimed each year, salinization and waterlogging still show a net annual increase to the order of 0.25 percent of the gross commandable area (GCA).

From this brief account it is obvious that a more integral approach is needed in order to solve this national twin-problem of salinity and water-logging effectually. Such a remedial solution was under consideration in our 'Indus Special Study' and proposals have been worked out for:

1) An adequate increase of water supplies through further development of both surface and ground water resources.

2) A partial remodelling of the existing canal system to obtain a more efficient distribution of water supplies.

3) A lowering and stabilization of ground-water tables at a safe depth through a tubewell drainage system and through additional improvement of surface drainage.

Once these improvements in the engineering sphere have been accomplished in a not too distant future, the basic conditions for subsequent large scale reclamation and continued salinity control will be fulfilled.

During our 'Indus Special Study' an answer had to be found to the technical problem as to how salt-affected soils in the Indus Plain could be most effectively and quickly restored to productivity under future conditions of improved water supply and drainage. To this end a survey was made of existing information, and additional tests were carried out in the field and laboratory so as to aid our judgement on the matter.

The most relevant aspects of this reclamation study which are typical for specific conditions in West Pakistan will now be discussed in more detail.

Basic information on soils

The fluviatile sedimentary soils of the Indus Plain show a textural pattern which is extremely variable over short distances in lateral as well as in vertical direction. This primary textural pattern shaped by rivers and water courses meandering all over the flat, gently sloping area, is further complicated by wind erosion. Soil genesis is still in a very juvenile stage so that, for all practical purposes, soils have been classified according to the textural stratification of their profiles.

The majority of soils have textures ranging from moderately coarse (sandy loams) to moderately fine (clay loams), while coarse and fine textured soils are of sub-ordinate importance in terms of total acreages. The sand fraction tends to be made up of fine to very fine sand and its dominant composing minerals are quartz and micas. Clay minerals are mainly of the non-expanding illite and chlorite type and the cation exchange capacity (c.e.c.) of these clays is about 51 meq./100 g.

For the majority of soils, therefore, the c.e.c. ranges between 8 and 16 and seldom exceeds 25 meq./100 g of soil.

Practically all soils contain calcium and magnesium carbonates in finely dispersed form with percentages ranging from 5 to 20. Solution and precipitation of these carbonates give rise to dispersed or stratified formation of carbonate concretions ('kankar') at various depths.

As to the physical soil properties it may be stated that the waterholding capacity of the majority of soils is favourable and the available moisture that can be stored between pF = 4.2 and pF = 2.0 ranges between 20 and 30 percentage by volume. Likewise, most soils showed satisfactory permeabilities and infiltration rates, if not affected by salts. There is a tendency of surface soils to puddle and to compact, a feature which is observed throughout the Indus Basin and which may be attributed to low organic matter and low clay contents of surface soils. Under saline-alkali conditions, infiltration rates may be reduced to almost zero presenting a major restraint on reclamation attempts.

Incidence of salinity and alkalinity

Soil salinity, like texture, is also a highly variable feature which changes qualitatively and quantitatively from one spot to another under influence of such external factors as relief, ground-water levels, climatic seasons, land-use and irrigation practices. The salts move upwards, downwards and sideways with the soil moisture and become diluted or concentrated in any one place according to prevalent moisture conditions. Broadly speaking, most salt-affected soils in the Indus Plain may be referred to as Solonchaks and their intergrades with Solonetzs.

There is little practical sense in using broad pedogenetic and taxonomic denominations for the classification of the multi-variety of salt-affected soils in relation to agricultural use and to reclamation requirements. For this purpose, mainly soil analytical criteria are used nowadays in West Pakistan in which the procedures and definitions of the well-known U.S. Agricultural Handbook No. 60 on salinity and alkalinity are being followed.

