

REPORT NO. C-7

11M/
631.7.S
6730
VAN

**Soil Salinity and Sodicty in Relation to
Irrigation Water Quality, Soil Type and Farmer Management**

Consultancy Report

by

**J.C. van Dam
Wageningen Agricultural University
Department of Water Resources
Wageningen, The Netherlands**

and

**M. Aslam
Pakistan National Program
International Irrigation Management Institute
Lahore**



**April 1997
PAKISTAN NATIONAL PROGRAM
International Irrigation Management Institute
Lahore**

H 9200

TABLE OF CONTENTS

List of Annexes	ii
List of Figures	ii
List of Tables	iii
Summary	iv
1. Introduction	1
2. Physical and chemical processes at salinization and sodication	2
2.1 Concentration	3
2.2 Precipitation	5
2.3 Association	6
2.4 Adsorption	6
2.5 Sodication	7
2.6 Criteria for water and soil quality in Pakistan	7
3. The simulation models LEACHM and UNSATCHEM	8
3.1 The LEACHM model	9
3.2 The UNSATCHEM model	10
4. Measurements in Chishtian Subdivision	13
5. Simulation of salinization and sodication processes during the growing season	16
5.1 Input	16
5.2 Simulation results	18
5.2.1 The reference situation	18
5.2.2 Fallow period during kharif	22
5.2.3 Application of gypsum	23
6. Simulation of the sodication rate	23
7. Most sensitive input parameters for sodication simulation	25
8. Conclusions and recommendations	29
References	30

List of Annexes

Annex A	General input file UNSATCHEM for the reference simulation (Par 5.2.1).	33
Annex B	Top boundary fluxes applied in UNSATCHEM for the reference simulation (Par. 5.2.1).	34

List of Figures

1.	Interactive chemical reactions in the soil water system (Tanji, 1990).	2
2.	Relationships between EC_e , EC_{iw} and leaching fraction under conventional irrigation management (Rhoades et al., 1992).	3
3.	Saturation of a mineral AB, illustrating the 'T-law'; A and B represent concentrations, (A) and (B) represent activities (Marlet, 1996).	5
4.	Volumetric water content profiles of the reference situation at five times of the year.	18
5.	Calcium concentration profiles in the soil water of the reference situation at five times of the year.	19
6.	EC_{sw} profiles of the reference situation at five times of the year.	20
7.	SAR profiles of the reference situation at five times of the year.	21
8.	EC_{sw} profiles at five times of the year in case the field is fallow during the kharif season.	22
9.	SAR profiles at five times of the year in case the field is fallow during the kharif season.	23
10.	SAR profiles in case of the reference (no gypsum) and when gypsum is applied; June 1 and January 1 correspond to 5 and 12 months after gypsum application.	24
11.	Sodium profiles over a 10 year period, due to a change from canal water to tubewell water for irrigation.	25

12.	<i>SAR</i> profiles over a 10 year period, due to a change from canal water to tubewell water for irrigation.	25
13.	Ca profiles after long term irrigation (9 years) in case of five scenarios.	26
14.	Na profiles after long term irrigation (9 years) in case of five scenarios.	27
15.	<i>SAR</i> profiles after long term irrigation (9 years) in case of five scenarios.	28

List of Tables

1.	Irrigation water quality criteria as used by WAPDA.	8
2.	Soil quality criteria derived from USDA (1954).	8
3.	Comparison between the simulation models LEACHM and UNSATCHEM.	12
4.	Average rainfall and potential evapotranspiration of the period 1951 - 1970 (SSP and IIMI, 1996).	13
5.	Measured water qualities of canal water in Chishtian Subdivision (C) tubewell water of Mr. Yaqoob (T1), and the average of tubewell waters at 5 watercourses (T2-T6).	14

Summary

In Pakistan, tubewells are increasingly used for irrigation. Although irrigation by tubewells has large advantages, especially in areas with a lack of canal water, the water quality of many tubewells in the Punjab may also cause serious problems. At many tubewells, sodium is the main ion, which may result in sodication and serious soil degradation of irrigated fields. This study explores the use of simulation models to analyse the physical and chemical processes that occur when tubewell water of bad quality is used. The main physical and chemical processes regarding salinization and sodication are briefly discussed. Two selected models, LEACHM and UNSATCHEM, are highlighted. Of these two, UNSATCHEM includes more processes that affect sodication and the model is more user-friendly. Simulations with UNSATCHEM are performed for the Chishtian Subdivision in South Punjab. When using tubewell water, sodicity, rather than salinity, is shown to be the problem. Water qualities of some tubewells is such that, within one year, serious degradation of the top soil can be expected. Data collection should focus on ion speciation of the tubewell water, the leaching fraction, and measurement of *SAR* values in soils with different sodicity status. Both LEACHM and UNSATCHEM seem very useful to interpret and generalize measured data and evaluate management options for Pakistani conditions.

Chapter 1 Introduction

In February 1995, a workshop was held in Lahore to discuss the current status of salinity and sodicity research in Pakistan. As the chairman, Dr. Kijne, noted, this workshop became necessary due to the changing environment of irrigated agriculture in Pakistan. These changes concern the development of private tubewells, doubling of cropping intensities compared with system design, decline in quality of tubewell water, no or limited access to canal water in many distributary tail ends, stagnant yields of wheat, rice and cotton, SCARP transition, poor maintenance of drains, possible privatization of parts of distributary commands (e.g. of maintenance), and competing demands for water from urban and industrial expansion (IIMI, 1995).

Especially, increasing use of tubewells has changed the irrigation environment. The advantages are evident for the farmer, as tubewells allow irrigation at times and with amounts as desired by the farmer. Especially in areas with insufficient canal water, use of tubewell water seems profitable. A side effect of the extraction of groundwater by tubewells is a decrease of groundwater levels, which is positive in areas where fields are waterlogged or salinized due to capillary rise from shallow groundwater (IWASRI, 1991). However, despite the advantages, serious concerns exist on the long term effects of irrigation with tubewell water. The salt amounts and ionic composition of the salts of most tubewells water are such that salinization and especially sodication of many fields will occur.

At the earlier mentioned workshop in Lahore, Dr. Chaudhry summarized the research achievements so far of the 25 organizations in Pakistan that currently are engaged in salinity/sodicity research:

- leaching of soluble salts has been studied;
- the efficiency of chemical amendments (e.g. gypsum) has been determined;
- biotic reclamation is receiving attention;
- identification of crops tolerant to waterlogged, saline and sodic conditions;
- reclamation and management of salt affected soils through an integrated approach of irrigation management and drainage facilities;
- in-situ determination of soil salinity through new technologies, like EM-38; and
- and screening and introduction of salt tolerant crop varieties.

Two of the main deficiencies identified in the discussions were knowledge and analysis of the soil chemical processes that result in sodication, and application of general, experimental data to site specific salinity/sodicity management issues. A useful tool to help solving both problems is a simulation model that incorporates the relevant physical, chemical and biological factors affecting the sodication process. Recently, users-friendly models have become available that simulate these processes with confidence and that can be used as a tool to analyse sodication management problems. This report describes the application of one of these models, the UNSATCHEM model, to salinization/sodicication issues in the Chishtian Subdivision in southeastern Punjab Province.

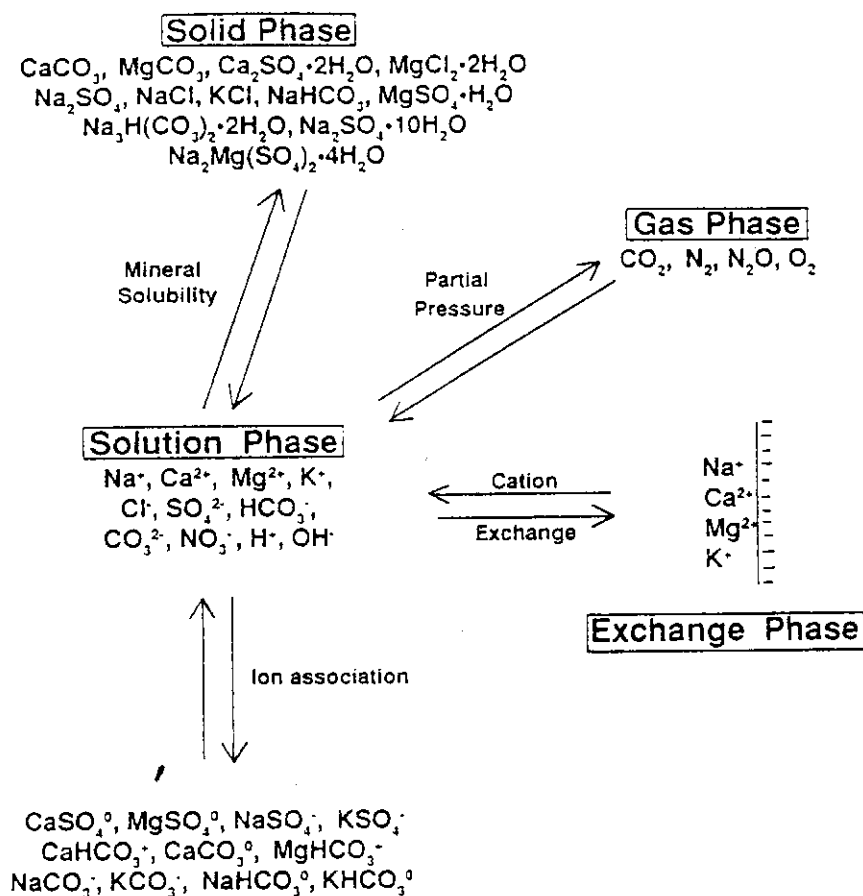


Figure 1. Interactive chemical reactions in the soil water system (Tanji, 1990).

In the soil water system, complex chemical reactions take place between the soil solution, exchange phase, solid phase and gas phase. Figure 1 shows the main chemical reactions and ions in salty soils. The irrigation water will concentrate in the soil profile due to water extraction. At higher concentrations some ions precipitate. Simultaneously, ions are exchanged between the soil water solution and exchange phase, and ion associations are formed. The next paragraphs will briefly discuss these processes of ion concentration, precipitation, association, and adsorption. Also, the characteristics of the sodication process are highlighted. Finally, the criteria of irrigation and soil water quality as applied in Pakistan are mentioned.

2.1 Concentration

Salinity usually refers to the total dissolved concentration of major inorganic ions (i.e. Na, Ca, Mg, K, HCO_3 , SO_4 and Cl) in irrigation, drainage and groundwaters. Individual concentrations of these cations and anions in a unit volume of water can be expressed on a chemical equivalent basis, meq/l, or on a mass basis, mg/l. Total salt concentration (i.e. salinity) is then expressed either in terms of the sum of either the cations or anions, in meq/l, or the sum of cations plus anions, in mg/l. A practical index of salinity is electrical conductivity EC , expressed in units of deciSiemen per metre (dS/m). An approximate relation (because it also depends upon specific ionic composition) between EC and total salt concentration is $1 \text{ dS/m} = 10 \text{ meq/l} = 700 \text{ mg/l}$ (Rhoades et al., 1992).

Salinization denotes the gradual increase of inorganic ions in soils, which might be caused by the use of salty irrigation water, insufficient leaching of irrigated soils, and/or capillary rise from salty groundwater. Extraction of soil water by plant roots and/or

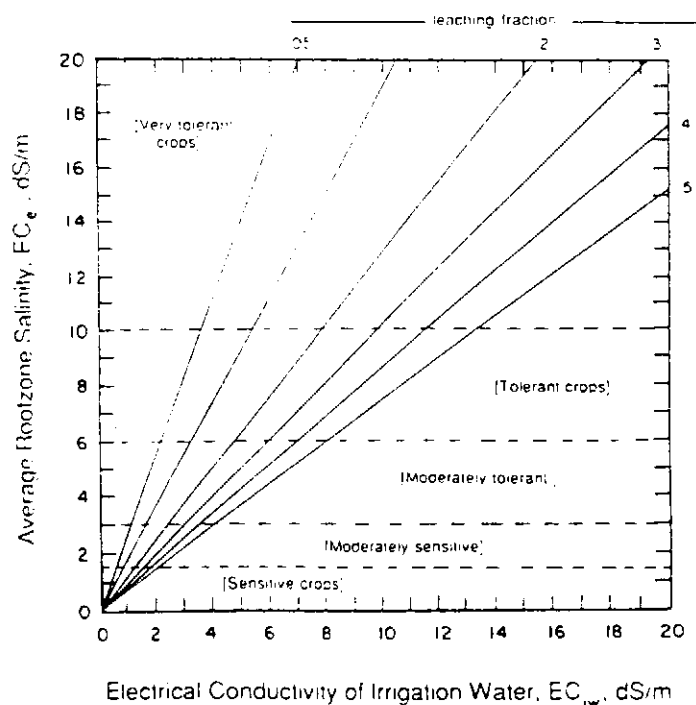


Figure 2. Relationships between EC_e , EC_w and leaching fraction under conventional irrigation management (Rhoades et al., 1992).

evaporation of soil water at the soil surface will increase the salinity of the remaining soil water. In case of irrigation, the salinity concentrations, in general, increase with depth, while in case of fallow fields, or fields with shallow groundwater tables, the highest salinity concentrations will be found in the top soil. Figure 2 shows the average root zone salinity as a function of EC_{iw} of the irrigation water and the leaching fraction LF . In case of $LF = 0.10$, which is supposed to be the case in many irrigated fields in the Chishtian Subdivision, the average root zone salinity is about twice as large as EC_{iw} .

