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SALINIZATION, ALKALINIZATION AND SODIFICATION IN PUNJAB (PAKISTAN): CHARACTERIZATION OF THE GEOCHEMICAL AND PHYSICAL PROCESSES OF DEGRADATION

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ABSTRACT

Evidence of soil degradation impeding soil tillage and irrigation in cultivated soils in Pakistan is identified, described and represented in a general process of degradation. Based on a chemical analysis of soil characteristics, it is shown that a more general geochemical degradation process may occur in these soils. Two paths of salinization, i.e. neutral salinization and alkalinization inducing a process of sodification, are identified. The wide range of chemical properties of soils and corresponding geochemical processes can be explained by the great diversity of quality in irrigation water that is taken either from the canal or from the groundwater. The basic module of a geochemical model AQUA (Vallès and DeCockborne, 1992) is calibrated with the help of a study of the soil geochemical properties (identification of minerals, characterization of exchanges) and then used to assess the effect of four different water qualities on sandy and loamy soils. Based on these scenarios, the salinity, alkalinity and sodicity hazard of irrigation water is assessed by taking into account simultaneously the electrical conductivity and the residual alkalinity (calcite-residual alkalinity, residual sodium carbonates) or irrigation water and the soil cation exchange capacity: these three indicators appear the most relevant in the context of the study. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: soil degradation; geochemistry; modelling; irrigation; Punjab; electrical conductivity; residual alkalinity; salinization; sodification; alkalinization

INTRODUCTION

For centuries, the main source of irrigation in Pakistan has been water diverted from the Himalayan rivers that traverse the country. The quality of this water is excellent, with a salinity level of 150–250 mg l^{-1}, a sodium adsorption ratio (SAR) of 0·2 (meq $l^{-1})^{0\cdot 5}$ and a residual sodium carbonates (RSC_{iw})† of −0·4 meq l^{-1}. This has enabled farmers to reclaim some of the areas that were affected by salinity of ancient origin. These salts have historically been associated with the Indus plains, which were formed by alluvial deposition into a shallow sea (Ghassemi, *et al.*, 1995).

In other areas, the rise in groundwater tables, brought about by the introduction of large-scale irrigation in the flat Indus plains, contributed to salinization due to capillary rise. This rise has come to a stop in recent

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†The RSC is defined as the alkalinity minus the concentrations (in meq/l) of Ca and Mg (Eaton, 1949).

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years and is even falling especially in parts of the Punjab. This is due to the massive deployment of tube wells, mainly owned by private farmers, as an important source of irrigation, presently estimated to contribute to 30–40 per cent of the total irrigation water at the farm level (Nespak/SGI, 1991).

The increasing use of groundwater has raised concerns, because of its poor quality (Ghafoor, *et al.*, 1991; Kijne and Kuper, 1995; Marlet, 1997). In a recent survey by the International Irrigation Management Institute (IIMI, 1995) for more than 400 tube wells on the left bank of the Sutlej river, it was found that the electrical conductivity (EC) of the water ranged from 0·3 to 4·8 dS m^{-1} ($\mu = 1{\cdot}1$ dS m^{-1}, $\sigma = 0{\cdot}6$). More than 15 per cent of the tube wells have a SAR higher than 7 (meq $l^{-1})^{0{\cdot}5}$ ($\mu = 3{\cdot}8$ (meq $l^{-1})^{0{\cdot}5}$, $\sigma = 3{\cdot}4$) and the pumped groundwater contains relatively high amounts of bicarbonates ($\mu = 4{\cdot}8$ meq l^{-1}, $\sigma = 1{\cdot}4$). The values of the residual sodium carbonate (RSC), i.e. the concentrations of carbonates and bicarbonates minus those of Ca and Mg (all in meq l^{-1}), go up to 13, and more than half of the tube wells have a positive value of RSC.

In the study area, evidence exists of reductions in infiltration rates and hydraulic conductivity due to the use of tube-well water (Kielen, 1996). Relatively low permeability of soils also became evident during surveys in 1989–90, when, in a few hundred fields, the hydraulic conductivity was determined with the help of a Guelph Permeameter (Reynolds and Elrick, 1985; Reynolds and Elrick, 1987). Kijne and Kuper (1995) report that for 40 per cent of these determinations, a zero reading was obtained. Parallel to the observation of degraded permeability, increased salinity and sodicity states in soil have been evidenced by measurements of the soil electrical conductivity and sodium adsorption ratio.

The objective of this study is 'firstly' to characterize the processes and different states of physical degradation in irrigated soils and, secondly, to identify and explain, mostly based on geochemistry information (mineral precipitation and dissolution, cations exchanges), the different soil chemical degradation processes that may cause them (neutral salinization, alkalinization and sodification) as well as relevant indicators to assess them.

Finally, we attempt to establish the relation between irrigation water quality and soil processes by simulating and evaluating the water degradation hazard. The underlying hypothesis of the study is that irrigation system management can contribute in helping farmers to reduce problems of soil salinity and sodicity and to mitigate the latter's effect on soil degradation and agricultural production (Kuper, 1997).

DESCRIPTION OF THE STUDY AREA

The study was carried out in a number of farmers' fields in eight tertiary units, located in the Chishtian subdivision, in south-east Punjab, Pakistan. The area forms part of the contiguous Indus Basin irrigation system. The predominant crops in the area are cotton, rice and fodder in summer (Kharif) and wheat and fodder in winter (Rabi). The climate is arid to semiarid with annual potential evaporation at 2000 mm far exceeding the rainfall, which is generally between 150 and 200 mm. The sample fields are irrigated through canal or groundwater resources or both. The latter are tapped through shallow, privately owned tube wells that have been installed in recent years; the tube wells have now reached a density of 6–7 per 100 ha. The soils in the area are of alluvial origin, in places mixed with aeolian deposits. The coarse to moderately coarse textures represent more than 60 per cent of the area; the moderately fine and fine textures represent less than 8 per cent (Soil Survey of Pakistan, 1996).

MATERIALS AND METHODS

Geochemical indicators

Usually, two main pathways of salinization can be distinguished: the neutral and alkaline paths of salinization (Cheverry, 1974; Servant, 1986), often referred to as salinization and alkalinization, respectively. The

Table I. List and formulas of the minerals likely to precipitate in the concentration process of fresh water and used for the geochemical modelling

Name	Formula
Calcite	$CaCo_3$
Sepiolite	$MgSi_3O_6(OH)_2$
Gypsum	$CaSO_42H_2O$
Illite*	$Si_{3\cdot5}Al_{2\cdot3}Mg_{0\cdot25}O_{10}(OH)_2K_{0\cdot6}$

Source: Appelo and Postma, 1996; *Marlet, 1996.

residual alkalinity* (RA) concept (Van Beek and Van Breemen, 1963) can be used to distinguish the two different paths; it is defined with respect to the precipitation of one or several minerals. While increasing the concentration of a soil solution, which happens typically during evaporation, different minerals, such as calcite, sepiolite and gypsum, precipitate (see Table I). If the RA of the soil solution is negative, the successive precipitation of these minerals causes a relative increase in Ca and Mg and decrease in alkalinity. This process leads to saline soils and, at high concentration levels, possibly to sodic soils. If the residual alkalinity is positive, mineral precipitation causes an increase in alkalinity and pH and decrease in Ca and Mg: Na becomes rapidly prevalent and causes sodification (Vallès, *et al.*, 1989). The calculation of calcite residual alkalinity as alkalinity $- Ca^{2+}$ (eq l^{-1}) is an application of the RA concept to the precipitation of calcite. The calculation of residual sodium carbonate (RSC) as alkalinity $- Ca^{2+} - Mg^{+2+}$ (eq l^{-1}) is an application of both calcite and Mg-silicate precipitation. The soil sodification level is appraised by the exchangeable sodium percentage† (ESP). The soil extract concentration can be assessed by the electrical conductivity.