Accordingly, a soil sample representing a certain soil layer, will qualify as 'saline' if the electrical conductivity of its saturation extract (EC_e) is more than 4 mmho/cm at 25 °C. Likewise, a soil sample will be classified as 'alkali' if more than 15% of

Table 1 Classification of bore-profiles in SCARP-areas (frequency percentages)

Classification of profile	*SCARP 1 Central Rechna Doab (%)*	*SCARP 2 Chaj Doab (%)*	*SCARP 3 Lower Thal Doab (%)*	*SCARP 4 Upper Rechna (%)*	*SCARP 5 Panjnad Abbasia (%)*	*Average (%)*
'Normal'	37	58	50	43	43	48
'Saline'	5	8	6	1	8	5.5
'Saline and alkali'	44	25	37	25	37	31.5
'Alkali'	14	9	7	31	12	15
Total number	100	100	100	100	100	100
of profiles	1944	4657	2158	3554	2147	14,460

Table 2 Classification of bore-layers in SCARP 4 (frequency percentages)

Classification of layer	*Layer*				*Average (%)*
	0–6" (%)	*6–18" (%)*	*18–36" (%)*	*36–72" (%)*	
'Normal'	60	56	54	55	56
'Saline'	1	0.5	0.5	0	1
'Saline-alkali'	18	10.5	9	7	10
'Alkali'	21	33	36	36	32
Not analysed	0	0	0.5	2	1
Total number	100	100	100	100	100
of layers	3554	3554	3554	3554	14,216

its c.e.c. is taken up by sodium ions (ESP > 15). If both these analytical criteria are met, a soil sample is classified as 'saline-alkali'.

In the Indus Plain a number of extensive grid-samplings have been carried out in which soil layers were sampled from regularly spaced bore holes. In the Northern Zone five large Salinity Control and Reclamation Projects (SCARP) were sampled this way with a density of one bore per square mile.

These five projects took up a total area of 9.3 million acres. The sampling comprised 14,460 boreholes and was carried out irrespective of land-use, waste land as well as cultivated land being included.

A borehole (= soil profile) was classified 'saline' or 'alkali' if any of its four sample layers was found in the laboratory to be either 'saline' or 'alkali'. If both conditions were simultaneously found in one or in several sample layers, the profile was classified as 'saline and alkali'.

In Table 1 the classification of these 14,460 boreholes is presented. For each SCARP-area the incidence of the four types of profiles is indicated as a percentage.

The table shows that the majority of profiles can be classified either as 'saline and alkali' or as 'alkali'.

In order to gain an impression of the vertical distribution of salinity and alkalinity within the profiles, the analytical data per soil layer were tabulated for the profiles of SCARP-4, in which project area the incidence of 'alkali' was most pronounced These data are presented in Table 2.

The figures indicate that the combined incidence of 'alkali' and 'saline-alkali' conditions for each of the four layers is fairly close to the average of 42%.

However, near and at the soil surface we note a distinct shift from 'alkali' towards 'saline-alkali' conditions. This must be due to the accumulation of salts in that upper soil layer. The remarkable fact that salt accumulation near the soil surface does not cause an increasing incidence of merely 'saline' conditions must be attributed to the relative shortage of divalent cations, as we will prove later.

According to experience obtained from soil surveys carried out in the Southern Zone of the Indus Plain, in Khairpur and Sind, most of the salt-affected soils in that area are either 'saline' or 'saline and alkali'. Real sodic soils or 'alkali' soil layers are alleged to be rare. This view seems to find support in the evidence emerging from a limited number of southern soil analyses which were made available to us. Out of a number of 1070 analyses, 49% proved to be 'normal', 12% was 'saline', 36% was 'saline-alkali' and only 2% was 'alkali'.

The same analyses revealed that southern soils usually have high concentrations of soluble divalent cations.

This is the crucial point when dealing with the development and with the reclamation of 'alkali' soils, as will be discussed in the following paragraphs.

Reclamation of 'saline' soils

A 'saline' soil, which is defined by an $EC_e > 4$ mmho/cm and an $ESP < 15$, only requires leaching with a sufficient high water delta in order to wash the salts down to a safe depth and to reduce the EC_e to a value well below 4 mmho/cm throughout the soil profile. The duration of this process mainly depends on the initial degree of salinization, the depth of soil to be desalinized and on the permeability of the soil. It is unlikely that reclamation attempts will be complicated and retarded by development of alkalinity during leaching, provided that good quality water is being used.

The very fact that a 'saline' soil is non-alkali, already implicates that it is sufficiently provided with divalent cations so as to keep its ESP-value below 15 and the corresponding SAR-value below 13.