Salinity increases the energy that plant roots need to extract soil water due to higher osmotic potentials in the soil root zone. In case of high salinity levels, plants will start to close the stomata in order to reduce the transpiration rate. When the stomata are closed, the oxygen level in the leaf rises, while the carbon dioxide level in the leaf drops. The photosynthesis process will stop and no assimilation products are formed. The reduction of crop yield is usually related to the EC_e of the soil water by:

$$Y_r = 100 - b(EC_e - a) \quad (1)$$

where Y_r is the percentage of the yield of the crop grown under saline conditions relative to that obtained under non-saline, but otherwise comparable conditions (-), a is the threshold salinity value (dS/m) and b is the percentage yield decrement per unit increase of the salinity in excess of the threshold. Values of a and b for many crops are listed by Maas and Hoffman (1977) and Maas (1990).

Currently, available simulation models employ the salinity concentration calculated at each depth in the root zone to derive the reduction of root water uptake at each depth. The reduction is based either directly on the salinity concentration in the soil water EC_{sw} (dS/m), similar to Eq. (1), or on the osmotic head h_{osm} (cm), which is caused by the salinity. In the range $3 < EC_{sw} < 30$, the osmotic head h_{osm} (cm) can be derived from the EC_{sw} (dS/m) by :

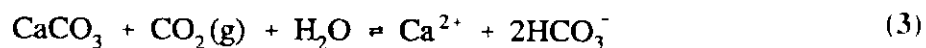
$$h_{osm} = -360 EC_{sw} \quad (2)$$

Generally, plants are more sensitive to osmotic stress during emergence and early seedling stages of growth and are most tolerant during germination. Most salt tolerance levels on salinity apply to later stages of plant growth. If salinity levels reduce plant stand (as it commonly does), potential yields will be decreased far more than predicted by literature salt tolerance data (Rhoades et al., 1992).

While the primary effect of soil salinity on herbaceous crops is one of retarding growth, as discussed above, certain salt constituents are specifically toxic to some crops. Boron is such a solute and, when present in the soil solution at concentrations of only a few mg/l, is highly toxic to susceptible crops. For some crops, especially woody perennials, sodium and chloride may accumulate in the tissue over time to toxic levels that produce foliar burn. Tolerance levels for boron and chloride are given by Rhoades et al., (1992).

2.2 Precipitation

Concentration of the soil water solution may lead to precipitation of ions, while dilution, e.g. in case of rainfall or irrigation with water with low ion concentrations, may result in dissolution of ions from the solid phase. A dynamic equilibrium exists between the ion concentrations in the soil water and the precipitates. In case of calcite or lime, which is one of the first solids formed upon concentration of many irrigation waters, the chemical equilibrium reaction is described by:



with the constant K_c (-) for the solubility product:

$$K_c = (\text{Ca}^{2+})(\text{CO}_3^{2-}) \quad (4)$$

where the parentheses denote ion activity.

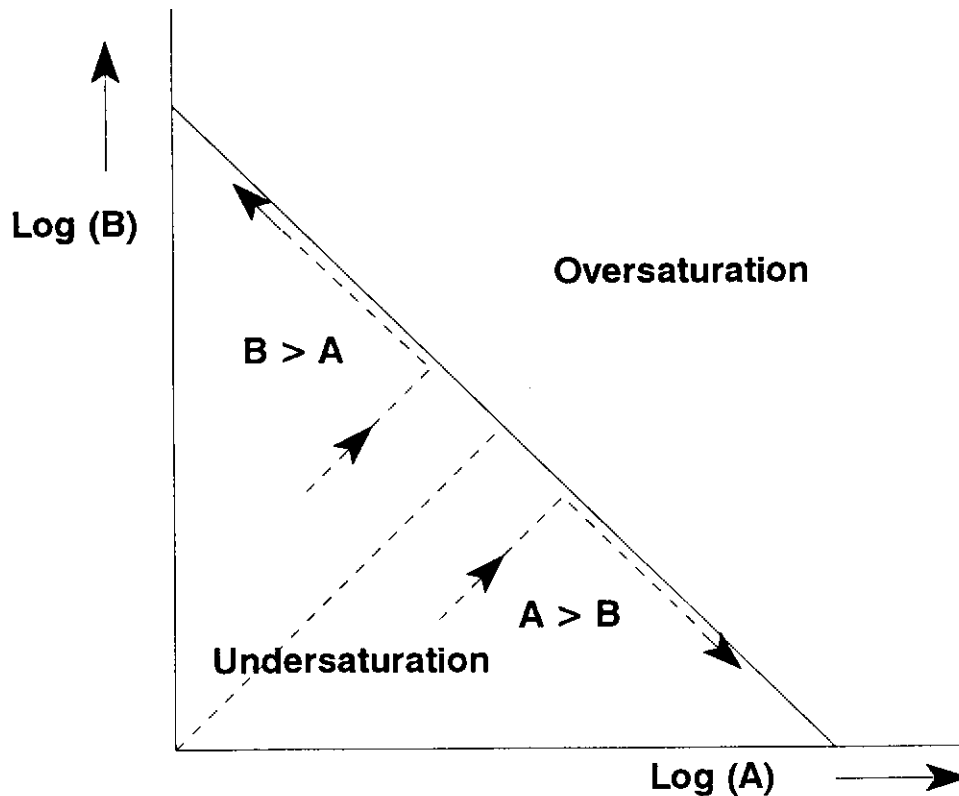


Figure 3. Saturation of a mineral AB, illustrating the 'T-law'; A and B represent concentrations, (A) and (B) represent activities (Marlet, 1996).

Let us consider a soil water solution which is undersaturated with the ions A^+ and B^-

(Fig. 3). Upon concentration of the soil water solution, the two ions concentrate simultaneously, until the solubility product reaches its maximum value K_{AB} :



If more water is extracted from the solution, the mineral AB is formed while the solubility product $(A^+)(B^-)$ stays constant. In case (A^+) is equal to (B^-) , both concentrations stay the same during water extraction. However, if the concentrations are unequal, the largest concentration will increase further, while the smallest concentration decreases, as shown in Fig. 3. This mechanism is known as the 'T-law'. The rapid decrease of the smallest ion concentration during water extraction has large consequences in case of Ca^{2+} and CO_3^{2-} , as discussed in Par. 2.5.

2.3 Association

Ion association (Fig. 1) increases when the ion concentrations in the soil water increase. Chemical equilibria and reaction constants similar to Eq. (4) are valid.

2.4 Adsorption

The exchange phase is a transition zone between the predominantly negatively charged clay minerals and organic matter and the soil water solution. The cations in the soil water are attracted or adsorbed to the clay minerals and organic matter, while the anions in the soil water are repulsed. The sum of the anions and cations in this exchange phase (meq/l) will be equal to the negative charge of the clay minerals and organic matter (meq/l), and is called the cation exchange capacity, *CEC*. The concentration of the adsorbed cations depends on the ionic composition of the soil water, and might be described by the Gapon equation. In case of the dominant cations Na^+ and Ca^{2+} , the Gapon equation reads:

$$K_G = \frac{[Ca^{2+}]^{1/2}}{[Na^+]} \frac{[NaX]}{[CaX]} \quad (6)$$

where $[Ca^{2+}]$ and $[Na^+]$ are the ion concentrations in the soil water (mmol/l) and $[CaX]$ and $[NaX]$ are the adsorbed concentrations (meq/kg soil) and K_g is the Gapon constant (mmol/l)^{-1/2}. A much used value of K_g is 0.015 (mmol/l)^{-1/2}. Similar equations can be derived for the combinations Ca^{2+}/Mg^{2+} and Mg^{2+}/Na^+ .

The thickness of the transition layer, which is also called diffuse double layer, depends on the valence of the cations and the ion concentration of the soil water solution. At larger valence (Ca^{2+} instead of Na^+) the thickness becomes smaller. Also, larger ion concentrations in the soil water result in thinner diffuse double layers. The thickness of the diffuse double layer has important consequences for the stability of soil aggregates, as discussed in the next paragraph.

2.5 Sodication

Sodication refers to an increase of Na with respect to Ca and Mg in the soil water solution and thus in the exchange phase. This will increase the thickness of the diffuse double layer, especially when the ion concentrations in the soil water are relatively low. A larger diffuse double layer weakens the chemical bonds between the clay platelets and organic matter. Individual clay platelets or organic particles may release from aggregates or aggregates may break down into smaller aggregates. The density of the soil increases and permeability and tilth properties are negatively affected. Repulsed clay platelets or small aggregates can lodge in the pore network, which further decreases the permeability.

A commonly used measure for the sodication risk is the Sodium Adsorption Ratio *SAR* (mmol/l)^{1/2}:

$$SAR = \frac{[Na]}{[Ca + Mg]^{1/2}} \quad (7)$$

where total analytical concentrations are used (mmol/l), with no account of ion association.

Also, the Exchangeable Sodium Percentage *ESP* (%) can be used:

$$ESP = 100 \frac{[NaX]}{CEC} \quad (8)$$

One of the causes of high *SAR* and *ESP* values in soils is the small solubility product ($Ca^{2+})(CO_3^{2-})$, which for irrigation water upon concentration in the root zone may lead to precipitation of $CaCO_3$. If the concentration of Ca in the soil water is less than the concentration of CO_3^{2-} , Ca will decrease rapidly according to the "T-law" (Fig. 3). The amount of Ca^{2+} with respect to CO_3^{2-} is conveniently expressed in the Residual Sodium Carbonates *RSC* (meq/l):

$$RSC = CO_3^{2-} + HCO_3^- - Ca^{2+} - Mg^{2+} \quad (9)$$

The *RSC* indicates, in the long term, when the irrigation water gets concentrated due to water extraction by roots and evaporation, whether Ca^{2+} or Na^+ becomes the dominant ion in the soil water solution and exchange phase. The more positive *RSC*, the larger the risk for sodication of the soil.

2.6 Criteria for water and soil quality in Pakistan

The soil water ion composition in irrigated top soils will closely reflect the ion composition of the irrigation water. Therefore, the ion concentrations in the irrigation water are an important criterium for the sodication hazard of the soil. To judge the suitability of

irrigation water, WAPDA uses the criteria mentioned in Table 1.

Table 1. Irrigation water quality criteria as used by WAPDA.

	Useable	Marginal	Hazardous
<i>EC</i> (dS/m)	0 - 1.5	1.5 - 2.7	> 2.7
<i>RSC</i> (meq/l)	0 - 2.5	2.5 - 5.0	> 5.0
<i>SAR</i> (mmol/l) ^{1/2}	0 - 10	10 - 18	> 18

The *EC* values of soil water will be higher than the *EC* of irrigation water; therefore, the criteria for soil water solutions are higher. Also, instead of the sodium concentrations in the soil water, the adsorbed sodium concentrations (*ESP*) are commonly used as criterium. Table 2 lists the criteria of the USDA (1954), which are adopted by WAPDA.

Table 2. Soil quality criteria derived from USDA (1954).

	$EC_e \leq 4$ dS/m	$EC_e \geq 4$ dS/m
$ESP \leq 15$ %	non-saline, non-sodic	saline
$ESP \geq 15$ %	sodic ($pH > 8.5$)	saline-sodic

Chapter 3 The simulation models LEACHM and UNSATCHEM

In recent years, several approaches have been developed for describing water and solute movement in field soils. A number of solute transport models have been developed, which vary widely in their conceptual approach and degree of complexity. Many of them have been produced as a result of research into the basic physics and chemistry of salt, nitrogen or pesticide transport and transformations in agricultural soils. Few of the models have been tested against field data and little attention has been paid to the use of models for the actual purposes of management problems in relation to salty irrigation water, fertilizers, amendments, and pesticides. Field testing of simulation models is a necessary component of solute transport research if confidence in model predictions are to be achieved. Though use of numerical models offers the opportunity of using physical and chemical theory for management purposes, and also as tools in the design and interpretation of future field research efforts, a sound knowledge of a model's capabilities and limitations is essential in order to obtain reliable and useful results from the model studies. Two possible models will be described for salinity and sodicity research in Pakistan: LEACHM (Hutson and Wagenet, 1992) and UNSATCHEM (Šimunek et al., 1996).

3.1 The LEACHM model

LEACHM (Leaching Estimating And Chemistry Model), developed at Cornell University, describes water flow and solutes transport and chemistry in unsaturated/saturated soils to a depth of about two meters (Hutson and Wagenet, 1992). LEACHM has evolved from modelling experiences of the last twenty years. It has been applied successfully to a wide range of field and laboratory situations and is used by many researchers in the United States and other countries.

The model uses Richards' equation to describe the water movement, and the convection dispersion equation is employed to solve the solute transport. Water flow and solute transport equations are solved by fully implicit, central difference numerical schemes. Nodal compartments are of equal thickness throughout the profile. Time steps in LEACHM are automatically reduced during periods of high water flux density. The soil may contain various soil layers. LEACHM may predict retentivity and conductivity functions according to Campbell from soil particle size distribution. Plants can be present or absent. If present, crop cover and root expansion can be simulated, or a static, established root system and crop cover can be defined.