Experiments on Soils

Characterization of degradation of soil physical properties

The top layer (0–40 cm depth) of 50 soil profiles was studied and compared. The selection of the sample fields was based on three main criteria:

1. Soil texture: soils with texture ranging from sand to silt loam were selected as these are predominant in the study area.
2. Soil cover: both cultivated fields (19) and barren areas with natural vegetation were chosen.
3. Soil moisture: soil moisture may introduce some variability in the observations of the soil structure. All the soils were in dry conditions; 10 of the cultivated fields were observed just after the wheat harvest, more than one month after the last irrigation; 7 were under cotton cultivation at the beginning of the summer season.

Four types of indicators were used to appraise soil physical degradation status:

1. Morphological indicators: type of crust, consistence and structure (FAO classification) of the underlying layers.
2. Physical indicators: crust strength was measured by a hand-held penetrometer (Soane, *et al.*, 1971): 25 repetitions of the measurements were done for each field.

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*The alkalinity is defined as the sum of the cations which may accept protons. In the case of the soils in the study area, the alkalinity can be considered as the sum of carbonates. The *residual* alkalinity is calculated as the alkalinity minus the cations and anions that are involved in mineral precipitation. Thus, 'calcite-sepiolite residual alkalinity', generally referred to as 'residual sodium carbonates (RSC)' is defined as the alkalinity minus calcium and magnesium concentrations (in eq l^{-1}).

†The exchangeable Sodium Percentage (ESP) is the ratio between the concentration of exchangeable sodium and the sum of concentrations of the other exchangeable cations (in eq l^{-1})

3. Chemical indicators: ESP, RSC and pH of the surface layer and at 30 cm depth were calculated from samples analysed in the laboratory (1 : 1 dilution); the pH of the surface soil was also measured in the field with a hand-held pH meter;
4. 'Farmers' indicators': farmers use indicators related to soil degradation, such as the presence of crust, soil hardness or unusual (temporary) ponding of the field after an irrigation (lower infiltration rate resulting from a surface crust) (Kielen, 1996).

Characterization of soil chemical properties

It was carried out in two steps:

Firstly, the minerals likely to be present in the soils, were determined from chemical analysis on soil samples from 15 irrigated fields. Activities of each chemical species of the soil solutions were calculated with the help of the model GYPSOL (Vallès and Bourgeat, 1988), the pressure in CO_2 was calculated from the alkalinity and the pH measured on 1 : 1, 1 : 5, 1 : 10 and 1 : 20 soil extracts; saturation charts were then drawn up to assess the saturation of the soil solution in calcite, gypsum, sepiolite and illite, as these are the minerals that precipitate first during the concentration of soil water. On the same set of samples, the selectivity coefficients (Gaines and Thomas, 1953) were calculated in order to characterize the exchanges between the main exchangeable cations.

Secondly, the identification and quantification of the geochemical processes were carried out on a larger set of 100 soil samples, collected on both cultivated and barren areas at the end of the winter season (rabi) in May 1996. The samples were classified in order of increasing concentration level. In order to appreciate the concentration level of each sample, the concentration in chlorides was used as a reference (Marlet, 1996). This was done because this ion was assumed to be conservative, i.e. was not involved in any geochemical process, and because it was present in appreciable quantities in the soils of the study area (from 0·3–40 meq/l). A concentration factor was defined as $FC_i = Cl_i/Cl_0$ with Cl_i as the chloride concentration of the sample *i*, Cl_0, the chloride concentration of the soil sample with the lowest chloride concentration* (in this case, 0·3 meq l^{-1}). The concentration values of the main chemical components, i.e. alkalinity, sodium, calcium, magnesium and sulphates, were then compared and studied at different concentration levels, as a function of equilibria between the soil water, minerals and soil complex.

Geochemical Model

Characteristics of the model

The model used in this study is AQUA (Vallès and DeCockborne, 1992), a geochemical model derived from GYPSOL (Vallès and Bourgeat, 1988), which has been applied in countries like Tunisia and Niger (Marlet, 1996).

The basic module of this module accounts for speciation of the major chemical components, precipitation and dissolution of minerals and ions exchanges. Seven chemical components are considered: K, Na, Ca, Mg, Cl, SO_4 and Si, the activities of which are calculated from their concentration. The mineral precipitation and dissolution processes are simulated by comparing the values of the ionic product (Q) and the solubility product (K_s) for each mineral. If $Q > K_s$, precipitation occurs; if $Q < K_s$, dissolution occurs. Binary exchanges are taken into account and characterized for some pairs of cations.

Calibration

Information on the type of minerals came from an analytical study presented later. Three pairs of cations (Ca/Na, Ca/Mg and Na/K) were considered to characterize the exchanges. The composition of the exchangeable complex and the concentration of the main cations in the soil solution were simultaneously determined in the laboratory. The selectivity coefficient (Gaines and Thomas, 1953) was then calculated by linearization of the exchangeable fraction ratio (EFR) (Rieu, *et al.*, 1991).

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*This was a field solely irrigated with canal (river) water.

Simulation procedure

Different irrigation waters were mixed with soil water, the chemical characteristics of which were determined experimentally. The equilibria between solutes, minerals and soil complex were then calculated until convergence was reached. This happened if either the ionic product for each mineral equaled the solubility product or the mineral had completely dissolved. Then, the concentration of the soil water was increased 1·2 times. The procedure was repeated until the final concentration equaled 30–300 times the initial concentration depending on the simulations.

RESULTS AND DISCUSSION

Evidence of Degradation of Physical Properties

Soil crusts and hard soils

Signs of soil degradation, i.e. top surface crusts and hard layers in the first 40 cm of the soil profile, can be observed both in cultivated fields and on barren lands.

A crust is defined as a thin surface soil layer (less than 10 mm thick) which is physically different from underlying soil layers (Hoogemoed, 1994). Two morphological types of crust can be distinguished: the structural and the runoff depositional crusts (Bresson and Boiffin, 1990). The structural crust displays microtopography on surface and vesicular porosity. The depositional crust is thin, flat and layered; it develops from a structural crust by a flow process that fills the surface microdepressions (making the crust flat) and sorts the particles, and thus layers the crust.

In the study area, structural crusts were mainly found on cultivated soils (17 of the 19 crusty cultivated soils were covered by a structural crust), whereas depositional crusts appeared to be characteristic of barren areas. Some fields covered by poor crops and showing some barren patches displayed both structural and depositional crusts in different places. Both morphological and physical characteristics were observed.

The crusts never exceeded 5 mm. The measurements of the resistance of the soil to penetration showed that crusts were weaker at the beginning of the agricultural year, after the first cultural practices and irrigations, than at the end. Signs of surface crusts were found for the whole range of soil textures except on very sandy soils.

Evidence of hard-setting was observed in the first 40 cm of some of the soil profiles. Using indicators of soil structure and soil consistence, it was shown that soils belonging to the same series could be variably differentiated in the top of the profile. The most differentiated profiles exhibited a crust. Some structureless and hard soil layers were identified, in some cases just below the crust, and in other cases, at 20 cm depth. The difficulties in soil tillage that farmers complain about in this area, were probably related to these phenomena.