Taking into account the fortunate circumstance that all irrigation water derived from the big rivers in West pakistan is of excellent quality, it can be concluded that the 'saline' soils in the Indus Plain will easily reclaim.

Reclamation of 'saline-alkali' soils

When 'saline-alkali' soil layers are exposed to leaching, alkali conditions may remain after desalinization has been completed. This result depends entirely on the rate at which divalent cations become available during leaching for the replacement of exchangeable sodium ions. Likewise, 'alkali' soil layers also need a sufficient supply of divalent cations during leaching. These divalent cations are to be derived from the irrigation water and from the soil.

Since the majority of salt-affected soils in the Northern Zone of the Indus Plain contain 'saline-alkali' and 'alkali' soil layers it seemed to us of greatest importance to investigate whether 'saline-alkali' and 'alkali' soil layers could be restored to normality by mere leaching, or, that the supply of divalent cations from water and soil together was so low that alkalinity would present a real constraint in reclamation work.

Not a great deal of information on this subject could be extracted from experience gathered in reclamation work carried out in the past, as relatively little attention was paid to the special aspects of alkalinity. The general approach to reclamation of all types of salt-affected soils was prolonged leaching. As the use of soil amendments was regarded as being unprofitable, time and labour consuming efforts were made to improve the soils' permeability by means of cultivation measures and the growing of deep-rooted Jantar (*Sesbania aculeata*). In this way, it took a long time before the first crop, including the Jantar, could be properly established on those saline-alkali soils. It is stated (Hussain, 1965) that reclamation of the heavier 'saline-alkali' soils, which are named 'Bara-soils', takes 6–8 years. Today, this approach to reclamation is still the same in West Pakistan. Taking into consideration that time is money, it may be observed that the technical, financial and economical aspects of the use of soil amendments deserve more attention and study in this country.

The thousands of soil analyses which have been produced in recent years by the Government's 'Water and Soil Investigation Department' (WASID), have thrown more light on the incidence of alkali conditions in the Northern Zone, as we have set out before. In addition we have found convincing evidence from field and laboratory studies that 'residual alkalinity' easily develops during leaching of soils in the Northern Zone. We have repeatedly noticed crop failure, or severe crop damage, in fields with non-saline soils which were markedly alkali.

Very useful information was also obtained from investigations carried out by WASID in the large Reclamation Pilot Scheme SCARP-1 in the Punjab. In this area, chemical changes of the soil were monitored in pre-selected reclamation plots. After 2 years of reclamation, under conditions of effective tubewell drainage and ample water supplies, changes in salinity and alkalinity for the two top-soil layers were recorded (Fireman and Ul-Haque, 1965).

In Table 3 the average conditions for 81 plots are given.

These results show that leaching greatly affected salinity in the top 6 inches of soil which were almost desalinized after 2 years of leaching. Salinity in the 2nd layer, however, has hardly improved. Alkalinity was reduced in the top layer but in the 2nd layer of soil the ESP-value did not diminish.

In that same area we investigated the chemical changes brought about in 20 selected reclamation plots. These plots were initially strongly 'saline-alkali' and had been submitted during 4 years to continuous leaching and subsequent cropping by farmers.

Table 3 Changes in salinity/alkalinity after leaching

Layers sampled and analysed	*Salinity (EC × 10^3)*			*Alkalinity (ESP)*		
	initial	*after 1 year*	*after 2 years*	*initial*	*after 1 year*	*after 2 years*
Surface layer (0–6″)	16.4	9.2	4.4	51	39	27
Next layer (6–12″)	6.0	7.5	4.9	31	38	31

Our own soil analyses could be compared with similar analyses made by WASID in the previous years on samples which we took in exactly the same way and the same spots.

It was found that the initial salinity of the uppermost foot of soil had decreased considerably during these 4 years of leaching. On an average, the salinity of this layer decreased from 9.0 to 3.5 mmho/cm. However, the average EC_e for the deeper soil layers (1′–5′), had increased from 3.5 to 4.5 mmho/cm. Alkali conditions, as denoted by an ESP well above 15, prevailed in most plots. Although the ESP in the uppermost foot of soil decreased from 64 to 41, on an average, there is no doubt that this final ESP = 41 is still far too high after 4 years of reclamation work.