LEACHM provides a choice of five lower boundary conditions: (i) a fixed pressure potential (fixed-depth water table), (ii) unit gradient flux (a free draining profile having unit hydraulic gradient at the lowest node), (iii) zero flux, (iv) a combination of (i), and (iii) to represent a lysimeter tank from which water drains when the bottom node reaches saturation but with zero flux when unsaturated, or (v) a specified fluctuating water table. The upper boundary can vary between zero flux, upward evaporative flux, constant flux infiltration or ponded (zero matric potential) infiltration. For solute transport, upper boundary conditions may be zero flux or a solute concentration of infiltrating water. The lower boundary is either a specified concentration or a concentration calculated in a mixing cell below the simulated profile. In case of unit gradient drainage, no solute moves up into the profile.

LEACHM incorporates five numerical codes, which are organized on a modular basis:

- LEACHW for water flow only;
- LEACHN for nitrogen transport and transformation;
- LEACHP for pesticide displacement and degradation;
- LEACHB for microbial population dynamics; and
- LEACHC for transport and chemistry of inorganic ions.

In LEACHC, each chemical species (Ca, Mg, Na, K, Cl, SO_4 , CO_3 , and HCO_3) is transported by diffusion and convection during each time step, but equilibration between exchange, precipitation, and solution phases is re-established at user-specified intervals, usually every four to ten time steps. Cation exchange, precipitation-dissolution and atmospheric exchange are described separately in a subroutine called CHEM, which in itself is composed of a number of subroutines dealing with each facet of soil solution

chemistry. The simplest way to calculate equilibria in a model is to assume that reactions are complete at a specified point in space and time (local equilibrium). LEACHC is based on this assumption, which is less valid when water fluxes are high. The LEACHC does not use kinetic reactions for precipitation of calcite. Also, the cation exchange capacity and selectivity coefficients are assumed constant, anion exchange is ignored, and CEC is assumed to equal the sum of exchangeable Ca, Mg, Na, and K. The model assumes that the soil solution for each node is an open system with respect to carbon dioxide, CO_2 (CO_2 can enter from roots or decomposing organic matter or leave in moving water or the soil-air system, but the system is not in equilibrium with atmospheric CO_2), the levels of which can vary with depth in the profile but not with time. LEACHC assumes either a fixed pH or a fixed CO_2 , which are questionable assumptions for soils, which usually exhibit fluctuations for both of these variables.

LEACHC may calculate selectivity coefficients and solubility products from the initial conditions, assuming chemical equilibrium of the input concentrations. Alternatively, if the selectivity coefficients are specified, LEACHC will calculate dissolved and adsorbed concentrations from total extractable (exchangeable + solution) ion concentrations.

The LEACHM model has the following limitations:

- uses only one value for the depth increment;
- does not predict runoff water quantity or quality;
- does not simulate the response of plants to water and/or salinity stress; and
- has no capability to model macropore or preferential flow of water and solutes.

The program is written in ANSI standard FORTRAN 77, and has no graphics routines. It will execute on any IBM-PC compatible with math coprocessor and at least 512 K RAM, and will compile on main frame computers with minor modifications to file declarations.

3.2 The UNSATCHEM model

UNSATCHEM is a one-dimensional solute transport model, which simulates variably saturated water flow, heat transport, carbon dioxide production and transport, and solute transport with major ion equilibrium and kinetic chemistry. The model was developed at the U.S. Salinity Laboratory in Riverside, California (Šimunek et al., 1996).

In UNSATCHEM, Richards equation governs the water movement, and convection dispersion equation (CDE) describes the solute transport through the soil profile. The model can be used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The flow region may be composed of non-uniform soils. Flow and transport can occur in the vertical, horizontal, or a generally inclined direction. The flow boundary conditions include specified head and flux boundaries, boundaries controlled by atmospheric conditions, as well as free drainage conditions. Flow and transport equations are solved numerically using finite differences and Galerkin-type linear finite element schemes, respectively. The Peclet number criteria

associated with spatial discretization and the Courant number criteria associated with time discretization are used for stabilizing the numerical solution or minimizing the numerical dispersion.

In UNSATCHEM, solute transport and chemical modules are coupled together. The major variables of the chemical system are Ca, Mg, Na, K, SO_4 , Cl, alkalinity, and CO_2 . The model accounts for equilibrium chemical reactions between these components, such as complexation, cation exchange, and precipitation-dissolution. Precipitation-dissolution of calcite can be optionally treated with either the equilibrium condition or by kinetic process expressions. Dissolution of dolomite is always considered as a kinetic process. Other dissolution-precipitation reactions considered include gypsum, hydromagnesite, nesquehonite, and sepiolite. The model has the option to adapt the hydraulic conductivity depending on the SAR and EC of the soil water solution.

UNSATCHEM also simulates the production and transport of CO_2 . CO_2 transport may occur both in the liquid and gas phases. The CO_2 concentration in the soil is subject to two transport mechanisms, convective transport and diffusive transport in both the gas and aqueous phases, and by CO_2 production and/or removal. The CO_2 production model considers the effect of moisture content, temperature, salinity, CO_2 concentration, and O_2 concentration in the soil atmosphere, on CO_2 production.

The program is written in FORTRAN. For the preparation and management of extensive input data files and to graphically display the simulation results, an interactive graphics-based user-friendly interface for the MS Windows 3.1, Windows 95, and Windows NT environment has been written.

The main features of LEACHM and UNSATCHEM are summarized in Table 3. A comparison of the models shows that, although one model may have more features than the other, both of them are good research tools that might be applied to various field situations for investigating salinity and sodicity problems in irrigated soils under current irrigation practices and environmental conditions, and also for evaluating the impact of various management scenarios on soil salinization and sodication.

Table 3. Comparison between the simulation models LEACHM and UNSATCHEM.

LEACHM	UNSATCHEM
Cornell University, 1987	U.S. Salinity Laboratory, 1996
1-D, Richards' Equation (FD)	1-D, Richards' Equation (FD)
CDE solute transport (FD)	CDE solute transport (FE)
simulates W, N, P, M, S, and H	simulates W, S, H, and CO ₂
upper boundary conditions:	upper boundary conditions:
. zero flux	. zero flux
. upward evaporative flux	. upward evaporative flux
. constant flux infiltration	. constant flux infiltration
. ponded (zero matric potential) infiltration	. ponded (zero matric potential) infiltration
lower boundary conditions:	lower boundary conditions:
. fluctuating groundwater table	. fluctuating groundwater table
. free drainage	. free drainage
. zero flux	. variable flux
. lysimeter	. lysimeter
chemical and solute transport modules not coupled	chemical and solute transport modules coupled
chemical species: Ca, Mg, Na, K, SO ₄ , Cl, CO ₃ , and HCO ₃	chemical species: Ca, Mg, Na, K, SO ₄ , Cl, CO ₃ , HCO ₃ , and CO ₂
Cation exchange, precipitation-dissolution (equilibrium)	Cation exchange, precipitation-dissolution (equilibrium and kinetic reactions)
uses fixed pH/CO ₂	predicts CO ₂
numerical dispersion correction applied	Peclet and Courant number criteria used
no reduction <i>K</i> due to sodicity	reduction <i>K</i> due to sodicity
no preferential flow	no preferential flow
no plant yield model	plant yield model present
tested and verified	tested and verified
written in FORTRAN	written in FORTRAN
no graphics routines for input and output display	interactive graphics-based user-friendly interface in MS windows environment
well documented	well documented

Abbreviations: FD = Finite Difference, FE = Finite Element, CDE = Convection Dispersion Equation, N = Nitrogen transport, P = Pesticide transport, W = Water flow, M = Micro-organisms transport, S = Salinity and Sodicity, H = heat flow.

Chapter 4

Measurements in Chishtian Subdivision

The Chishtian Subdivision, located in south-east Punjab, comprises an irrigation scheme of 70,000 ha, which receives irrigation water from the Fordwah Branch Canal. Increased cropping intensities have prompted farmers to augment available canal water supplies by groundwater, pumped by over 4000 tubewells in the area. Consequently, groundwater tables have dropped and waterlogging is generally not a problem in the area (Smets et al., 1997).

The climate of the area is arid. Average annual rainfall ranges between 150 and 179 mm, of which two-thirds is received during the monsoon (mid-July to September). The mean annual temperature is 26.1 °C. May and June are the hottest months with maximum temperatures that may exceed 50 °C. Low relative humidity (± 0.46) and high radiation result in a high potential evapotranspiration: 1500 mm per year. Average rainfall and potential evapotranspiration of the period 1951 - 1970 are summarized in Table 4.

Table 4. Average rainfall and potential evapotranspiration of the period 1951 - 1970 (SSP and IIMI, 1996).

Month	Potential evapotranspiration (mm)	Rainfall (mm)
January	63.4	4
February	78.7	5
March	96.0	14
April	138.2	4
May	166.1	10
June	175.2	11
July	166.1	59
August	158.9	41
September	153.1	23
October	131.5	1
November	102.7	2
December	71.5	5
Annual	1501.4	179

During the period kharif '94, rabi '94-'95, and kharif '95, IIMI has intensively monitored four fields of two watercourses in the Chishtian Subdivision:

- field 351/15/17 of watercourse Fordwah 62-R
- field 351/10/21 of watercourse Fordwah 62-R
- field 173/15/22 of watercourse Azim 111-L
- field 173/11/07 of watercourse Azim 111-L

The measurements at these fields included:

- cropping pattern;
- irrigation amounts with tubewell and canal water;
- chemical analysis of tubewell water (*pH*, *EC* and *SAR*);
- chemical analysis of canal water (*pH*, *EC*, Ca, Mg, Na, CO₃, Cl, SO₄, and *SAR*); and
- soil texture (% sand, silt and clay) and chemical analysis of soil water extract (*pH*, *EC*, Ca, Mg, Na, CO₃, Cl, SO₄, and *SAR*) at 10 locations per field and at 15, 30, 60, 90, 120, 150, and 200 cm depth.

The cropping pattern in the area is predominantly cotton in kharif and wheat in rabi. The farmers apply about 115 cm irrigation, either by canal or tubewell water. Typical irrigation gifts (events) are:

Wheat (during rabi):		Cotton (during kharif):	
rauni	13.0 cm	rauni	6.5 + 8.7 cm
5 gifts	6.5 cm/gift	8 gifts	6.8 cm/gift
Total	45.5 cm	Total	69.6 cm

Table 5 lists tubewell water quality data on *EC*, *SAR* and *RSC* in the case of 5 watercourses in the Chishtian Subdivision. Unfortunately, in general, no data of the tubewell water ionic composition are available. In case of Mr. Muhammad Yaqoob, who has irrigated fields in watercourse Fordwah 130, the ionic composition was available (Table 5). His water has a bad quality for all criteria, *EC*, *SAR* and *RSC*.

Table 5. Measured water qualities of canal water in Chishtian Subdivision (C), tubewell water Mr. Yaqoob (T1), and average values for 5 watercourses (T2-T6).

	Ca	Mg	Na	HCO ₃	SO ₄	Cl	<i>EC</i>	<i>SAR</i>	<i>RSC</i>
	<----- meq/l ----->						dS/m	(mmol/l) ^{1/2}	meq/l
C	0.7	0.9	0.2	7.5	0.3	0.4	0.19	0.2	-0.4
T1	1.2	1.2	12.6	9.8	5.3	1.9	1.51	11.5	6.6
T2	(average tubewells Fordwah 130)						1.38	6.9	4.4
T3	(average tubewells Fordwah 62)						1.08	4.9	2.8
T4	(average tubewells Fateh 184)						3.35	13.0	1.2
T5	(average tubewells Azim 111)						1.10	3.0	0.8
T6	(average tubewells Azim 63)						0.9	2.1	1.2

The soils consist of mixed river alluvium, which range in texture from sand to silty clay. Five textural groups can be distinguished in the area (SSP and IIMI, 1996):

1. *Coarse textured soils* (17.7 %). The Jhang and Sodhra soil series, which are non-saline and non-sodic (pH 8.0 - 8.4), except for a small area of Sodhra series, affected by salinity/sodicity (pH 8.5 - 9.0) with a high groundwater table (90 - 150 cm depth);
2. *Moderately coarse textured soils* (41.8 %). The Rasulpur soil series, which is non-saline, non-sodic (pH 8.0 - 8.4), except a small proportion deteriorated by brackish tubewell water with pH ranging from 8.5 to 8.8;
3. *Medium textured soils* (28.8 %). The Bagh, Gandhra, Harunabad, Jhakkar, Nabipur and Sultanpur soil series, which are mainly non-saline, non-sodic (pH 8.0 - 8.4), except the Gandhra and Jhakkar soil series, which are genetically saline-sodic (pH 8.5 - 9.6), but with good porosity and relatively easy to reclaim;
4. *Moderately fine textured soils* (5.1 %). The Adilpur and Miani soil series, of which Adilpur is saline-sodic with pH ranging from 8.5 to 9.0, but has a good porosity, which is needed for reclamation; and
5. *Fine textured soils* (2.2 %). Matli, Pacca and Satghara soil series, of which Satghara is severely saline-sodic (pH 8.8 - 10.0) with high density, which makes it very difficult to reclaim.

The remaining area, 4.4 %, is mapped as miscellaneous land (stabilized sand dunes, urban land, lakes and graveyards).