Degradation over time

The observation of different states of degradation illustrates the general process of soil degradation in the Chishtian subdivision:

- Structural crusting occurs fairly rapidly, i.e. within a crop season. Structural crusts were observed both at the end of the winter season and at the beginning of summer on fields with cotton that had just germinated. This indicated that crusts can appear after one or two irrigations, which can explain temporary ponding after the second irrigation observed by farmers.
- Depositional crusts do not generally develop within a wheat-growing season, as no wheat fields was found covered by a depositional crust even at the end of the crop season.
- Depositional crusting is the result of a transformation of structural crusts. This was observed on a fodder field, containing gypsum and displaying an uneven stand of the crop, and on some barren fields with natural vegetation, covered in some places by a structural crust and in other places by a depositional crust.

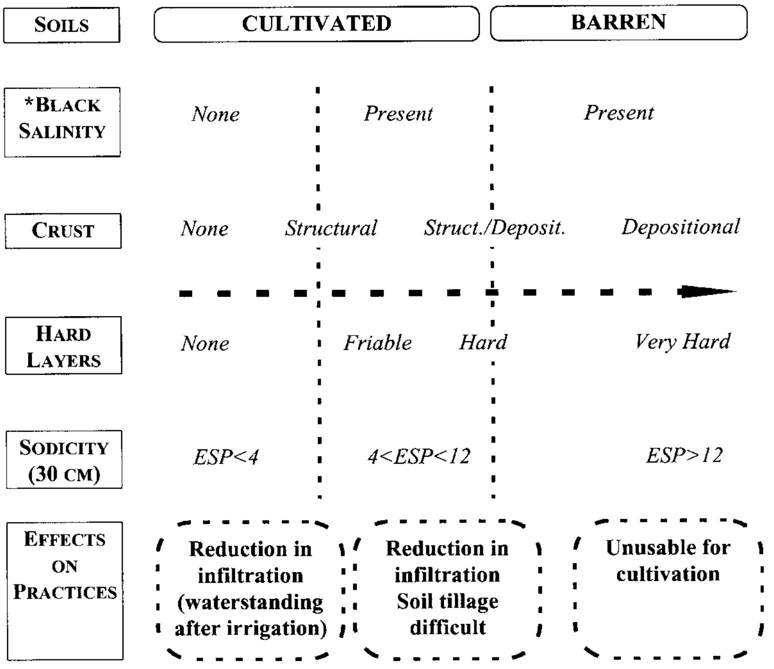


Figure 1. Indicator values and degradation states ordered in a general process of degradation

- Hard-setting of the soil deeper in the profile appears to take longer. While signs of crusting appeared within the course of an irrigation season, farmers noticed the occurrence of hard layers by some changes in soil tillage after several years of irrigation with water of constant (poor) quality.

The changes in degradation over time are illustrated in Figure 1.

Geochemical Aspects of Chemical Soil Degradation (Salinization/Sodification/Alkalinization Processes)

Identification of minerals in soils

In order to identify the minerals of importance to this study, saturation charts of calcite, sepiolite, gypsum and illite were considered. Because the concentration of silica was not available, illite and sepiolite was considered in equilibrium with amorphous silica.

The saturation charts of calcite and illite are shown in Figures 2a and 2b. They clearly indicate that most of the soil samples show chemical conditions in agreement with the assumption that both minerals are present and play a role in precipitation/dissolution processes.

In Figure 2c, a similar chart is shown for gypsum. All the soil samples except one are undersaturated with respect to gypsum. This indicates that gypsum does not play an important role in these soils. Because of frequent irrigation, we can assume that the high concentration necessary for gypsum precipitation cannot be reached. When soil samples were taken from barren fields, gypsum was found to be present in larger quantities. The gypsum-saturated soil sample has a higher concentration in all the solutes than the other soil samples. This implies that gypsum has precipitated.

The mineral precipitation involving magnesium is more difficult to appraise. Though it is not formed in these thermodynamic conditions, sepiolite is traditionally used to appraise the precipitation of magnesium. The presence of aluminium, the determination of which is difficult, makes the identification of this mineral difficult. The saturation chart of sepiolite is presented in Figure 2d. Although the results of the chart are not as straightforward as those of, for example, calcite, and other Mg silicate may precipitate, sepiolite is assumed to represent the main mineral explaining the precipitation of magnesium.

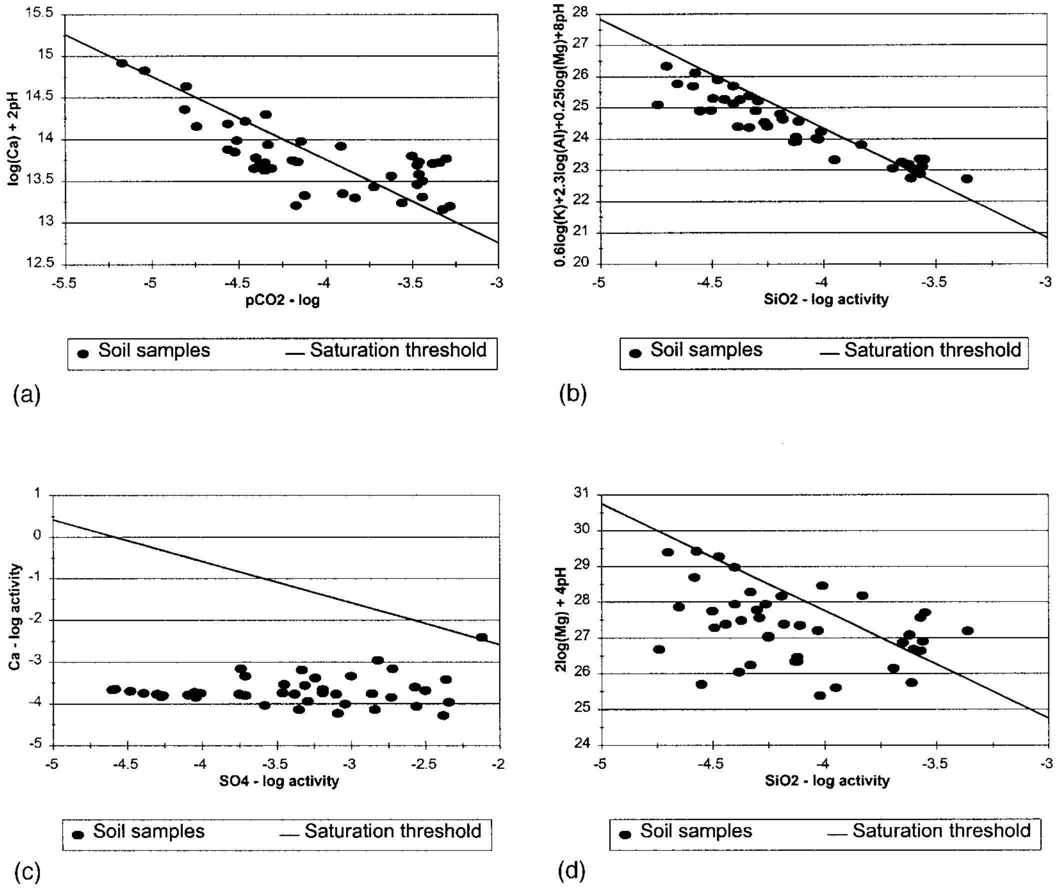


Figure 2. (a) Saturation chart for calcite; (b) saturation chart for illite; (c) saturation chart for gypsum; (d) saturation chart for sepiolite