Only 7 out of the 120 soil layers which we analysed proved to have an ESP < 15 and these layers were restricted to two profiles. The soil reaction in most plots was alarmlingly high throughout the profiles as pH_{sp} -values ranged from 8.6 to 10.3. The very few soil layers which proved to have a pH_{sp} below 8.5 were those with high concentrations of $(Ca + Mg)^{++}$ in the saturation extracts.

On account of these observations, which are supported with much more analytical and observational evidence, we have concluded that the larger part of the saline-alkali soils of the Northern Zone can be reclaimed only slowly through high-delta leaching and subsequent cropping, because *residual alkalinity retards the progress of reclamation.*

We will now focus our attention to the supply of divalent cations during reclamation from the two main sources, the irrigation water and the soil.

Divalent cations in irrigation water

All surface water used for irrigation and derived from the big rivers, is of good quality throughout West Pakistan. The use and development of groundwater resources by means of tubewell pumpage will be left undiscussed in the present paper.

Apart from seasonal fluctuations and relatively small variations between one river and the other, we may state for the purpose of our present subject, that the average concentrations of the cations Na^+, Ca^{++} and Mg^{++} are close to the values of 0.50, 1.75 and 0.75 meq./l, respectively.

In this respect there is no essential difference between the Northern and the Southern Zone. The SAR-values calculated for these river waters are very low and vary between 0.2 and 0.9. The average content of bicarbonate ions (HCO_3^-) is less than that of divalent cations, so that the RSC-value is nihil.

Consequently, this water is very suitable for irrigation agriculture and never will create any salinity-alkalinity hazard, provided that both crop and leaching requirements are fully met.

However, its low content of divalent cations (2.5 meq./l) renders the water rather ineffective in the combat against alkalinity in soils. Although prolonged leaching will eventually lower the ESP of an alkali soil to the very low level which is in accordance with the SAR = 0.45 of the water, this procedure will take a very long time. The following simple calculation will show that it requires large amounts of water for the supply of divalent cations which are quantitatively needed for the replacement of exchangeable sodium in a sodic soil.

Calculation sample: One cubic decimeter of sodic soil, weighing 1500 g and having a c.e.c. = 12 meq./100 g, will have a total exchange capacity of 180 meq. We wish to reduce its ESP = 90 to the safety level of ESP = 15, by using water that contains the usual 2.5 meq. of $(Ca + Mg)^{++}$ per litre. We assume that no divalent cations are supplied by the soil, and that there is a 100% exchange efficiency in the interaction between water and soil.

To attain our goal, we will have to replace $75/100 \times 180 = 135$ meq. of exchangeable Na^{+}. The quantity of 135 meq. $(Ca + Mg)^{++}$ needed, is contained in $135/2.5 = 54$ litres of water. Consequently, it needs a water delta of 54 times the depth of soil to be reclaimed, i.e. 54 ft. of water for 1 ft. depth of soil.

It would take many years to apply this amount of water under field conditions. Even if half of this water delta would evaporate when standing in the field, it would still take a long time before the remaining water would have passed through the soil.

From this calculation example it follows, that the greater part of the required quantity of divalent cations has to be derived from resources in the soil, if we wish to accomplish the reclamation within a reasonably short time and without having an interstage of residual alkalinity.

Divalent cations in the soil

From the foregoing it follows that it is important to know whether high or low concentrations of divalent cations normally prevail in West Pakistan soils.

Only for the Northern Zone a large body of analytical data are made available by WASID.

In Table 4 the analytical data for 24,673 soil samples from the SCARP-areas No. 1, 3 and 4 are presented.

The samples include normal as well as salt-affected soils. It has been mentioned that all soils are calcareous and contain the almost insoluble calcium and magnesium carbonates. Some soils contain soluble magnesium salts and some contain gypsum. The gypsum is often present in only one or two soil layers. In case more than 15 meq./l $(Ca + Mg)^{++}$ was analysed, a qualitative reaction mostly indicated the presence of gypsum; in the range 10–15 meq./l this reaction was negative. The figures in Table 4 indicate that 70% of all samples are in the lowest class of 0–5 meq./l $(Ca + Mg)^{++}$. This percentage was as high as 86% for samples from SCARP-4, which area also had the highest incidence of alkali soil layers (Table 1).