The dominant clay mineral in various regions of Pakistan is illite (Ilyas, 1990). Reports from Australia indicate that soils dominant in illite, such as red-brown earths, are susceptible to dispersion at low SAR values and under weak mechanical forces (e.g. Rengasamy et al., 1984; Kijne and Kuper, 1995).

Soils in the Chishtian Subdivision are moderately calcareous with $5\% < CaCO_3 < 15\%$ (SSP and IIMI, 1996).

The cation exchange capacity CEC ($meq\ kg^{-1}$) depends on the soil texture. From a soil survey in Rechna Doab (WAPDA, 1960) the following approximate figures were derived:

<u>Texture</u>	<u>CEC ($meq\ kg^{-1}$)</u>
loamy sand	80
loam	150
clay	250

Ranges of EC_e and SAR , measured in soil-water extracts of the Adilpur soil series in the period October - November 1995, are:

$$1 < EC_e < 14\ dS/m$$

$$8 < SAR < 75\ (mmol/l)^{1/2}$$

Chapter 5 Simulation of sodication processes during the growing season

5.1 Input

Simulations were performed with UNSATCHEM, rather than with LEACHM, because of the extra features of UNSATCHEM with respect to sodication processes (e.g. CO_2 production in the root zone, kinetic precipitation-dissolution of calcite, reduction K due to sodication) and its user's friendly shell. The main goal of the simulations in this stage is to show the potential of the model for analysis of the sodication processes as occurring in the Chishtian Subdivision. To this end, a reference situation is defined which is based on the measured data listed in Chapter 4:

- rainfall and potential evapotranspiration according to Table 4;
- irrigation gifts as specified in Chapter 4; the farmer is assumed to use tubewell water, except for the three rauni gifts, which consist of canal water in order to guarantee plant germination and proper early development;
- chemical speciation of canal and tubewell water as specified in Table 5; the tubewell data of T1 were used, which quality is relatively bad;
- growth of wheat from January 1 until April 30; growth of cotton from June 1 until December 15;
- soil texture is loam, soil hydraulic functions are based on Carsel and Parrish (1988) as supplied by UNSATCHEM; and
- no groundwater influence, free drainage at 1 meter depth.

In addition, the following assumptions were used:

- linear decrease of root water uptake between 0 and 100 cm depth;
- sensitivity to water and salinity stress for wheat and cotton were defined by $h_{50} = -2000$ cm and $h_{950} = -10.800$ cm;
- constant soil temperature $T = 25$ degrees Celsius;
- CO_2 concentration ($\text{cm}^3 \text{ cm}^{-3}$) increasing linearly from 0.00033 at the soil surface to 0.0020 at the bottom of the root zone;
- molecular diffusion was neglected; the dispersivity length was assumed to be 5 cm;
- cation exchange capacity of loam $\text{CEC} = 150 \text{ meq kg}^{-1}$; and
- moderately calcareous soil: 10 % $\text{CaCO}_3 = 500 \text{ meq kg}^{-1}$.

Initial conditions directly affect the water and salt balance. The measurements were not adequate to define the initial conditions properly. Therefore, the following procedure was adopted. First, a year was simulated with approximate initial conditions. The pressure heads at the end of the year were used as initial pressure heads. In a next run, the dissolved and adsorbed ion amounts at the end of the year were calculated, assuming that the initial values were sufficiently close to the actual value to attain equilibrium in both adsorbed and dissolved concentrations within one year. The dissolved and adsorbed ion amounts at the end of the year were used as initial conditions. In this way, the water and solute amounts (except for precipitation) after a year hardly change, only seasonal changes occur.

Accurate simulation of the soil-water fluxes is important for a correct simulation of the sodication process. One difficulty is the partitioning of potential evapotranspiration into potential transpiration and potential evaporation. This requires the soil cover by the plants or the leaf area index, which is only known from literature. The reduction of potential evaporation, which depends on soil physical properties of the top soil layer is, in general, much larger than the reduction of potential transpiration, which is determined by the soil water potential in the root zone and plant physiology. Therefore, any mistake in soil cover affects the soil water loss by actual evapotranspiration ET_{act} . For instance, in case of a leaching fraction of 0.10, the relative error in the amount of drainage will be approximately 10 times the relative error in ET_{act} . As the sodication processes are very sensitive to the amount of drainage, ET_{act} should be determined as accurately as possible. For future simulations, it is recommended to collect local data on soil cover by the plants during the growing season. In the current simulations, the soil cover is based on general agronomic data in Doorenbos and Pruitt (1984).

Annex A lists the input file generated by the UNSATCHEM shell for the reference case. It shows the parameters used for the soil hydraulic functions, relevant soil chemical parameters, and the concentrations of ions dissolved and adsorbed. A complete description of the input variables is given in the UNSATCHEM user's manual (Šimunek et al., 1996). Annex B lists, for the reference simulation, the input of rainfall, irrigation, potential transpiration and potential evaporation during the year.

Biggar (1996) observed that where the system would allow (i.e. water table deep enough and some canal water available) crops of rather low salinity threshold were growing next to a field that was clearly saline-sodic. Both fields were farmed by the same personnel. Apparently, a decision had been made to protect the sensitive crop (e.g. sugarcane) and let the other field deteriorate. Although the sugarcane crop may not have reached maximum production potential, it was a viable crop. Such examples demonstrate the potential for returning these salt-affected areas to production for a variety of crops. The simulation model is useful for identifying the most promising management strategy.

In addition to the reference case, the following two situations were simulated:

- fallow period during kharif; and
- application of gypsum.

Other situations for which salinization and sodication processes might be analysed with UNSATCHEM, include:

- deficient irrigation, resulting in salt precipitation in the subsoil;
- applications of amendments such as sulphuric acid or organic matter;
- waterlogging and/or capillary rise from a shallow groundwater table;
- crops with different tolerance levels for water and/or salinity stress; and
- different irrigation frequency.

Unfortunately, time and data constraints did not allow accurate simulations of each measured field in particular and detailed comparison between simulated and measured data for these fields.

5.2 Results

5.2.1 The reference situation

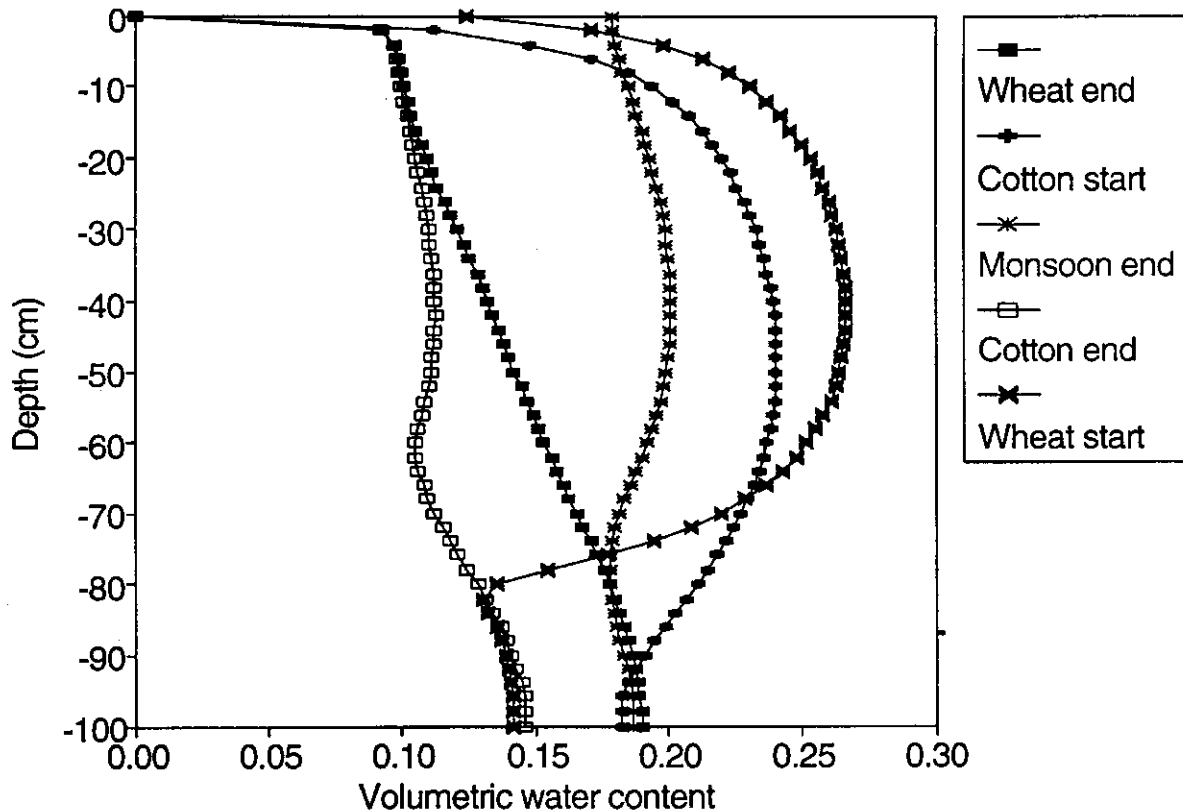


Figure 4. Volumetric water content profiles of the reference situation at five times of the year

Figure 4 shows the soil water profile as simulated at the beginning and end of the growing seasons and at the end of the monsoon period. The rauni irrigations moisten the soil profile until 80 to 90 cm depth, and decrease considerably the water and salinity stress during the germination and initial development of the crops. Between the irrigation and rainfall events the soil dries out until volumetric water contents of approximately 0.10. In an average year, the monsoon supplies only 180 mm rain water. If the farmer adapts his irrigation application to these amounts, as assumed in the reference simulation, the soil becomes only moderately wet (Fig. 4).

Figure 5 shows the simulated Ca profiles, again at the beginning and end of the growing seasons and at the end of the monsoon period. At the beginning of the growing seasons,

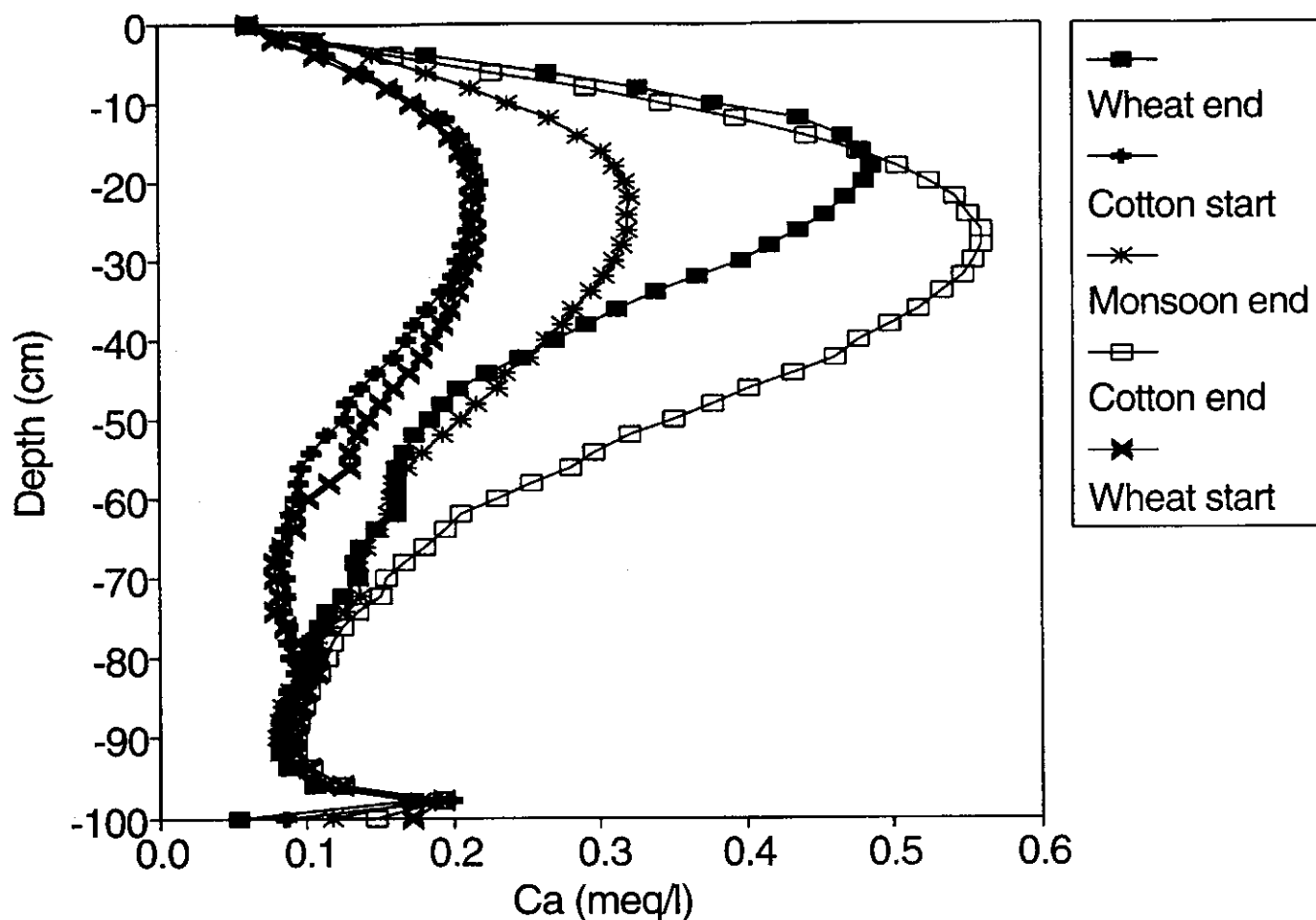


Figure 5. Calcium concentration profiles in the soil water of the reference situation at five times of the year.

after the rauni irrigations the concentrations are significantly smaller than at the end of the growing seasons. In the top soil, the Ca concentrations are equal to the Ca concentrations in the irrigation water. In the root zone, Ca concentrations increase due to water extraction. At larger depth, Ca concentrations again decrease, which is attributed to increasing amounts of HCO_3^- , which induces precipitation of calcite. Between the various times of the year, root water extraction and irrigation/rainfall clearly affect the concentrations (Fig. 5).