Characterization of cations exchanges

Cations isotherms were established for three pairs of cations (Ca^{2+}/Mg^{2+}, Ca^{2+}/Na^{+}, Na^{+}/K^{+}). General exchange reaction between two cations writes as:

$$\mathrm{Soil} - bA + aB^{b+} \Longleftrightarrow Soil - aB + bA^{a+}$$

The equilibria are appraised by the selectivity coefficient (K_{GT}) (Gaines and Thomas, 1953):

$$K_{GT(A-B)} = \frac{(A)^b \cdot E_B^a}{(B)^a \cdot E_A^b}$$

where (A), (B): activities of the species A and B; a, b: valences of A and B; E_A, E_B: charge fractions of the adsorbed ions A and B. The charge fraction is defined as the ratio between the concentration in ion A adsorbed on the complex and the CEC (meq l^{-1}).

Based on the chemical analysis on the 15 soil samples collected in the area, the selectivity coefficients for the present study are calculated by linearization and calculation of the EFR. For the three pairs of cations, the results are the following ones:

$$\frac{E_{Na}}{\sqrt{E_{Ca}}} = 0{\cdot}6761{*}\left[\frac{(N_a)}{\sqrt{C_a}})\right]^{0{\cdot}867206}, \frac{E_{Ca}}{E_{Mg}} = 1{\cdot}118{*}\left[\frac{(C_a)}{(M_g)}\right]^{0{\cdot}953}, \frac{E_K}{E_{na}} = 6{\cdot}974{*}\left[\frac{(K)}{(Na)}\right]^{0{\cdot}804}$$

Characterization of the salinization processes (neutral salinization/alkalinization/sodification)

The soil samples were classified in two groups based on the sign of the RSC_{sw} value in order to appraise the different salinization pathways. RSC was selected for it, because most of the soils are saturated in calcite, which makes the calcite residual alkalinity indicator superfluous.

In the case of soils with negative RSC_{sw} values, the alkalinity is only slightly higher for soils with a high soil water concentration, whereas the concentration of chlorides is far higher (Figure 3a). Concentrations of calcium and magnesium are proportional to the chloride concentration up to a concentration factor of $10^{1{\cdot}5}$ (Figure 3b). We can thus assume that calcite and sepiolite are present and control the degree of alkalinity. Beyond $Fc = 10^{1{\cdot}5}$, gypsum is present in the soil solution: both sulphates and calcium are absorbed (Figure 3c). These soils typically represent the neutral pathway of the salinization process, a process of concentration where alkalinity is consumed through precipitation of calcite and sepiolite minerals ($RSC_{sw} < 0$). This is evidenced by the fact that the concentrations of calcium and magnesium remain high up to the point where gypsum precipitates.

In the case of soils with positive RSC_{sw} values and similar concentration levels, alkalinity is far higher than in the previous case, and even more so as the soil concentration is also high, see Figure 3d. Calcium and magnesium concentrations remain relatively low (Figure 3e). There is no evidence for the presence of gypsum in the soils even at high concentration levels (Figure 3f). These soils typically represent the alkaline pathway of salinization: calcite and sepiolite precipitate consuming calcium, magnesium and alkalinity. Since alkalinity is initially prevailing over the cations ($RSC_{sw} > 0$), cation concentrations in the soil solution are reduced and the saturation point of gypsum is never reached.

The results obtained from the soils samples classified by the RSC indicator are confirmed by the pH and ESP values as a function of the concentration. In the case of soils with $RSC_{sw} > 0$ both pH and ESP are considerably higher (Figures 4a and 4b). Both pathways of salinization cause sodification, but at similar concentration levels the ESP is higher in alkaline soils than in saline soils. The results obtained for the sample set, i.e. the identification and quantification of the geochemical processes (Figures 3a–3f), were confirmed in a separate study on 100 soil samples in the study area collected by the Soil Survey of Pakistan (1996) and analysed by Condom (1997).

Relationships Between Irrigation Water and Soil Geochemical Properties and Soil Degradation

Relationships between irrigation water quality and salinization processes

The model was used to assess the effect of different irrigation water qualities on the concentrations of different cations and anions, leading to soil salinity, alkalinity and sodicity. The qualities of four different irrigation waters were evaluated: canal water and that of three representative tube wells that are used by farmers in the study area. These tube wells were selected for their contrasting EC_{iw} and RSC_{iw} levels. SAR_{iw} was not taken into account because it is highly correlated to EC_{iw}; thus it is impossible to evaluate independently the influence of both of these parameters. The water qualities are listed in Table II. The model was run for two different soil types in order to assess the influence of the CEC.

The scenarios that were selected are presented in Table III.