In Table 5 it is shown that this very high incidence of the lowest (0–5 meq.) class, prevails throughout all four soil layers of SCARP-4 profiles.

A similar count was made for 200 soil samples which we collected at a depth of

Table 4 Classification of $(Ca + Mg)^{++}$ concentrations in saturation extract (frequency percentage)

Total number of samples	*SCARP-areas*	*(Ca + Mg)++ concentrations in meq./l*			
		0–5 (%)	*6–10 (%)*	*11–15 (%)*	*> 15 (%)*
2396	No. 1	52	25	5	18
8093	No. 3	44	29	10	17
14184	No. 4	86	10	2	2
24673	Average	70	17	5	8

10–20 inches in 20 different water courses all over the Punjab. It proved that 79% of these special samples contained less than 5 meq./l of $(Ca + Mg)^{++}$. This evidence indicates that a large proportion of soils in the Northern Zone have a very low supply of divalent cations.

Moreover, the examination of thousands of analyses also revealed that the greater part of these soils with low divalent cation supply contained not more than 0.5 to 1.5 meq./l of $(Ca + Mg)^{++}$ in their saturation extracts. It is quite obvious that these soils do not contain soluble magnesium salts or gypsum. The low concentration of 0.5 to 1.5 meq. of divalent cations apparently reflect the solubility of the Ca/Mg-carbonates under average conditions. In vitro, a saturated $CaCO_3$-solution contains 2.7 meq./l of Ca^{++} at a $pH = 7.85$ and only 1.1 meq./l of Ca^{++} at a $pH = 8.60$, according to the U.S. Salinity Handbook No. 60.

In 'saline' soils, the solubility of these carbonates may be somewhat increased in the presence of neutral sodium salts, but under 'alkali' conditions which prevail in 'saline-alkali' and 'alkali' soils the solubility is suppressed.

This finding that calcareous, 'saline-alkali' soils do not contain appreciable amounts of divalent cations, if no gypsum or soluble magnesium salts are present, is of great importance when considering the reclamability of these soils.

In order to illustrate the importance of an adequate supply of divalent cations in 'saline-alkali' soils which are being leached with good quality water, chemical data are presented in Table 6 of six different saline-alkali surface soils which were leached in reclamation fields to a certain degree of desalinization.

From these data we may tentatively draw the following guidelines as to the reclamability of four main types of 'saline-alkali' soils:

1) If the initial concentration of divalent cations is really high and the ratio $Na^+/(Ca + Mg)^{++}$ is very low, no residual alkalinity will develop as an interstage during leaching (soils a.1 and a.2).

2) If the initial concentration of $(Ca + Mg)^{++}$ and the ratio $Na^+/(Ca + Mg)^{++}$ are medium, but a sustained supply of Ca^{++} is released from gypsum in the soil, no residual alkalinity will develop during leaching either (soils b.1 and b.2).

3) If the initial concentration of divalent cations and the ratio $Na^+/(Ca + Mg)^{++}$ are medium, residual alkalinity may develop as an interstage during leaching if the soil does not contain gypsum for the supply of calcium ions (soil a.3).

4) If the initial concentration of divalent cations is well below 5 meq./l, severe alkalinity will develop during leaching (soil c.1).

Table 5 Classification of $(Ca + Mg)^{++}$ per soil layer in SCARP 4

Total number of samples	*Soil layer (inches)*	*$(Ca + Mg)^{++}$ concentrations in meq./l*			
		0–5 (%)	*6–10 (%)*	*11–15 (%)*	*> 15 (%)*
3566	0–6	79	14	3	4
3551	6–18	86	10	2	2
3540	18–36	86.5	9.5	2	2
3527	36–72	93	5	1	1
14184	Average	86	10	2	2