Dilution and concentration effects during the year are also reflected in the EC_{sw} profiles, as shown in Fig. 6. Measured EC_{sw} values in the Chishtian Subdivision for the Adilpur soil series are between 2 and 28 dS/m, which is somewhat larger than the range simulated for the reference case, $2 \leq \text{EC}_{\text{sw}} \leq 16$. Probably the measured values include some fields with hardly any leaching.

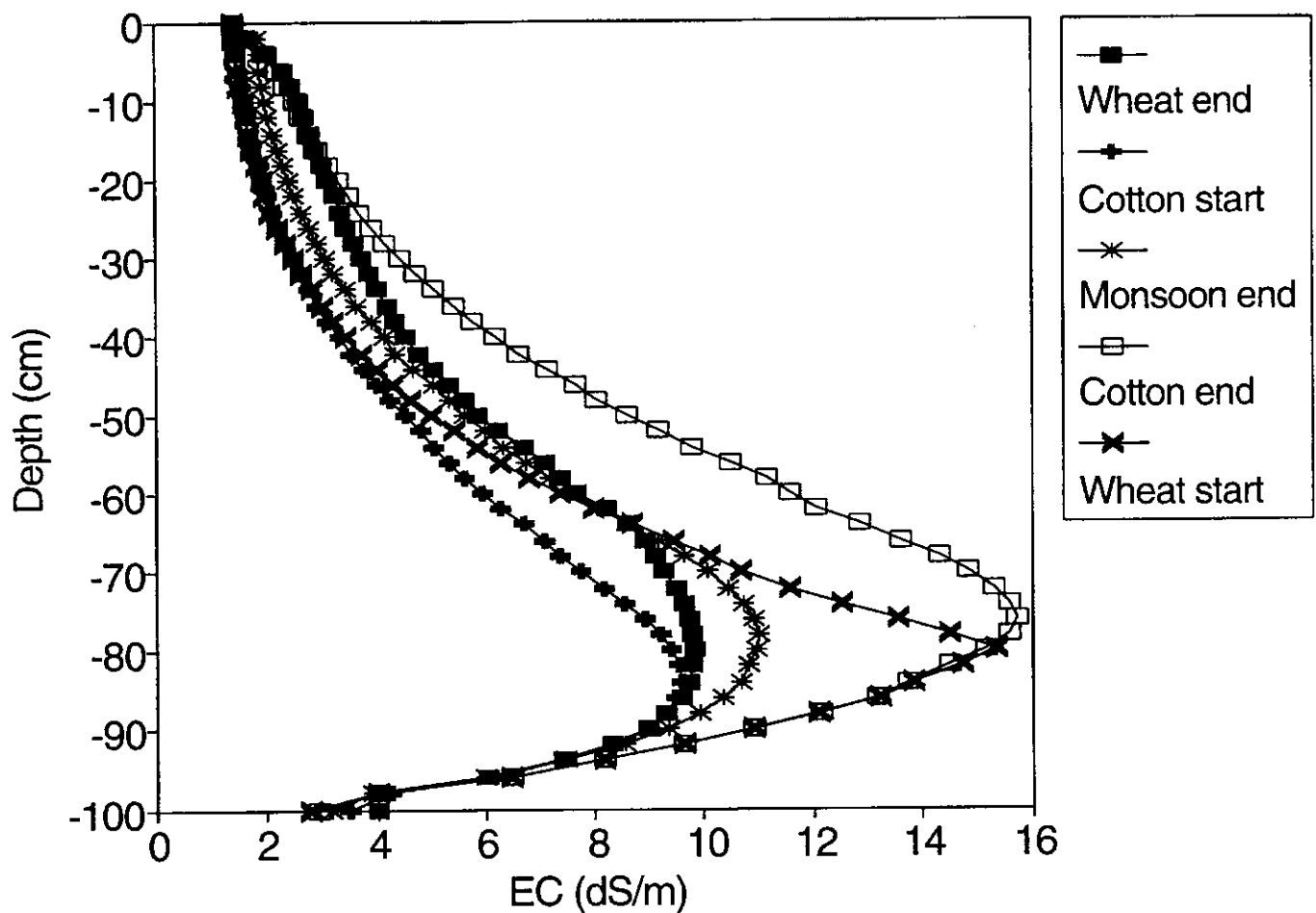


Figure 6. EC_{sw} profiles of the reference situation at five times of the year.

Measured SAR values in the Chishtian Subdivision are between 8 and 75 $(\text{mmol/l})^{1/2}$. The simulated SAR values, as shown in Fig. 7, are relatively high $20 \leq SAR \leq 125 (\text{mmol/l})^{1/2}$. Probably farmers in the area with this bad tubewell water quality will maintain a larger leaching fraction than 0.09, as adopted in this simulation.

Despite the inflow of good quality water during rainfall and at rauni applications, and water extraction by plant roots and evaporation at the soil surface, Fig. 7 shows that the SAR value hardly changes during the year. More detailed analysis of the development of SAR between irrigation and rainfall events, which is not shown here, indicates also a rather constant SAR value with time. Ordinary dilution or concentration of a water solution without soil, will in theory cause a change of the SAR value. The negligible changes of the SAR value in this loamy soil can be explained by considering the amounts of cations dissolved in the soil water compared to the amounts of cations adsorbed by the clay minerals. The cation exchange capacity equals 150 meq/kg, which corresponds to 195 eq/m² (assuming a dry bulk density of 1300 kg/m³). The concentrations in the soil water

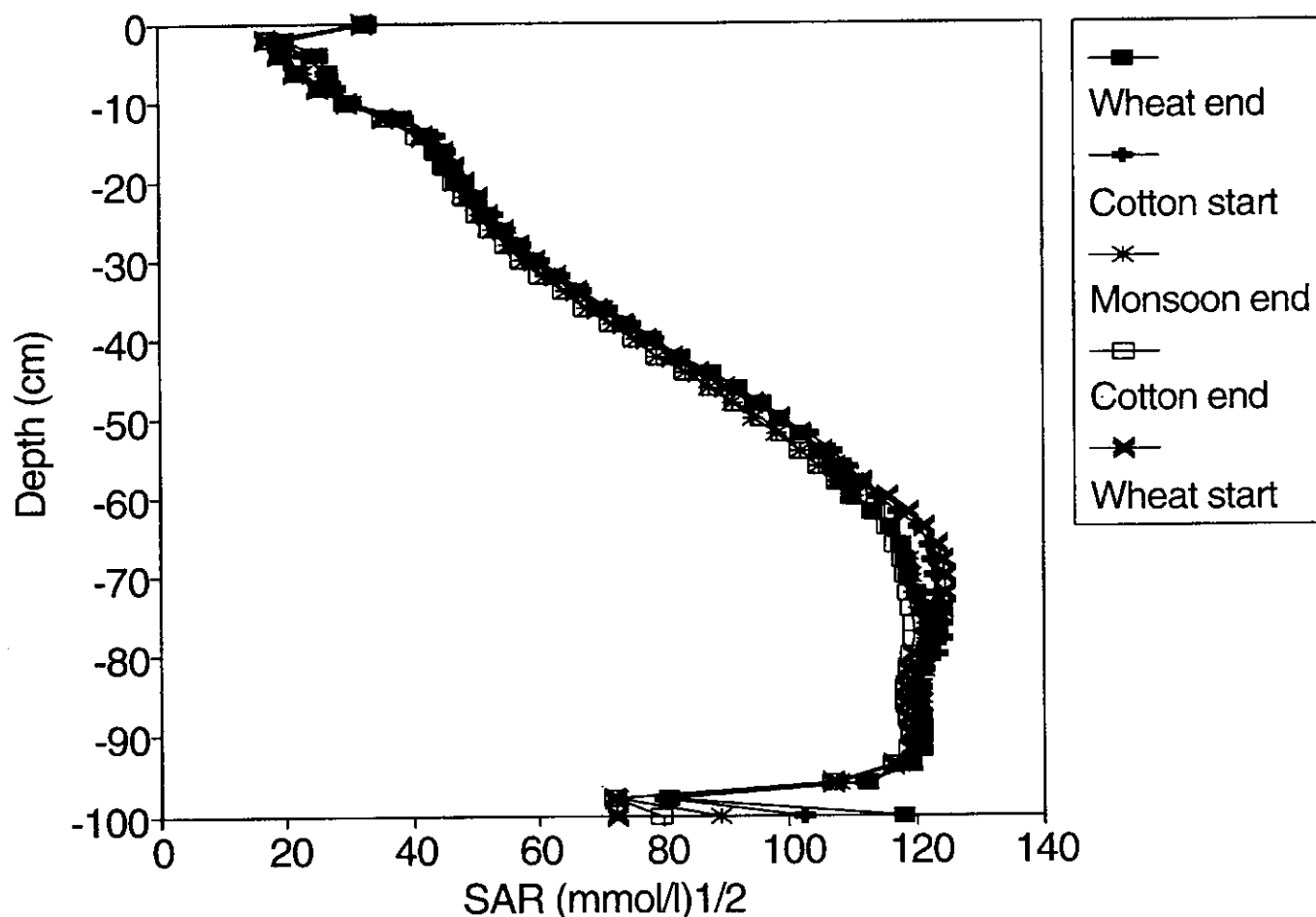


Figure 7. SAR profiles of the reference situation at five times of the year.

fluctuate around 70 meq/l. In case of an average volumetric water content of 0.17 (-), of the ions 11.9 eq/m² are stored in the soil water, or only 6 % of the amount adsorbed by the clay minerals! The large amounts of adsorbed cations will determine to a large extent the ion ratios in the soil water. Without considering adsorption, dilution would cause a decrease of the SAR value. However, due to exchange with the adsorbed cations, the SAR value hardly fluctuates. Later, it will be shown, that in the long term SAR values do change!

In the reference case, water and salinity stress decrease potential transpiration $T_p = 99.4$ cm to actual transpiration $T_a = 95.6$ cm, so a reduction of 3.8 %. This reduction is only caused by drought stress! The salt amounts in the tubewell water, in combination with the leaching fraction, keep the osmotic heads in the root zone below the threshold value of salinity stress for cotton and wheat. The amount of leaching is 10.3 cm, at a total amount of irrigation of 115 cm, which corresponds to a leaching fraction of $10.3/115 = 0.09$ (-). Despite this relatively low leaching fraction, no salinity stress occurs.

The ESP values in the top 50 cm are as high as 40 %, and increase to 70 % in the lower 50 cm of the soil profile. In combination with the *EC* profiles (Fig. 6), this classifies the top 50 cm as sodic, and the lower 50 cm as saline/sodic (Table 2). These unfavourable conditions result from the very bad ionic speciation of the tubewell water (T1 in Table 5).

It is remarkable that the presence of lime in the soil (500 meq kg^{-1}) does not help to increase the Ca concentrations in the soil water, thereby decreasing the sodicity level. On the contrary, despite the low levels of Ca in the soil water, it still precipitates, due to the high levels of HCO_3^- . This is reflected in the high RSC of the tubewell water (6.6 meq/l), indicating a rapid decrease of Ca during water extraction once ion saturation is reached (Fig. 3).

5.2.2 Fallow period during kharif

In order to leach the soil, the farmer may consider leaving the field fallow during the kharif and just apply the rauni irrigation for the next rabi season. The saved amounts of irrigation water (54.4 cm) can be used at other fields to increase leaching, which is very

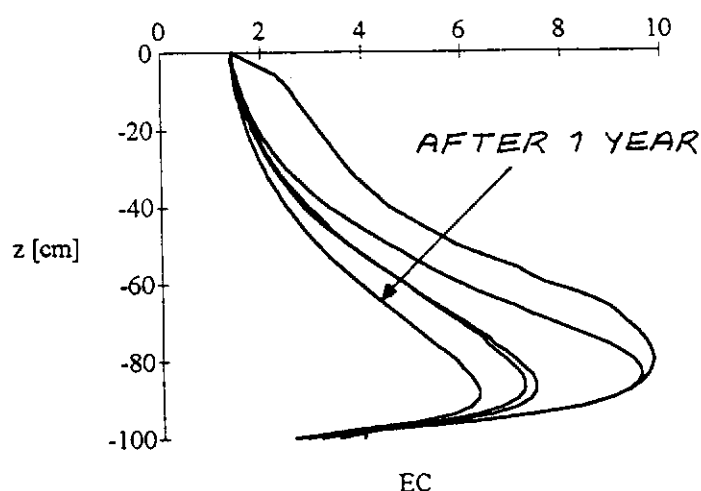


Figure 8. *EC_{sw} profiles at five times of the year in case the field is fallow during the kharif season.*

effective in decreasing the *EC* and *SAR* values, as will be shown in Chapter 7. In case of the fallow field, Fig. 8 shows the *EC* profile during the year. After one year, the *EC* levels are decreased, especially in the sub soil. However, the *SAR* values hardly decrease, see Fig. 9. The small effect on the *SAR* value again can be explained from the large reservoir of cations in the exchange complex, which will determine mainly the ionic composition in the soil water. Despite the larger amounts of percolation and good water quality of the rain water, after the fallow period, the whole soil profile should be classified as sodic. The lower *EC_{sw}* concentrations may further

deteriorate the permeability and tilth properties of the soil due to expansion of the cation exchange phase and disaggregation of clay minerals.