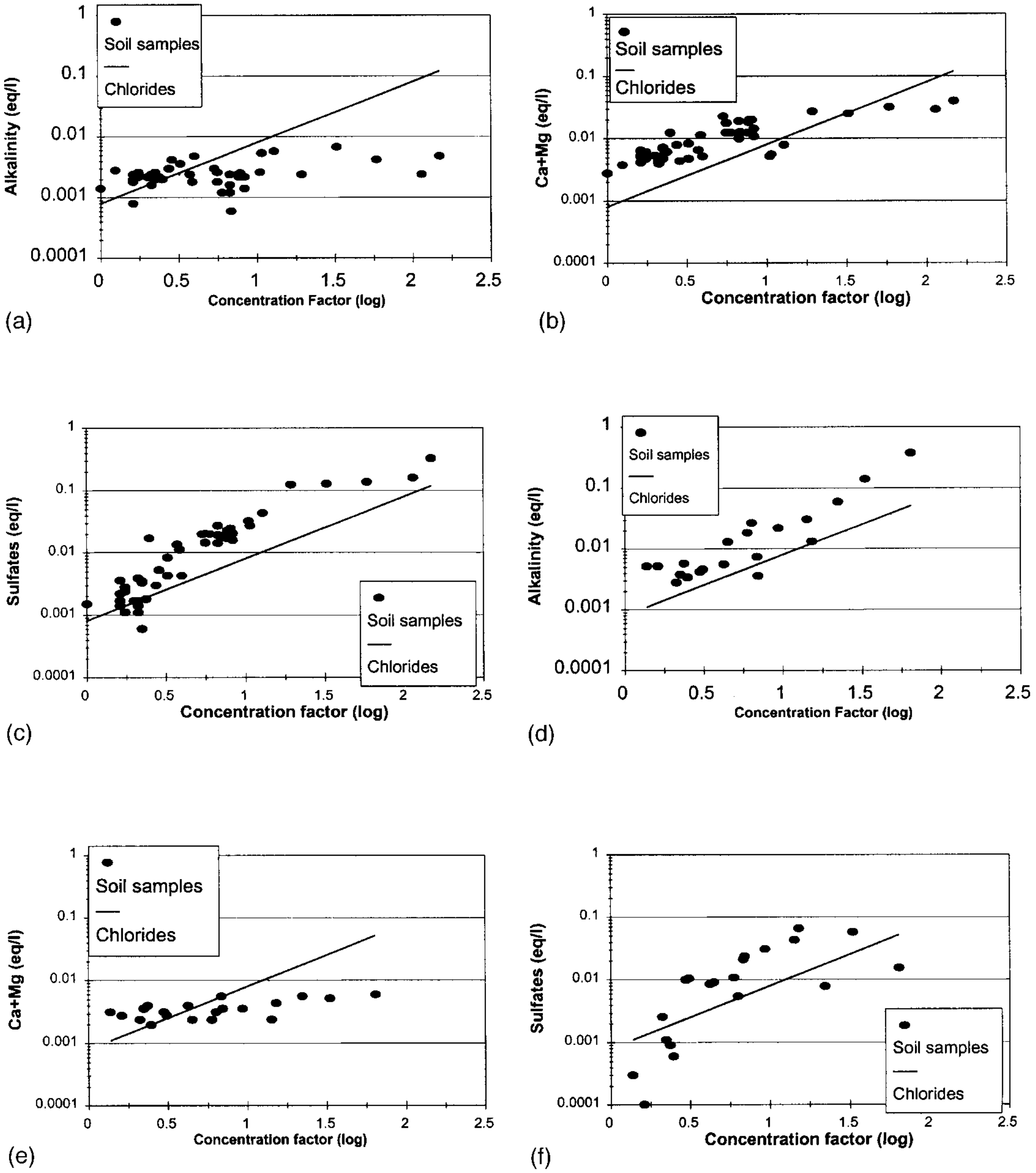


Figure 3. (a) Alkalinity related to the soil extract concentration level for soils characterized by negative RSC_s values; (b) calcium and magnesium concentration related to the soil extract concentration level for soils characterized by negative RSC_s values; (c) sulphates concentration related to the soil extract concentration level for soils characterized by negative RSC_s values; (d) alkalinity related to the soil extract concentration level for soils characterized by positive RSC_s values; (e) calcium and magnesium concentration related to the soil extract concentration level for soils characterized by positive RSC_s values; (f) sulphate concentration related to the soil extract concentration level for soils characterized by positive RSC_s values

Irrigation by canal water. Initial mixing between canal water and soil water results in a soil solution with a low concentration and a negative RSC_{sw} value. Thus, the concentration of cations increase in the concentration process, whereas alkalinity decreases, see Figures 5a and 5b. These trends characterize the neutral pathway of salinization with precipitation of calcite and sepiolite minerals. No soil sodification occurs, as

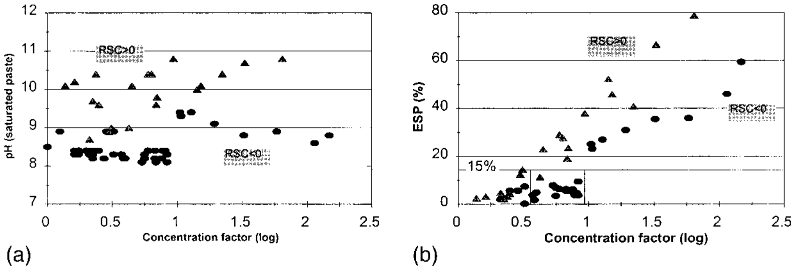


Figure 4. (a) pH paste related to soil extract concentration level; (b) ESP related soil extract concentration level

Table II. Soil and irrigation water qualities used for the geochemical simulations

	Soil A	Soil B	Canal (C)	Tube well 1	Tube well 2	Tube well 3
Concentrations* (meq l^{-1})						
Na	0·96	0·96	0·2	9·6	6·7	10·5
K	0·087	0·087	0·1	0·3	0·2	0·4
Ca	4·46	4·46	0·7	1·8	0·9	1·2
Mg	1·6	1·6	0·9	2·9	0·6	2·1
Cl	1·8	1·8	0·4	1·8	1	1·5
SO4	0·9	0·9	0·3	8·9	3·2	7·2
C-RA_{iw}	0	0	0·5	2	3·3	4·3
RSC_{iw}	−1·6	−1·6	−0·4	−0·9	+2·7	+2·2
CSG-RA_{iw}	−0·75	−0·75	−0·1	+8·08	+5·9	+9·4
SAR	0·6	0·6	0·2	6·3	7·7	8·2
EC_{iw} (dS/m)	1·0	1·0	0·2	1·4	0·8	1·3
Soil complex components (% CEC)						
Ca	69	69				
Mg	27	27				
Na	2	2				
K	2	2				
CEC (meq kg^{-1})	45	7·5				

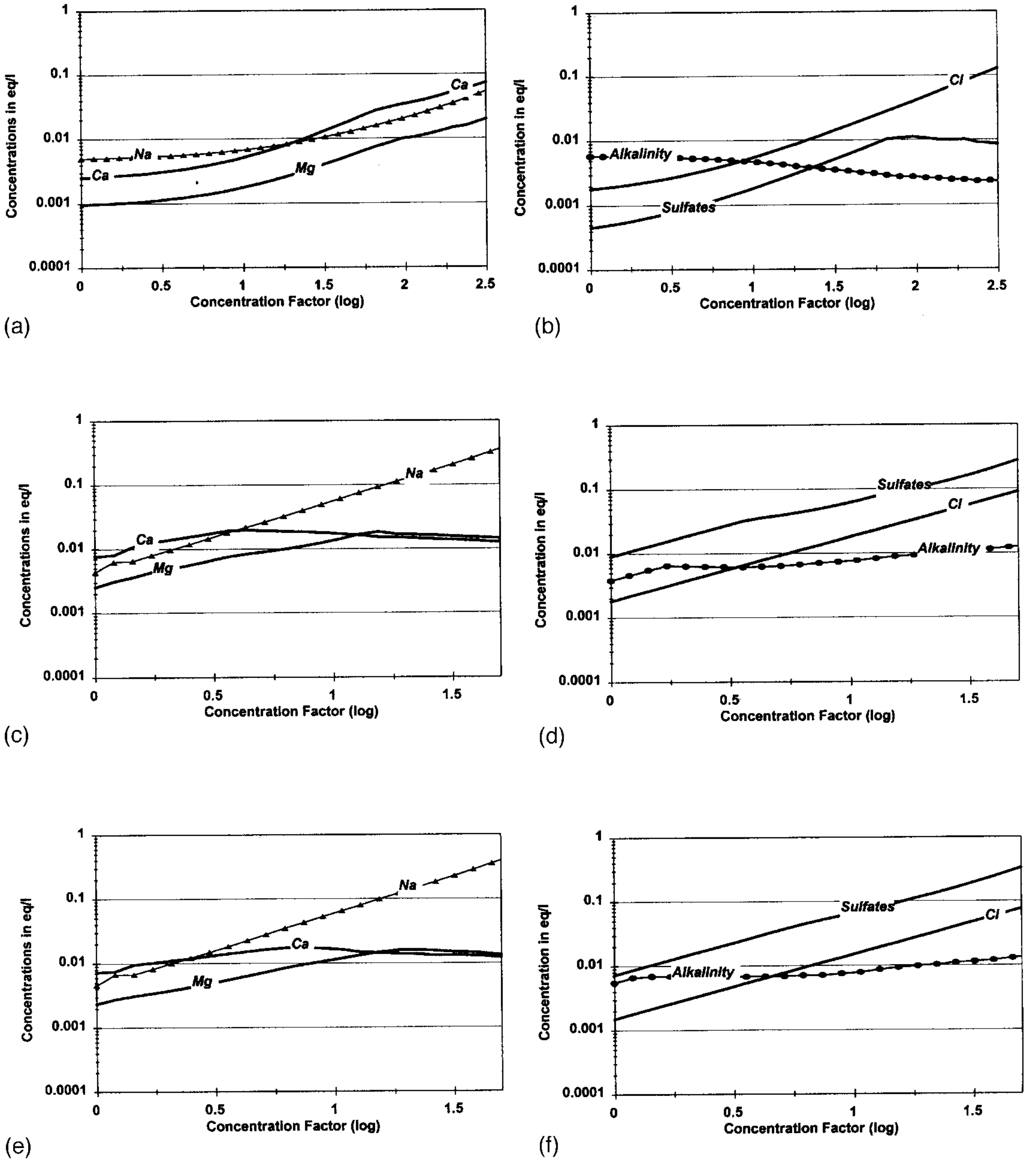
*All concentrations are given in meq l^{-1}, except the CEC (in meq kg^{-1}), which is converted in meq l^{-1} by considering a bulk density of 1·5 and a porosity of 41·6 per cent.