Table 6 Soil conditions in (4–10") layer initially and after leaching

Condition	*Soil*	*SP*	*$EC \times 10^3$*	*meq./l saturation extract*			*Na (Ca+Mg)*	*SAR-value*	*ESP-value*
				gypsum	*Na*	*(Ca+Mg)*			
Initial	a.1	42	83.4	0.0	824.9	394.9	2.1	58.9	46.0
Leached	a.1		28.4	0.0	1095.7	79.7	2.2	28.1	28.8
Initial	a.2	46	156.8	0.0	177.4	611.8	1.8	61.0	47.0
Leached	a.2		18.6	0.0	114.8	78.6	1.7	18.2	20.4
Initial	a.3	46	72.0	0.0	925.0	34.5	27	222	77.3
Leached	a.3		9.9	0.0	102.3	8.2	13	51.5	42.5
Initial	b.1	40	96.7	10.9	1218.0	244.0	5	109	61.5
Leached	b.1		7.0	3.6	45.2	39.8	1.1	10.3	11.9
Initial	b.2	41	80.4	4.5	782.6	43.8	18	167	71.1
Leached	b.2		3.9	0.5	24.8	12.2	2.1	10	11.3
Initial	c.1	43	69.5	0.0	945.0	0.5	1890	1290	>80
Leached	c.1		7.3	0.0	75.7	1.0	76	106	61

For diagnostic purposes it may be mentioned that 'saline-alkali' soils with less than 5 meq./l of (Ca + Mg)++ in the saturation extract are mostly typified by a $pH_{sp} > 8.5$. When the concentration of divalent cations drops as low as 1.5 meq./l we invariably measured a $pH_{sp} > 8.8$. This high pH_{sp} -value for a 'saline-alkali' soil was not the result of a lowered salt content, as stated in Handbook No. 60, but it was found at any EC_e -value above 4 mmho/cm, if (Ca + Mg)++ concentrations were extremely low.

The role of Ca/Mg-carbonates in reclamation work

In the previous paragraphs we have shown that a large proportion of 'saline-alkali' soils in the Northern Zone of the Indus Plain have no other source of divalent cations than the almost insoluble Ca/Mg-carbonates.

We have seen that the saturation extracts of these soils show concentrations of divalent cations well below 5 meq./l, while mostly these concentrations range from 0.5 to 1.5 meq./l. Even with the use of good quality water, containing 2.5 meq./l of divalent cations, these soils will develop pronounced 'alkali' conditions during leaching. This will happen firstly in the surface layer of soil which is most rapidly desalinized. Deterioration of only this layer is already sufficient to impair the progress of leaching and to prevent the establishment of a crop.

It is obvious that further improvement of the surface soil mainly depends on the concentration of (Ca + Mg)++ that can be maintained in the soil moisture.

If the concentration of the (Ca + Mg)++ is too low, there is no possibility to achieve a satisfactorily low equilibrium ESP < 15.

Only in the final stage of desalinization, when Na+ concentrations have been drastically reduced by leaching to a very low level, these very low (Ca + Mg)++ concentrations become sufficiently effective to induce a SAR-value below 15, and to reach a corresponding equilibrium ESP below 15.

This principle is illustrated with the three graphs in Fig. 1, which show the decrease of SAR-values with the increase of $(Ca + Mg)^{++}$ concentrations for three fixed Na^+ concentrations of 50, 25 and 15 meq./l, respectively.

Only for the lower concentration of 15 meq. Na^+, which corresponds approximately with an $EC_e = 1.5$ mmho/cm, an equilibrium ESP < 15 can be attained if the saturation extract contains at least 3 meq./l of $(Ca + Mg)^{++}$. With $(Ca + Mg)^{++}$ concentrations as low as 1.5 meq./l, it needs even more leaching and a further decrease of Na^+ concentration, in order to attain an equilibrium ESP < 15.

Even though a final attainment of an ESP < 15 is feasible after prolonged leaching at the very low concentration of 0.5–1.5 meq./l of $(Ca + Mg)^{++}$, we still face the fact that it takes a long time and a very high water delta in order to supply the total amount of $(Ca + Mg)^{++}$ which are needed for the desired replacement of exchangeable Na^+.

Under *Divalent cations in irrigation water* we calculated that for the de-alkalinization of 1 ft. of 'alkali' soil, a water delta of 54 ft. was required if the water was the only source of divalent cations and contained 2.5 meq./l of $(Ca + Mg)^{++}$.

Only in the event that the Ca/Mg-carbonates of the soil would release extra divalent cations at a fair rate during leaching, this extra supply could be added to the divalent cations contained in the irrigation water and we would need a lesser water delta than the one we calculated in our example.