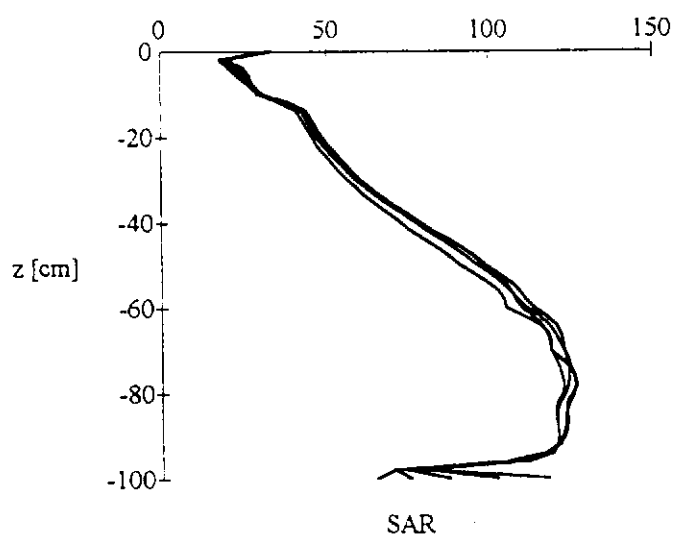


Figure 9. SAR profiles at five times of the year in case the field is fallow during the kharif season.

5.2.3 Application of gypsum

A better way to combat sodication is the application of gypsum. Gypsum amounts of 1500 kg/acre are often recommended in the Chishtian Subdivision, although most farmers apply considerably less (100 kg/acre). The sodication was simulated after application of gypsum at January 1. Figure 10 shows the SAR values after 5 months (June 1) and after one year (January 1), without (= reference case) and with application of gypsum. Over the entire soil profile the SAR values are decreased by about 50 % when the gypsum is applied. However, the top 50 cm still should be classified as sodic,

and the lower 50 cm as saline/sodic soil. The small amounts of gypsum that are normally applied by the farmers are clearly insufficient when tubewell water with these high *RSC* and *SAR* values (T1 of Table 5) is used.

Chapter 6 Simulation of the sodication rate

During the growing season, dilution and concentration cause fluctuating cation concentrations and EC_{sw} values, while *SAR* values hardly fluctuate. However, in the long term, also *SAR* will change and ultimately reflect the ionic composition of the irrigation water. It is important to know at which rate the sodication process takes place once a farmer starts using bad quality tubewell water. Such a situation was simulated using the tubewell water quality T1 specified in Table 5 on a loamy soil, that had been irrigated for 10 years with good quality canal water. The remaining input data were similar to those of the reference case, except that the transient boundary conditions were changed to stationary boundary conditions. Also, because of the use of the bad quality tubewell water, it seemed realistic to increase the leaching fraction from 0.09 to 0.15 (-).

Figure 11 shows the simulated increase of Na concentrations over a period of 10 years. Analysis of the adsorbed Na amounts show that after 3 years the limit $ESP = 15\%$, is superseded at 50 cm depth, while after 5 years the sodicity 'front' has reached 80 cm depth. Figure 12 shows the *SAR* profiles, which indicate the same speed of sodication. With this quality of irrigation water, the whole soil is spoiled within 10 years.

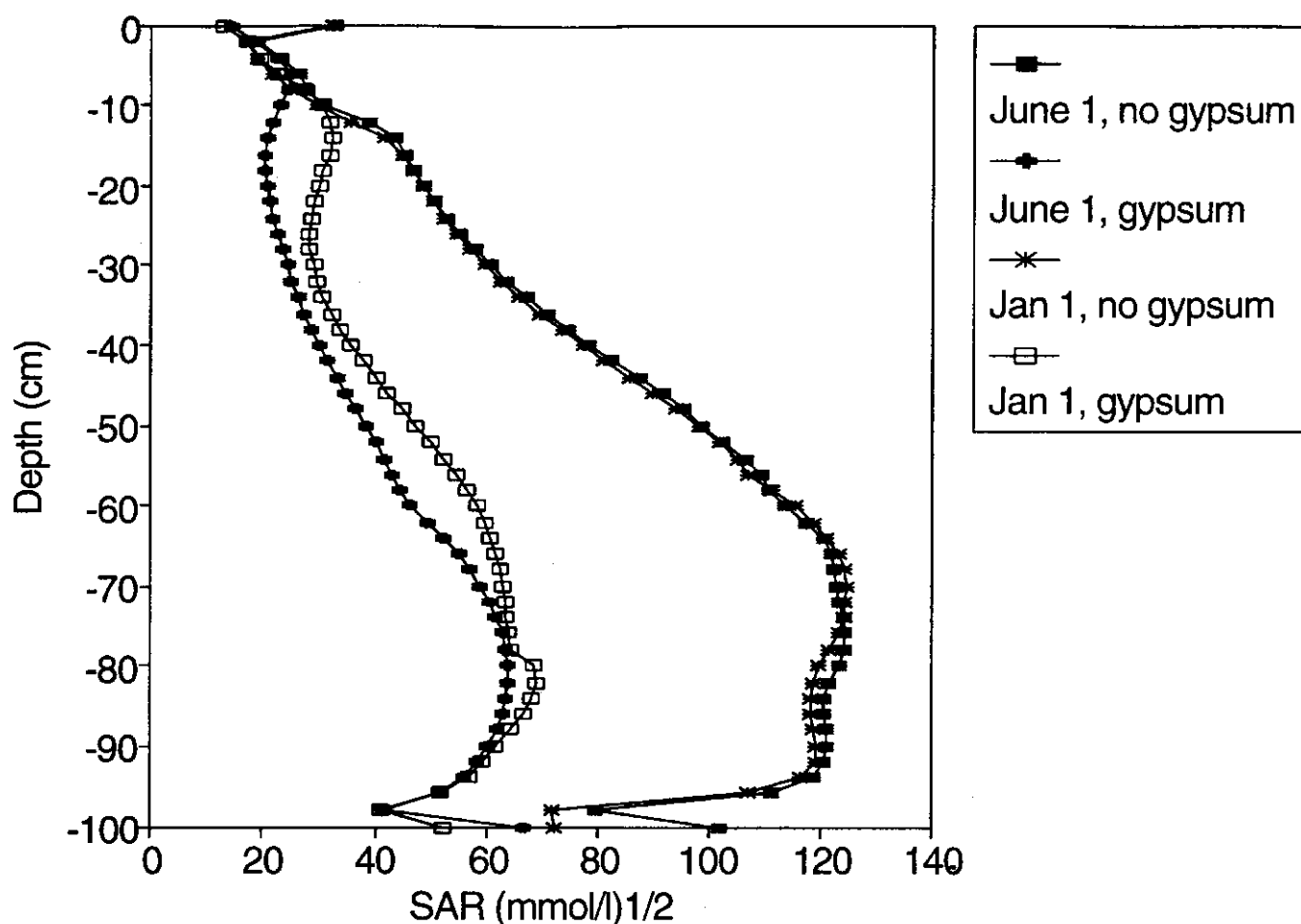


Figure 10. SAR profiles in case of the reference (no gypsum) and when gypsum is applied; June 1 and January 1 correspond to 5 and 12 months after gypsum application.

In this simulation rather bad quality tubewell water was adopted, resulting in a rapid degradation of the soil. Simulations by Condom (1997) also revealed significant soil degradation within one year with this type of tubewell water. It is interesting to use UNSATCHEM to calculate the sodication rate for irrigation water qualities that are in between the canal and tubewell water qualities used in this study. Simulation of the time frame of expected changes is an important application of sodication programs.

Chapter 7 Most sensitive input parameters for sodication simulation

Measurement of many input data is expensive, and also cannot be applied on a regional basis. In order to select the most relevant input data. The sensitivity of the simulation results to various input data was checked.

The following input data were changed:

- water quality (tubewell, canal water and blending with each water type 50 %)
- leaching fraction (0.15 ---> 0.25)
- root water uptake pattern (maximum rooting depth 100 cm ---> 40 cm)
- soil cation exchange capacity (150 meq/kg of loam ---> 250 meq/kg of clay)

Except from the canal water and blending case, each time tubewell water (including the rauni's) was used for irrigation. A leaching fraction of 0.15 was adopted. The other input data were similar to the reference case (Par. 5.1). The interest was in long-term effects; therefore, a period of 9 years was calculated.

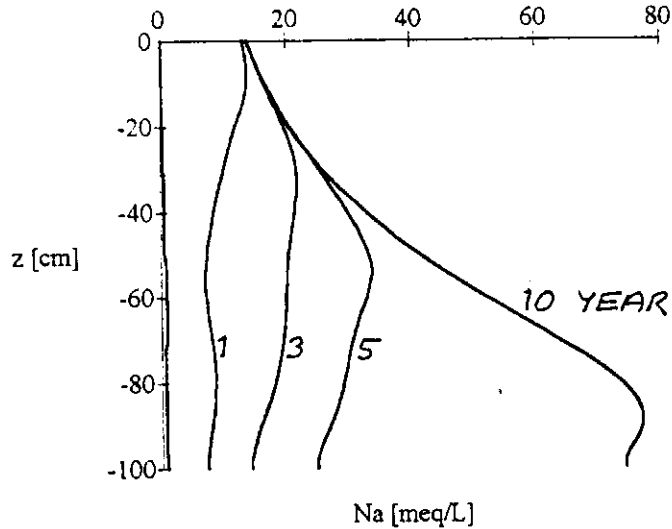


Figure 11. Sodium profiles over a 10 year period, due to a change from canal water to tubewell water for irrigation.

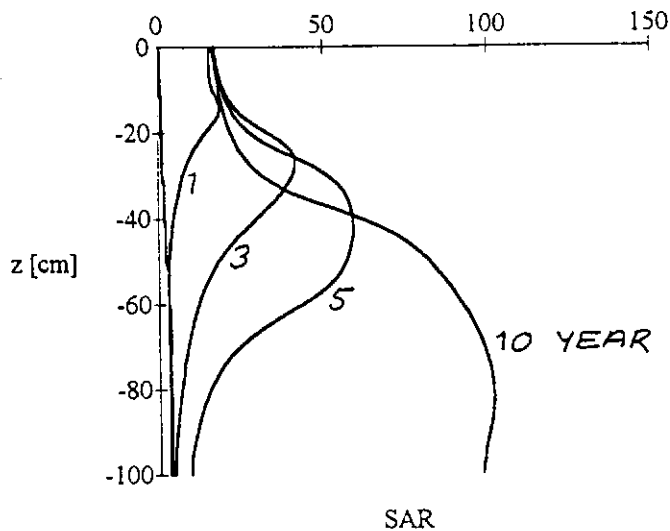


Figure 12. SAR profiles over a 10 year period, due to a change from canal to tubewell water for irrigation.

Figure 13 shows the Ca profiles after the 9 year period. The difference between irrigation with tubewell water and canal water is relatively small. Leaching causes larger Ca concentrations in the subsoil. In case of shallow roots, the drainage concentrations are attained directly below the maximum rooting depth of 40 cm.