Table III. Scenarios for the geochemical simulations

Irrigation water	Soil A	Soil B
Canal	x	
Tube well 1	x	
Tube well 2	x	x
Tube well 3	x	

illustrated in Figure 6a. It is further found that no change in the trends of the chemical composition occurs once gypsum has precipitated. As indicated by the negative values of CSG-RA_{sw}, neutral soil salinization goes on without any signs of alkalinization.

Irrigation by tube-well waters: effect of RSC_{iw}. The effect of the sign and value of RSC_{iw} can be appraised by comparing the effects of tube well 1 ($RSC_{iw} = 0{\cdot}9$ meq l^{-1}) and tube well 3 ($RSC_{iw} = +2{\cdot}2$ meq l^{-1}), which have similar EC_{iw} and SAR_{iw} values, with opposite values of RSC_{iw}.



(a) (b) (c) (d) (e) (f)

Figure 5. (a) Trend of cations concentration through soil water concentration process – results of geochemical simulation (soil A, canal water); (b) trend of anions concentration through soil water concentration process – results of geochemical simulation (soil A, canal water); (c) trend of cations concentration through soil water concentration process – results of geochemical simulation (soil A, tube well 1); (d) trend of anions concentration through soil water concentration process – results of geochemical simulation (soil A, tube well 1); (e) trend of cations concentration through soil water concentration process – results of geochemical simulation (soil A, tube well 3); (f) trend of anions concentration through soil water concentration process – results of geochemical simulation (soil A, tube well 3)

Initial mixing between water of tube well 1 (C-RA$_{iw}$ > 0 RSC$_{iw}$ < 0) and the soil A (C-RA$_{sw}$ = 0, RSC$_{sw}$ < 0), results in negative C-RA$_{sw}$ and RSC$_{sw}$ values. The same observation on the trends of the main chemical components of the soil water can be made as in the scenario with canal water before gypsum precipitation (Figures 5c and 5d). Neutral salinization occurs but with higher concentration levels due to the

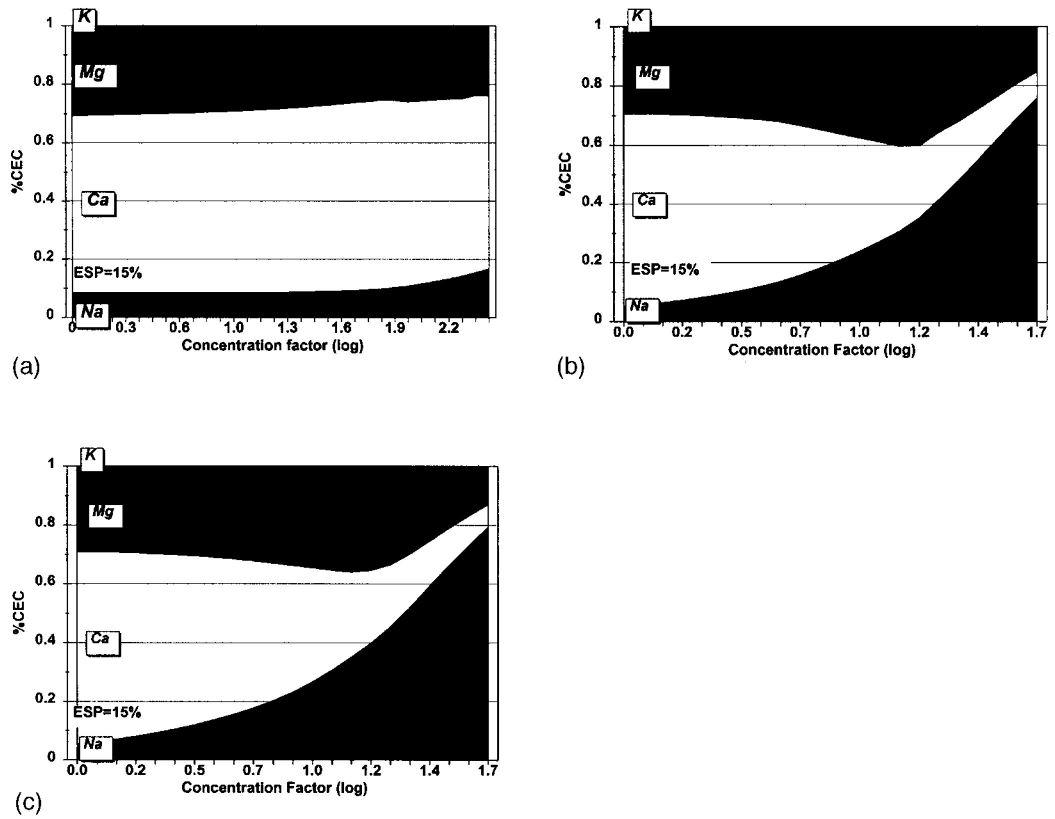


Figure 6. (a) Trend of the soil complex components through soil water concentration process – results of geochemical simulation (soil A, canal water); (b) trend of the soil complex components through soil water concentration process – results of geochemical simulation (soil A, tube well 1); (c) trend of the soil complex components through soil water concentration process – results of geochemical simulation (soil A, tube well 3)

higher EC_{iw} levels of tube well 1 than found in canal water. Because the water has a fairly high concentration, there are exchanges between the divalent cations of the soil complex and the sodium of the soil water. The divalent cations are subsequently absorbed in calcite, gypsum and sepiolite precipitation. Consequently, ESP increases rapidly, showing evidence of a sodification process (Figure 6b). In this case, because of the large amount of calcium released by the soil complex, and because of the high concentration of water in sulphates, the soil water becomes oversaturated in gypsum before sepiolite. When gypsum is present, alkalinization occurs as could be predicted by the negative initial positive CSG-RA_{sw} value, and sodification continues.

Initial mixing between water of tube well 3 (C-$RA_{iw} > 0$, $RSC_{iw} > 0$) values and soil ($RSC_{sw} < 0$) also results in negative C-RA_{sw} and RSC_{sw} values. Similarly to the previous case, when in contact with water with high concentrations of salts, the soil acts as a buffer by releasing divalent cations, which then become involved in mineral precipitation. This reduces the alkalinity and changes the sign of the RSC_{sw} (Figure 5e and 5f). In this simulation, sodification is more intensive (Figure 6c) because initial RSC_{sw} value is higher.

This comparison clearly shows that the sign and the value of RSC_{iw} cannot be used alone to appraise water salinization/alkalinization/sodification hazards, but has to be considered with regard to the buffer ability of the soil and thus to its texture.