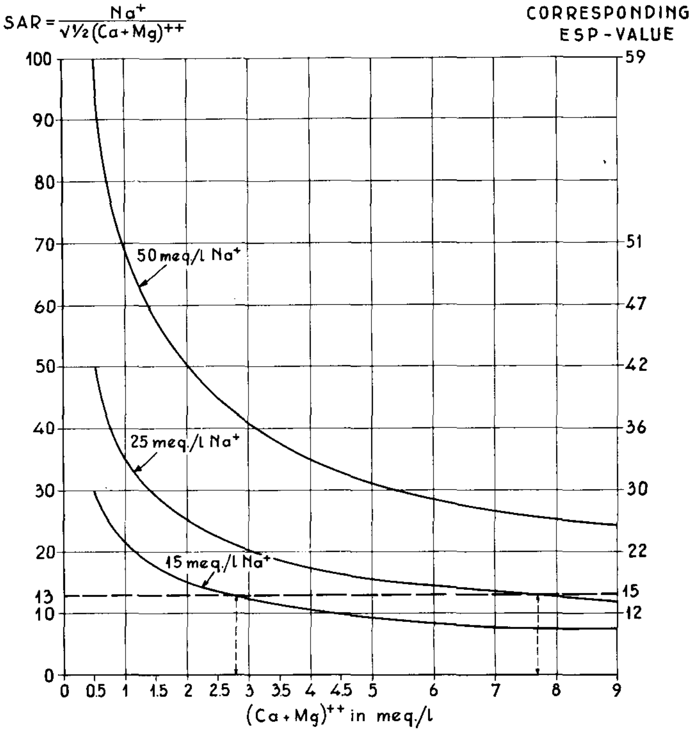

Fig. 1 Calculated SAR-values for three fixed Na^+ concentrations at increasing concentrations of $(Ca + Mg)^{++}$ in saturation extract.

We have tried to gain some first-hand information about the release of $(Ca + Mg)^{++}$ from the soil's carbonates during leaching by carrying out a lysimeter pottest. Unfortunately, there was no time and opportunity available for elaborate research work and only some orientative information could be collected.

In our pottest 4000 g of a 'normal' soil was exposed during 10 weeks to a high leaching regime with 43.5 litres of water, which application corresponded with a water delta of 17 ft. per 1 ft. of soil. The total input and output of Ca^{++}, Mg^{++} and HCO_3^- was measured.

In one leaching series of six pots, water was used which contained 4.1 meq./l of $(Ca + Mg)^{++}$, 5.4 meq./l of Na^+. The bicarbonate content of the water was neutralised with diluted HCl and adjusted at $pH = 7$. Accordingly, the SAR-value of this neutralised water 'N' was 3.8 and its RSC = nil.

The input/output balance sheet, including soluble and exchangeable ions present in the soil, showed for all pots a marked positive balance respective to $(Ca + Mg)^{++}$ and HCO_3^-. This surplus found in the leachate suggested that approximately 2 meq. $CaCO_3$ per 100 g soil had dissolved which amounts to 0.2 percent by weight. The dissolved carbonate appeared to be mainly calcium carbonate.

The mobilization of calcium ions from the soil's carbonates in this series was also to be expected on theoretical considerations which are developed by Langelier (1936), who devised an index for the equilibrium in a closed system between pure $CaCO_3$ and various types of water.

The Langelier Saturation Index (SI) $= pH_a - pH_c$ represents the difference between the actual pH of the water (pH_a) and the calculated pH of the water : $pH_c = (pK'_2 - pK'_c) + pCa + pAlk$.

He found that, if the SI-value is positive, there is a tendency for $CaCO_3$ to precipitate from the water, and, if negative, there is a tendency for $CaCO_3$ to be dissolved by the water.

In our test the neutral water 'N' had a $pH_a = 7.0$. With the aid of tables, presented by Bower and Maasland (1963) we calculated the $pH_c = 2.35 + 2.67 + 4.00 = 9.00$. Accordingly, the Langelier $SI = 7.0 - 9.0 = -2.0$ (negative). On account of experimental work, reported by Wilcox et al. (1954b), on the interaction between irrigation waters and calcareous soils, it is generally accepted that waters with a pH_c greater than 8.35 will dissolve $CaCO_3$ when passing through the soil, whereas waters with a pH_c below this critical value will lose divalent cations through precipitation.