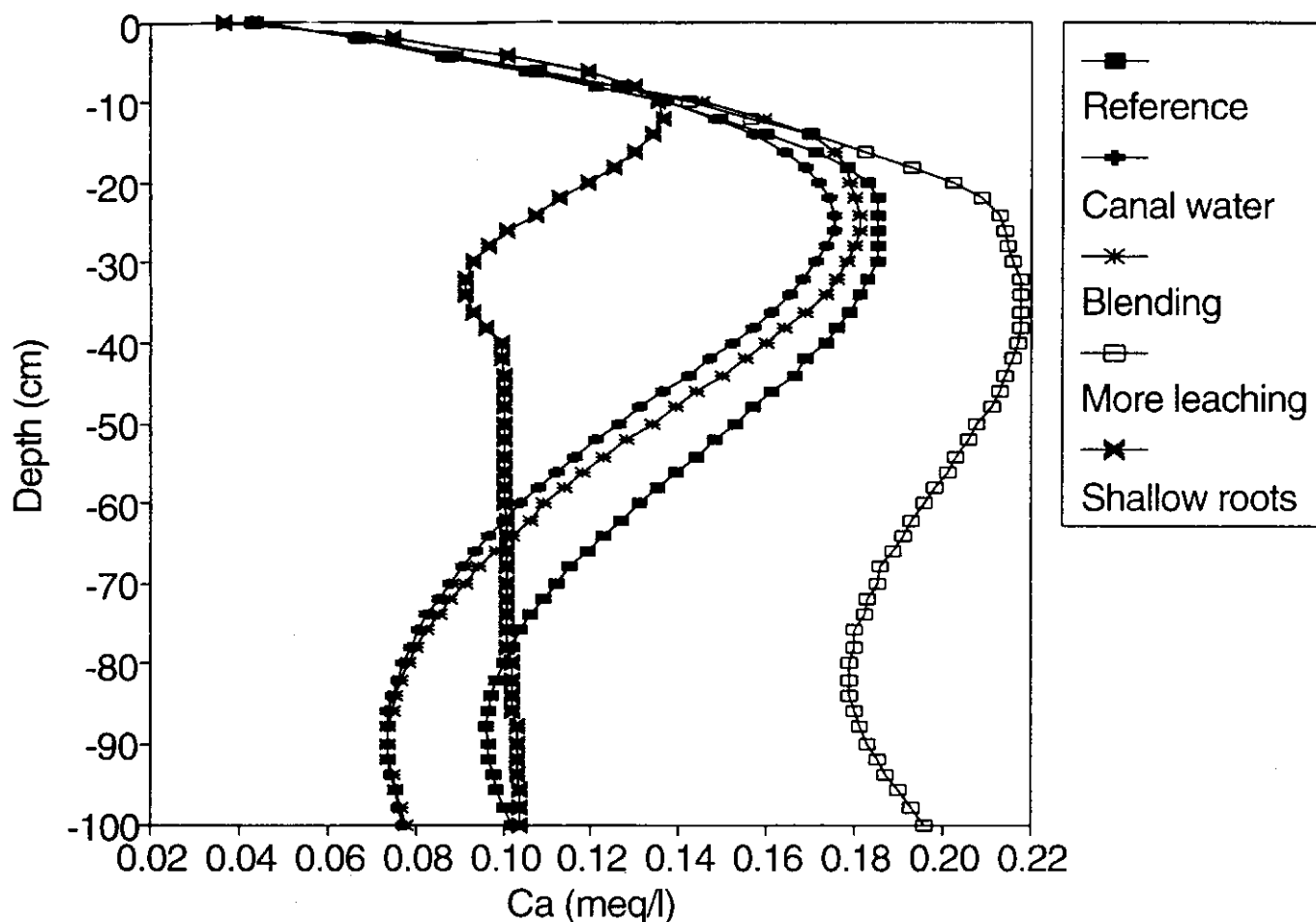


Figure 13. Ca profiles after long term irrigation (9 years) in case of five scenarios.

Figure 14 shows the Na profiles after the 9 year period. In contrast to Ca, the concentration increases continuously with depth to a maximum concentration at the root zone bottom. A large difference exists between the simulated Na profiles of canal and tubewell water due to the large difference of the input concentration (Table 5). Blending with 50 % canal water and 50 % tubewell water results in concentrations midway between concentrations caused by either canal water or tubewell water. While more leaching increases the Ca concentrations in the subsoil, it decreases the Na concentrations in the subsoil. This will decrease the SAR value in the subsoil. As the Na ion in this case is not involved in any precipitation reaction, the Na concentrations of the percolating water below the root zone can directly be derived by considering the mass balance: $[\text{Na}]_{\text{irrigation water}} = \text{leaching fraction} \times [\text{Na}]_{\text{percolation water}}$. With $[\text{Na}]_{\text{irrigation water}} = 12.6 \text{ meq/l}$ and a leaching fraction of 0.15, this results in $[\text{Na}]_{\text{percolation water}} = 87.0 \text{ meq/l}$, which was also simulated (Fig. 14).

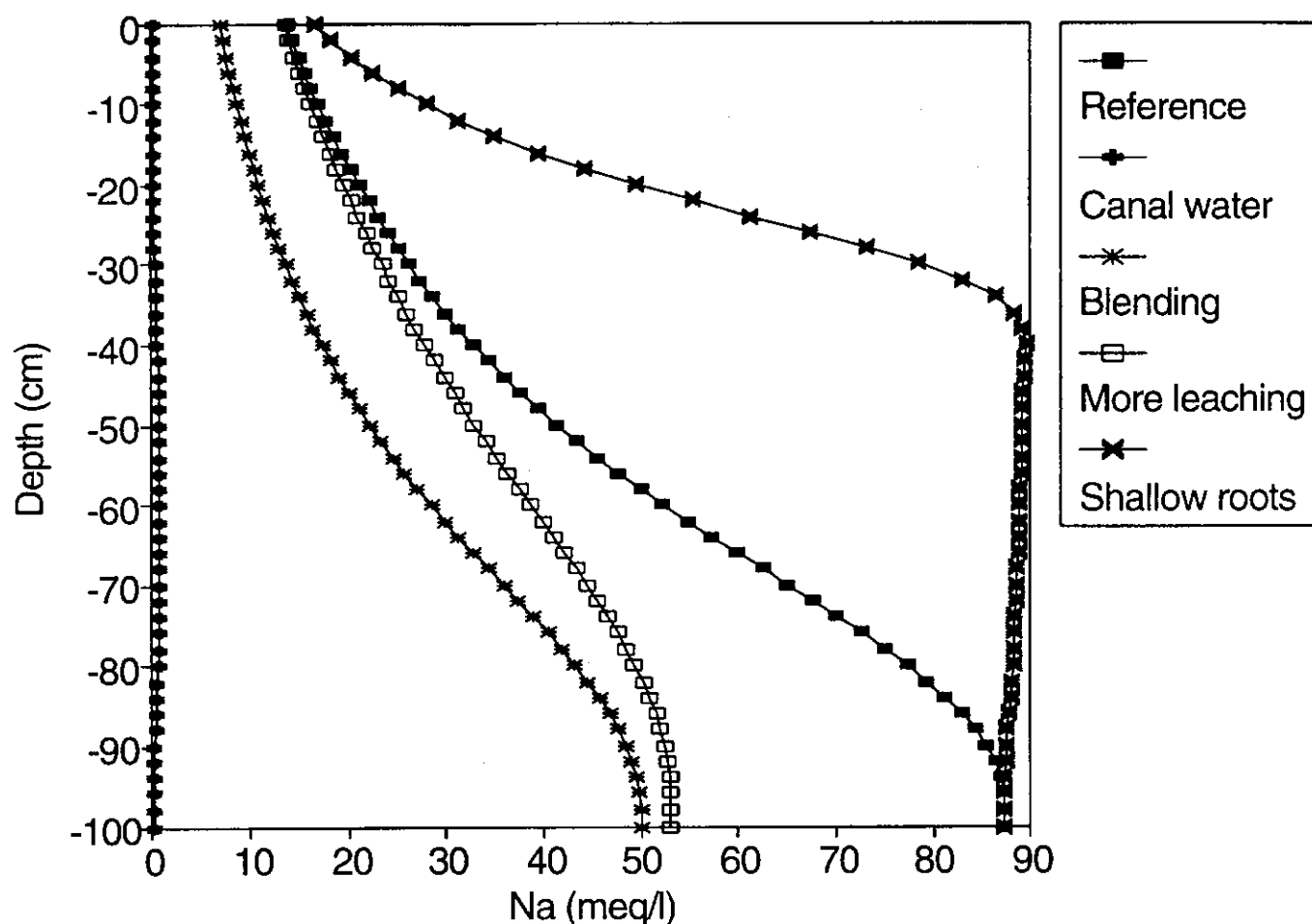


Figure 14. Na profiles after long term irrigation (9 years) in case of five scenarios.

Blending of good quality water with bad quality water in general is not recommended, as in many cases the water is used less effectively compared to the use of different water qualities for crops with various sensitivities (Rhoades et al., 1992). However, blending might be the only option to use bad quality tubewell water. Figure 15 shows that, in contrast to e.g. Na and *EC*, blending does not result in a proportional decline of the *SAR* value. For instance, at 20 cm depth, $SAR_{\text{canal}} = 0.85 \text{ (mmol/l)}^{1/2}$, $SAR_{\text{tubewell}} = 49.6 \text{ (mmol/l)}^{1/2}$, and $SAR_{\text{blending}} = 32.1 \text{ (mmol/l)}^{1/2}$. More leaching decreases the *SAR* values in the subsoil, but still the soil is sodic. Shallow root water uptake makes the soil very sodic at shallow depth.

In the long run, the ionic composition of the irrigation water determines the ionic composition in the soil water. At a change of irrigation water quality, the exchange phase acts as a buffer; it determines the rate at which the ionic composition of the soil water changes. A larger cation exchange capacity *CEC* results in a slower change of the soil water solution with time. The simulations results showed no difference in the ionic

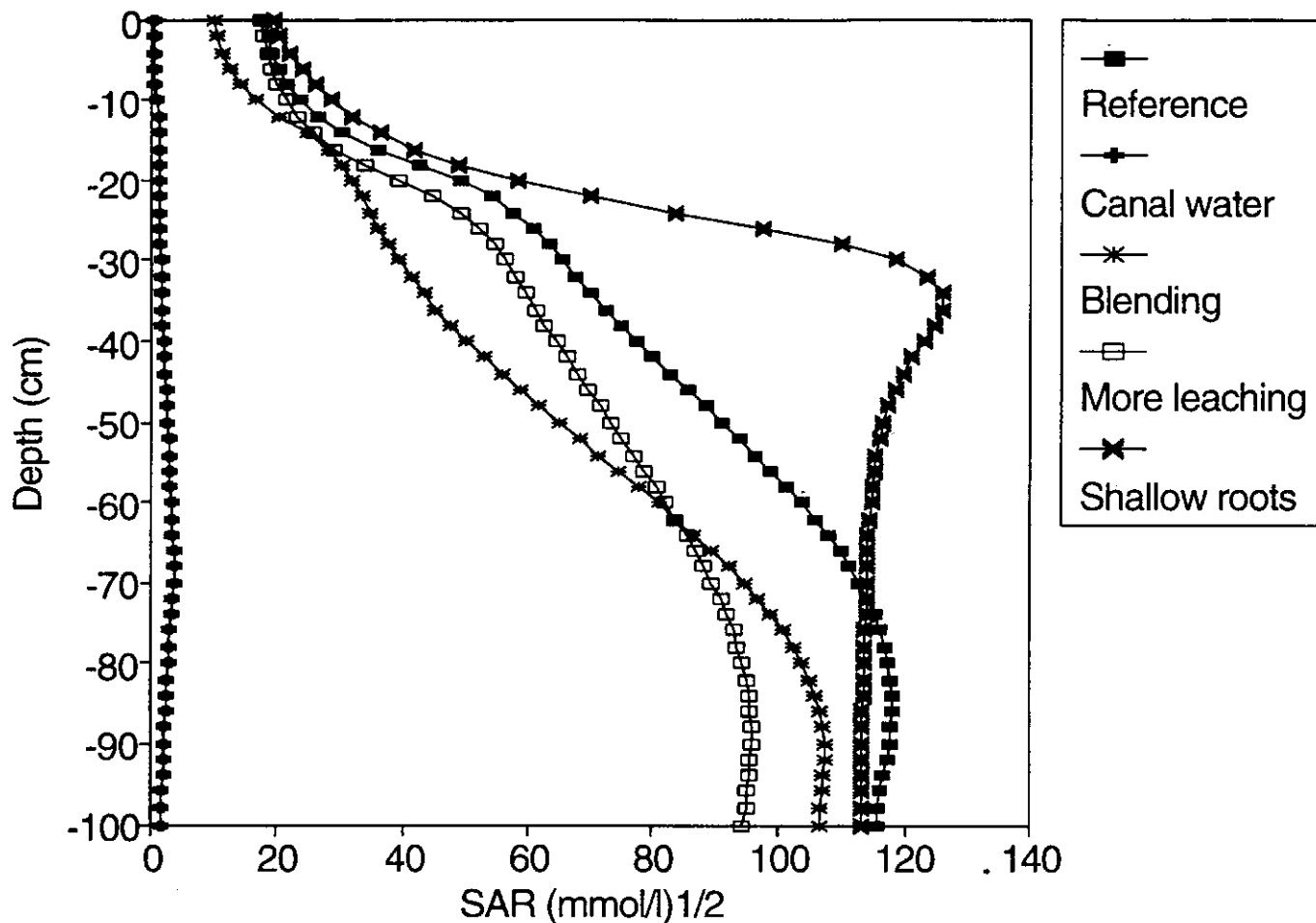


Figure 15. SAR profiles after long term irrigation (9 years) in case of five scenarios.

composition of the soil water after the 9 year period due to changes of *CEC*. The percolation rate and the ion amounts in the irrigation water are large enough to refill the exchange phase in these 9 years.

What can be concluded from the analysis so far for the data collection?

The irrigation water quality is the main factor for the sodicity status. Although a buffer of cations may exist in the soil and the soil may be calcareous, ultimately, the irrigation water, in combination with the leaching fraction, determines the cation and *SAR* profiles. Therefore, the irrigation water quality, especially of the tubewell water, needs to be measured.

Leaching is very effective in decreasing the *EC* levels, but is less effective in decreasing the *SAR* levels. The leaching fraction is an important criterium to judge the irrigation efficiency. Leaching needs to be determined, either from lysimeter experiments or from

water balance simulations. In case of water balance simulations, more accuracy is required for the actual evapotranspiration of cultivated soils without a closed canopy.