Irrigation by tube-well waters: effect of salt concentration (EC_{iw}). The influence of the salt concentration can be appraised by comparing the effect of water of tube well 3 (C-$RA_{iw} > 0$, $RSC_{iw} > 0$, $EC_{iw} = 1{\cdot}3$ dS

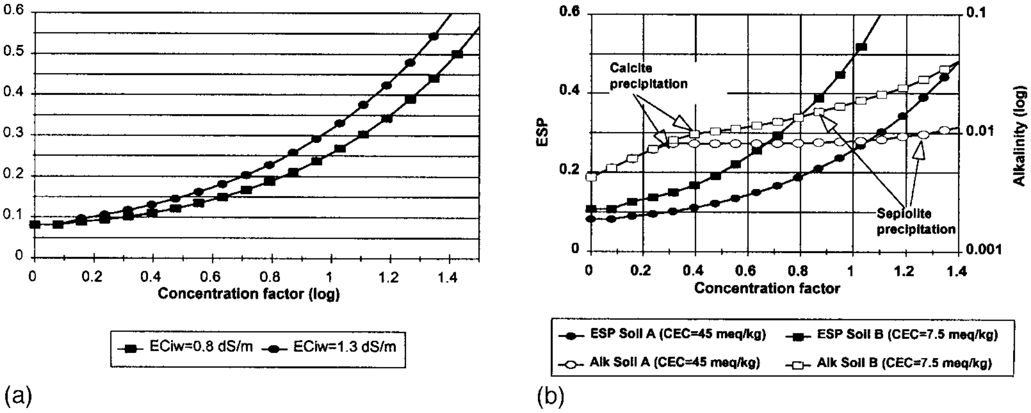


Figure 7. (a) Effect on EC_{iw} on the soil sodification process; (b) effect of texture on the alkalinization process

m^{-1}) and tube well 2 ($C\text{-}RA_{iw} > 0$, $RSC_{iw} > 0$, $EC_{iw} = 0{\cdot}8$ dS m^{-1}) on the salinization, alkalinization and sodification processes. The results of the simulations, depicted in Figure 7a, show the impact of the initial concentration of the irrigation water on the processes. Neutral salinization and the resulting sodification is all the more rapid with increasing concentrations of irrigation water.

Influence of soil texture. In order to assess the influence of soil texture, the water of tube well 2 was applied to soil A ($CEC = 45$ meq kg^{-1}) and soil B ($CEC = 7{\cdot}5$ meq kg^{-1}). Regarding the alkalinity trend, once calcite precipitates, the alkalinity increases in the case of coarse-textured soil, whereas it is kept constant for the fine-textured soil (Figure 7b). It indicates that, in the first traject of the water concentration process – the ability for a soil to lower or stop the alkalinization process by releasing divalent cations – it is all the more important that the CEC is high. In the further traject, once sepiolite precipitates, alkalinization occurs for both of the soils. Regarding the sodification, the Figure 7b illustrates that the sodification rate is far higher in the case of the coarse-textured soil.

Conclusion on water quality characterization with regard to the salinization, alkalinization and sodification processes. Modelling of the geochemical processes allows us to assess the water and soil characteristics with respect to the types and intensity of the salinization process that can take place. The concentration and chemical composition of the irrigation water were shown to affect soil sodicity. The soil can act as a buffer to mitigate the effects. Thus, three indicators appear relevant to appraise the soil and water characteristics: the electrical conductivity of irrigation water (EC_{iw}), the residual alkalinity of the irrigation water (RSC_{iw} and $CSG\text{-}RA_{iw}$) and the CEC of soil.

Based on the simulations, some keys for a classification of water salinity/sodicity and alkalinity hazard* can be suggested. Two cases can be distinguished with regard to soil texture: firstly, coarse-textured soils with CEC of 7·5 meq kg^{-1} (Table IV) and secondly, medium-textured soils with CEC of 45 meq kg^{-1} (Table V).

The type of salinization process caused by irrigation water depends highly on the texture of the soil, which determines its ability to act as a buffer by releasing sodium and neutralizing alkalinity. In the case of medium- to fine-textured soils, irrespective of the sign of RSC_{iw}, water will cause sodification (at different levels) through neutral salinization in the first steps of the concentration process and then by alkalinization. In the case of coarse-textured soils, water with a positive RSC_{iw} and medium EC_{iw} will cause sodification through alkalinization.

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*This hazard is defined as the critical limits beyond which there is a risk for salinisation, sodification or alkalinisation.

Table IV. Indicators to appraise neutral salinization, alkalinization and sodification hazards of irrigation water applied on coarse-textured soils (CEC = 7·5 meq kg^{-1})

	EC_{iw} very low (0·2 dS m^{-1})	EC_{iw} medium (0·8 dS m^{-1})	EC_{iw} high (1·4 dS m^{-1})
$RSC_{iw} < 0$	*Low neutral salinization* *No sodification*	Neutral salinization Low sodification	*Neutral salinization* *Sodification*
$RSC_{iw} > 0$		Alkalinization Sodification	*Neutral salinization* *High sodification*

Note: In italic: results of simulations not presented here.

Table V. Indicators to appraise neutral salinization, alkalinization and sodification hazards of irrigation water applied on medium-textured soils (CEC = 45 meq kg^{-1})

	EC_{iw} very low (0·2 dS m^{-1})	EC_{iw} medium (0·8 dS m^{-1})	EC_{iw} high (1·4 dS m^{-1})
$RSC_w < 0$	Low neutral salinization No sodification		Neutral salinization Sodification
$RSC_w > 0$		1*-neutral salinization/low sodification, 2*-alkalinization/ sodification	1-neutral salinization/high sodification; 2-alkalinization/high sodification

*: 1- and 2- refer respectively to the first traject of the concentration process (soil water saturated with regard to calcite and undersaturated with regard to sepiolite) and advanced traject (soil water saturated both with regard to calcite and sepiolite).

The importance of sodification depends on the irrigation water characteristics: the higher the EC_{iw} is, the more sodic the soil becomes; in the case of high EC_{iw}, the rate of sodification increases with the height of the RSC_{iw} value.

For soils with a high concentration of salts, when gypsum can show up, the sign of CSG-RA has to be considered instead of RSC. Analytical results showed, however, that gypsum was very rarely present in cultivated fields, and we will not consider this issue further.

Relationships between soil geochemical properties and physical degradation

The ESP of the soils that were studied was calculated from the SAR Values measured in 1 : 1 soil extracts of soil samples taken at the soil surface and at 30 cm depth. The soils were split into three groups: non-crusty soils; soils covered by structural crust; and soils covered by depositional crust. The samples were classified in order of increasing concentration.

Figure 8a shows clearly that the ESP on the surface is not relevant in distinguishing degraded from non-degraded soils. However, the ESP measured at 30 cm depth appears to be a good indicator of possible sodicity and degradation level (Figures 8b and 8c). The electrical conductivity (dilution 1 : 1) is higher in crusty soils, which indicates that degradation is linked with a process of soil water concentration. RSC and pH in situ are not relevant as indicators for soil degradation.