In our test this modified Langelier $SI = 8.35 - 9.00 = -0.65$.

In a second leaching series, we used alkalinized water 'A'. This water contained 4.1 meq./l of $(Ca + Mg)^{++}$, 8.4 meq./l of Na^+ and 10.0 meq./l HCO_3^-. The SAR-value was 5.9 and the RSC = 5.9 meq./l.

In this leaching test with the same soil the ionic balance sheet showed for all pots a marked deficit of $(Ca + Mg)^{++}$ and of HCO_3^-. This result suggested that approximately 2.5 meq. $(Ca + Mg)^{++}$ per 100 g of soil were precipitated as carbonates in the soil. The losses for Mg^{++} were higher than those for Ca^{++}.

This experimental evidence finds support in the theoretical prediction of the modified Langelier Index, which in our case becomes markedly positive: $SI = 8.35 - 7.11 = + 1.24$.

The pH_c of water 'A' is $2.44 + 2.67 + 2.00 = 7.11$, which is much lower than the pH_c of water 'N'. This is mainly due to an increase of the titratable bases: $Alk = CO_3^- + HCO_3^-$, and the corresponding decrease of the negative logarithm pAlk.

If we calculate the pH_c-value for the average river water in the Punjab we find: $pH_c = 2.11 + 3.25 + 2.75 = 8.11$. This value seems to suggest that normal irrigation water in the Indus Basin has a tendency to lose Ca^{++} by precipitation rather than to dissolve $CaCO_3$ when passing through the soil.

Furthermore, we want to observe that the validity of the modified Langelier Index is complicated by a few factors which have not yet been thoroughly investigated.

One of these is a high pH-value of a 'saline-alkali' or 'alkali' soil. It is more likely that for these soils the pH_a-value in the SI-formula has to be replaced by a higher value than 8.35 which holds good for average 'normal' soils. To our opinion, this critical value should be at least 8.8. This will reduce the probability that SI becomes negative.

Another complication of the interaction between water and soil is the concentration effect which is caused by evapotranspiration losses. It was found by Wilcox et al. (1954a) that the relation between the amount of carbonates in the irrigation that precipitates (y) and the fraction of the inflow water that is evapotranspired (x) can be presented as a linear regression of high significance. In accordance with this principle we found in our leaching series with water 'A', that the loss of $(Ca + Mg)^{++}$, through conversion of the bicarbonates into carbonates, was markedly reduced if the outflow/inflow ratio of the water was artificially increased by elimination of the evaporation losses.

Reversely, it may be expected that a substantial reduction of the outflow/inflow ratio during the hot season, will very much accelerate any tendency of water to lose divalent cations through carbonate precipitation.

Conclusions

When summarizing the foregoing evidence and considerations, it appears that for 'saline-alkali' and 'alkali' soil layers which are devoid of gypsum or other soluble Ca/Mg-salts, the probability is very small that extra supplies of divalent cations will be released from the soil's carbonates during leaching. Therefore, we regard the role of Ca/Mg-carbonates respective to reclamation progress as almost negligible, when no other measures than leaching are taken to activate the solubility of theses carbonates. However, it may be expected that this role of the Ca/Mg-carbonates will be activated when crop remains and green manures are ploughed into the soil. The organic acids, including carbon dioxyde, which are produced in the soil during decomposition of the organic matter, will directly dissolve the carbonates and also neutralize the soil's alkalinity.

This expectation is in accordance with practical experience of farmers in West Pakistan who can afford to apply large dressings of organic manures. Likewise, we found in our own reclamation fields that after one season of high leaching a dressing of 20 tons of farmyard manure greatly reduced alkalinity, as measured by pH_{sp} and ESP, whereas in the control plots the alkalinity remained very high.

The first aim of soil survey in reclamation areas should be the identification and separation of soils with and without additional sources of divalent cations.

On the latter category of soils, reclamation is not only a labour and time consuming affair, but also large quantities of precious surface water are lost due to the inefficiency of leaching under conditions of alkali surface soils and high evaporation losses. On these soils the use of soil amendments is essential for obtaining a higher efficiency in reclamation work. The cost of these commodities, like farmyard manure, gypsum or sulphur, will have to be balanced against savings in time, water and labour and, also, against the revenues derived from early and better crop yields.

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