Change of the rooting depth from 100 cm to 40 cm (in both cases assuming a linear decrease of the root water uptake with depth) does not decrease the *EC* of the percolating water, as is directly clear from mass balance considerations. The *SAR* values in the top soil, which mainly determine the infiltration capacity, are hardly affected. Only, at 25 - 65 cm depth, the *SAR* values increase considerably due to shallow root water uptake. A complicating factor in measuring the actual root water uptake distribution is that the distribution changes during the growing season and depends on the actual water and salt stress in the soil profile. Although it might be interesting, measurement of the actual root water uptake distribution seems less relevant.

The simulation program generates *EC* and *SAR* profiles for various management options in specific situations. In a next step, it is important to apply relevant criteria to judge the severeness of sodication. The criteria from the USDA (1954) seem to be somewhat different from the farmer perceptions of the sodicity problem (Kielen, 1996). It should be clear for Punjabi soils, at which *SAR* levels the soils show intolerable crust formation and disaggregation.

Regarding data collection, the conclusion is that priority should be given to the irrigation water quality, the leaching fraction, and the soil quality criteria.

Chapter 8 Conclusions and recommendations

- 1) The salinity levels due to the use of tubewell water in the Chishtian Subdivision don't hamper root water uptake in case of cotton and wheat.
- 2) The water quality of many tubewells in the Chishtian Subdivision will create serious sodicity problems.
- 3) After starting the use of bad quality tubewell water, a loam soil profile may be spoiled to 50 cm depth within 3 years.
- 4) In the simulation runs shown in this report, tubewell water of relatively bad quality has been used. Simulations with more moderate tubewell water qualities are recommended, in order to get an overview of the sodicity hazard over the full range of water qualities.
- 5) The numerical model UNSATCHEM simulates the main processes that affect salinization and sodication. These processes include:
 - transient water flow in the saturated and unsaturated zone;
 - convection-dispersion type equations for carbon-dioxide, heat and solute transport;
 - root growth and root water uptake;

- complexation, cation exchange and precipitation-dilution for the ions Ca, Mg, Na, K, SO_4 , Cl, and HCO_3 ; and
- kinetic precipitation-dilution in case of the precipitates calcite and dolomite.

6) The main differences between the models LEACHM and UNSATCHEM are:

- LEACHM includes modules that simulate nitrogen transport and transformation, pesticide displacement and degradation, and microbial population dynamics;
- UNSATCHEM is more extensive with respect to sodication processes as it includes simulation of CO_2 production in the root zone, kinetic precipitation of calcite, and reduction of hydraulic conductivity due to sodicity; and
- input and output analysis are more user-friendly with UNSATCHEM.

7) The simulations with UNSATCHEM show that the model is very useful to:

- gain an understanding of the main mechanisms in case of sodication;
- identify data collection for specific problems;
- interpret and generalize measured data; and
- evaluate management options for Pakistani conditions.

8) Data collection in areas like Chishtian Subdivision should focus on:

- ion speciation in the irrigation water;
- leaching fraction; and
- measurement of SAR values in soils with different sodicity status.

9) Running a simulation model just requires a press on the button. However, correct interpretation of sodication simulation results requires knowledge, both in practice as in theory, of water flow and salt transport processes in cultivated fields.

References

- Biggar, J.W., 1996. Regional salinity-sodicity issues in Punjab, Pakistan. Consultancy Report, IIMI Pakistan, Lahore, Pakistan.
- Carsel, R.F., and R.S. Parrish, 1988. Developing joint probability distributions of soil water retention characteristics. *Water Resources Research*, 24, 755-769.
- Condom, N., 1997. Characterisation of the geochemical and physical processes and the impact of irrigation water on these processes by the use of a hydro-geochemical model. Report R-22, IIMI, Lahore, Pakistan.
- Doorenbos, J., and W.O. Pruitt, 1984. Crop water requirements. *FAO Irrigation and Drainage Papers* 24, Rome, Italy.

- Hutson, J.L., and R.J. Wagenet, 1992. LEACHM, Leaching Estimation and Chemistry Model. a proces-based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Research Series 92-3, Dept. of Soil, Crop and Atmospheric Sciences, Cornell University, Ithaca, New York.
- IIMI, 1995. Salinity and sodicity research in Pakistan. Proceedings of a one-day workshop held on February 6, 1995, in Lahore. IIMI, Lahore, Pakistan.
- Ilyas, M., 1990. Some saline-sodic soils of Pakistan and their reclamation: a case study. PhD thesis, Utah State University, Logan, Utah.
- IWASRI, 1991. Control of waterlogging and salinity in Pakistan: A review of information and methods. Publication 21, IWASRI, Lahore, Pakistan.
- Kielen, N.C., 1996. Farmers' perceptions, their strategies and practices for dealing with salinity and sodicity in their farming systems. Report R-6, IIMI, Lahore, Pakistan.
- Kijne, J.W., and M. Kuper, 1995. Salinity and sodicity in Pakistan's Punjab: A threat to sustainability of irrigated agriculture? *Water Resources Development*, 11, 73-86.
- Maas, E.V., 1990. Crop salt tolerance. In 'Agricultural salinity assessment and management', K.K. Tanji (Ed.), ASCE Manuals and Reports on Engineering practice, No. 71, New York.
- Maas, E.V., and G.J. Hoffman, 1977. Crop salt tolerance - current assessment. *Journal of Irrigation and Drainage Division*, ASCE, 103, 115-134.
- Marlet, S., 1996. Alcalinisation des sols de la vallée du fleuve Niger. Modélisation des processus physicochimiques et évolution des sols sous irrigation. Dr. thesis, France.
- Rengasamy, P., R.S.B. Greene, G.W. Ford, and A.H. Mehanni, 1984. Identification of dispersive behaviour and the management of red-brown earths. *Australian Journal of Soil Research*, 22, 413-431.
- Rhoades, J.D., A. Kandiah and A.M. Mashali, 1992. The use of saline waters for crop production. *FAO Irrigation and Drainage Papers* 48, Rome, Italy.
- Šimunek, J., D.L. Suarez and M. Šejna, 1996. The UNSATCHEM software package for simulating the one-dimensional variably saturated water flow, heat transport, carbon dioxide production and transport, and multicomponent solute transport with major ion equilibrium and kinetic chemistry. Version 2.0. Research Report 141, Soil Salinity Laboratory, ARS-USDA, Riverside, California.

Smets, S.M.P., M. Kuper, J.C. van Dam, and R.A. Feddes, 1997. Salinization and crop transpiration of irrigated fields in Pakistan's Punjab. Submitted to Journal of Agricultural Water Management.

SSP and IIMI, 1996. Detailed soil survey of eight watercourse command areas in Chishtian and Hasilpur tehsils. Report R-19, IIMI, Lahore, Pakistan.

Tanji, K., 1990. Nature and extent of agricultural salinity. In 'Agricultural salinity assessment and management', K.K. Tanji (Ed.), ASCE Manuals and Reports on Engineering practice, No. 71, New York.

USDA, 1954. Diagnosis and improvement of saline and alkali soils. USDA Handbook 60, Riverside, California.

Annex A. General input file UNSATCHEM for reference simulation (Par 5.2.1).

```

*** BLOCK A: BASIC INFORMATION *****
Heading
Reference
LUnit TUnit MUnit (indicated units are obligatory for all input data)
cm
days
mmol
lWat lChem lTemp lCO2 lSink lRoot lShort lScreen lVariabBC lKRed
t t f f t f t t t f
NMat NLayer CosAlpha
1 1 1
*** BLOCK B: WATER FLOW TRANSPORT INFORMATION *****
MaxIt TolTh TolH (maximum number of iterations and tolerances)
20 0.0001 0.1
TopInf WLayer KodTop
t t -1
BotInf qGWLf Freed SeepF KodBot
f f t f -1
hTab1 hTabN NPar
-0.0001 -10000 9
thr ths tha thm Alfa n Ks Kk thk
0.078 0.43 0.078 0.43 0.036 1.56 24.96 24.96 0.43
*** BLOCK C: TIME INFORMATION *****
dt dtMin dtMax DMul DMul2 ItMin ItMax MPL
0.01 0.001 1 1.3 0.8 3 7 5
tInit tMax
0 365
TPrint(1),TPrint(2),...,TPrint(MPL)
120 151 273 350 365
*** BLOCK D: SINK INFORMATION *****
P0 P50 Pphi0 Pphi50
3 -2000 3 -1e+020
*** BLOCK G: SOLUTE TRANSPORT INFORMATION *****
Epsi lUpW lArtD lLagr PeCr lTort
0.5 f f f 2 f
lRate lSilica UCrit MaxChIter xConv tConv
f f 0 5 0.01 86400
Bulk.d. Difuz. DisperL. CEC Calcite SA Dolomite SA DOC
K1 K2 K3 5 150 0 0 0
1 2 2
kTopSolute SolTop kBotSolute SolBot
-1 1 0 1
nSolConc nAdsConc nPrecConc
8 8 1
Ca Mg Na K Alk SO4 Cl Tracer
1.2 1.2 12.6 0.1 9.8 5.3 1.9 1
0.7 0.9 0.2 0.1 7.5 0.3 0.4 1
0.136 0.39 14.3 0.116 9.39 5.61 2.01 0
0.195 0.0886 17.9 0.155 11.9 6.44 2.31 0
0.197 0.118 22.9 0.235 15.1 8.39 3.01 0
0.176 0.178 31.3 0.425 20.1 12 4.3 0
0.1 0.547 63.2 1.61 36.2 29.2 10.6 0
0.945 0.7 137 5.2 50 40 18 0
Ca Mg Na K
39.2 67.8 42.6 0.345
53.2 36.2 60.1 0.52
45.9 36 67.4 0.69
35.4 36 77.5 1.04
24.2 36 88.2 1.66
14.9 35.8 97 2.45
7.71 36.7 111.5 3.7
9.4 39.8 115 4.2
Calcite Gypsum Dolomite HydroMg Nesquohon. Sepiol.
500 0 0 0 0 0

```

Annex B. Top boundary fluxes applied in UNSATCHEM for the reference simulation (Par. 5.2.1).

Date	Julian day number	Water type	Water flux	Potential evaporation rate	Potential transpiration rate
			cm d ⁻¹	cm d ⁻¹	cm d ⁻¹
January 15	15			0.16	0.04
January 17	17	tubewell	3.25	0.16	0.04
February 1	32			0.10	0.10
February 3	34	tubewell	3.25	0.14	0.14
February 16	47			0.08	0.20
February 18	49	tubewell	3.25	0.08	0.20
March 1	60			0.03	0.25
March 3	62	tubewell	3.25	0.03	0.28
April 1	91			0.0	0.31
April 3	93	tubewell	3.25	0.0	0.46
May 1	121			0.09	0.37
May 3	123	canal	3.25	0.54	0.0
May 15	135			0.54	0.0
May 17	137	canal	4.35	0.54	0.0
June 1	152			0.54	0.0
June 16	167			0.46	0.12
June 18	169	tubewell	3.4	0.46	0.12
July 1	182			0.29	0.29
July 3	184	tubewell	3.4	0.27	0.27
July 9	190			0.19	0.35
July 11	192	rain	3.0	0.19	0.35
July 16	197			0.14	0.40
July 18	199	tubewell	3.4	0.14	0.40
July 23	204			0.08	0.46
July 25	206	rain	3.0	0.08	0.46
August 1	213			0.03	0.51
August 3	215	tubewell	3.4	0.00	0.51
August 16	228			0.00	0.51
August 18	230	rain	3.0	0.00	0.51
September 1	244			0.00	0.51
September 3	246	tubewell	3.4	0.00	0.51
September	259			0.00	0.51
September	261	tubewell	3.4	0.00	0.51
October 1	274			0.00	0.51
October 3	276	tubewell	3.4	0.04	0.38
November 1	305			0.10	0.32
November 3	307	tubewell	3.4	0.08	0.26
December 1	335			0.10	0.24
December	355			0.10	0.16
December	357	canal	6.5	0.23	0.0
December	365			0.23	0.0

IIMI-PAKISTAN PUBLICATIONS

CONSULTANCY REPORTS

S.No.	Title	Author	Year
C-1	Consultancy inputs for the preparation of project inception report on social organization in irrigation management	P. Ganewatte P. Pradhan	Jan 1995
C-2	Regional Salinity - Sodicty Issues in Punjab, Pakistan Consultancy Report	Dr. James W. Biggar	Apr 1996
C-3	Study of Water and Salt Balances for Eight Sample Watercourse Commands in Chishtian Sub-division, Punjab, Pakistan - Consultancy Report	E.G. van Wayjen	June 1996
C-4	Unsteady Flow Simulation of Pehur High-Level Canal Including Automatic Downstream Water Level Control Gates - Consultancy Report	Dr. Kobkiat Pongput	June 1996
C-5	Distributary Level Water Users Associations in Pilot Projects for Farmer-Managed Irrigated Agriculture, Punjab and Sindh Provinces, Pakistan	Dr. P. Pradhan	Sept 1996
C-6	Water Users Organization Program in IIMI's Pilot Projects in the Punjab and Sindh Provinces, Pakistan	Piyasena Ganewatte	Oct 1996
C-7	Soil Salinity and Sodicty in Relation to Irrigation Water Quality, Soil Type and Farmer Management - Consultancy Report	J.C. van Dam M. Aslam	Apr 1997