It can be noted that degradation may occur at relatively low sodicity levels. Because of their coarse texture, the soils in this area may be degraded quickly. Such observations have already been made on Indian soils with similar texture characteristics and for Australian soils (Ramadan, *et al*., 1993; So and Aylmore, 1993). Moreover, the presence of illites in these soils may argue for a higher susceptibility to degradation (Oster, *et al*., 1980). Finally, wetting such sodic soils with good-quality water, e.g. canal water or rain, may cause dispersion even at low ESP levels (Quirk and Schofield, 1955; Shainberg, *et al*., 1981; Agassi, *et al*., 1981;

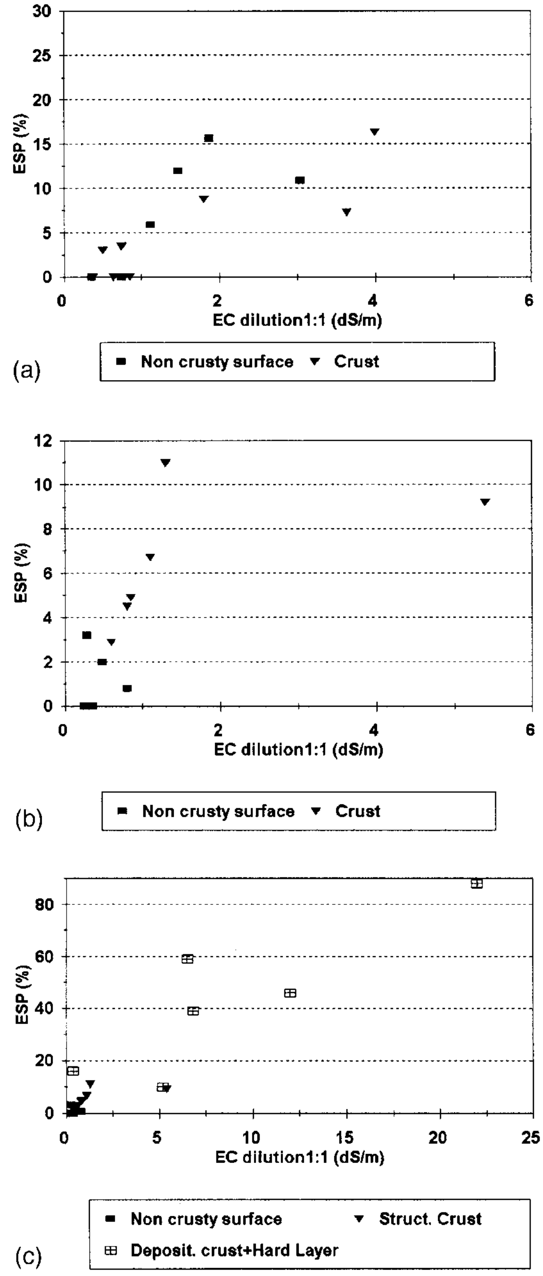

Figure 8. (a) Comparison of sodicity level at top-surface between non-crusty and crusty soils; (b) comparison of sodicity level at 30 cm depth between non-crusty and crusty soils; (c) comparison of sodicity level at 30 cm depth for soils with different types of structural degradation

Rengasamy, *et al.*, 1984; Crescimanno, *et al.*, 1995). Parallel studies in the study area showed a significant detrimental effect of sodicity on the yield of cotton, caused by difficulties at the germination stage of the cotton seeds, which, in turn, are due to the loss of soil structure in combination with aeration problems due to infiltration problems (ponding of water) (Meerbach, 1996).

CONCLUSIONS

Irrigated soils in Punjab display a considerable range of chemical characteristics that result from the diversity in the origins and qualities of the irrigation water. The use of tube-well waters of varying quality has resulted in a variety of contrasting situations in soils that are threatened now by neutral salinization, alkalinization and sodification at different levels of concentration and by degradation of their structure. However, this considerable diversity also offers opportunities, because it allows several types of irrigation management and thus different options for a better salinity/alkalinity/sodicity management and soil reclamation. The relationships determined in this study between water quality, salinization, sodification, alkalinization and land degradation can help irrigation managers in better defining the allocation of good-quality canal (river) water to those areas threatened by soil degradation, i.e. those areas faced with poor-quality groundwater, that is used for irrigation through tube wells. A judicious allocation of this water would help farmers to avoid problems of salinity and sodicity and mitigate the latter's effects on soil degradation and agricultural production.

Soil degradation was shown to occur at levels of ESP as low as 4 per cent, which confirms earlier observations in Australia. However, in Pakistan the old standards of the US Department of Agriculture, which determined an ESP of 15 per cent as a critical limit for soil degradation, are still the reference adopted by government departments and researchers. It is recommended that a study is carried out by the national research centres to validate the risk of land degradation due to the application of poor-quality groundwater for larger areas in Pakistan. The study should be conducted in collaboration with the extension agencies to ensure that the results will be useful for farmers in Pakistan. Indicators such as electrical conductivity, the residual alkalinity and soil texture that is irrigated will need to be established. The effect of irrigation practices should be studied taking into account water quality, water quantity and frequency of the water supply. The modelling approach that was used here for geochemical processes can be extended to water flow, solute transport and physical degradation processes, and then be used to follow the soil processes over time during the cropping seasons and along a soil profile. If such coupled hydrogeochemical models exist and have already been used in some places (Simunek and Suarez, 1994; Marlet, 1996; Condom, 1997), their validation in situ remains one of the major objectives to achieve in future. Such a validation would have to comprise the following steps: firstly, the calibration based on soil chemical analysis (characterization of the minerals and of the exchanges) and studies of soil hydrodynamic properties; secondly, a sensitivity test of the different parameters of the processes; thirdly, the monitoring of conditions through an experimental set-up (e.g. undisturbed soil columns) and collection of hydrogeochemical data; fourthly, a comparison of simulated and observed data: error analysis; and, finally, a test of the model in field.

ABBREVIATIONS

Ca: calcium cation
CEC: cationic exchange capacity (eq $\mathrm{kg}^{-1}_{\mathrm{Soil}}$)
C-$\mathrm{RA}_{\mathrm{sw}}$: Calcite residual sodium carbonates of soil water (eq l^{-1})
C-$\mathrm{RA}_{\mathrm{iw}}$: Calcite- residual sodium carbonates of irrigation water (eq l^{-1})
CSG-$\mathrm{RA}_{\mathrm{iw}}$: Calcite-sepiolite-gypsum residual alkalinity of irrigation water (eq l^{-1})
CSG-$\mathrm{RA}_{\mathrm{sw}}$: Calcite-sepiolite-gypsum residual alkalinity of soil water (eq l^{-1})
E_A (E_B): charge fraction of the adsorbed cation A (B), defined as the ratio between the cation concentration and the CEC
EC_{e}: Electrical conductivity of soil extract in dS m^{-1}: dilution levels 1 : 1 or 1 : 2·5 are given in the text
$\mathrm{EC}_{\mathrm{iw}}$: Electrical conductivity of irrigation water (dS m^{-1})
EFR: Exchangeable fraction ratio
ESP: Exchangeable sodium percentage (per cent)
K: Potassium cation

K_{GT}: Selectivity coefficient (Gaines and Thomas, 1953)
K_s: Solubility product
Mg: Magnesium cation
Na: Sodium cation
Q: Ionic product
RA: Residual alkalinity (eq l^{-1})
RSC_{sw}: Residual sodium carbonates of soil water (eq l^{-1})
RSC_{iw}: Residual sodium carbonates of irrigation water (eq l^{-1})
SAR: Sodium Adsorption Ratio (eq $l^{-1})^{0.5}$

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