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**MANAGING IRRIGATION FOR ENVIRONMENTALLY SUSTAINABLE
AGRICULTURE IN PAKISTAN**

**MODELLING SOIL SALINITY AND SODICITY PROCESSES IN
AN UNSATURATED ZONE USING LEACHM: A CASE STUDY FROM
THE CHISHTIAN IRRIGATION SUB-DIVISION**

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FOREWORD

This report is the result of a modeling study on soil salinity and sodicity processes in irrigated soil profiles under the soil moisture chemistry and groundwater management Subcomponent of the Salinity Management Component of the Dutch Phase II Project, **"MANAGING IRRIGATION FOR ENVIRONMENTALLY SUSTAINABLE AGRICULTURE IN PAKISTAN"** funded by the Government of The Netherlands.

The International Irrigation Management Institute (IIMI) has been undertaking research on soil salinity and sodicity associated with irrigated agriculture in Pakistan since 1989. The goal of this research is to provide tools and methodologies to policy makers and irrigation managers to evaluate the economic and environmental impact of irrigation management interventions. Proper management of salinity and sodicity problems in irrigated areas requires a comprehensive understanding of the processes that control the movement of water and salt through the root zone of irrigated soils. This detailed understanding requires the knowledge of chemical reactions taking place when irrigation water moves through the soil profile. These chemical reactions in the root zone of an irrigated soil affect soil salinity and sodicity and the quantity (load) of subsurface drainage water.

As a first step in understanding soil salinity and sodicity processes, Dr. James W. Biggar, eminent soil chemist from the University of California, Davis, USA, visited IIMI-Pakistan for three weeks in February 1996. During his stay in Pakistan, he worked with IIMI's staff involved in the Salinity Management Study for Rechna Doab, and the Fordwah Eastern Sadiquia North (FESN). Dr. Biggar described the behaviour of sodic and saline-sodic soils, and the processes of sodification of soils in his consultancy report titled, **"REGIONAL SALINITY-SODICITY ISSUES IN PUNJAB, PAKISTAN"**. He mentioned that unless a soil is sodium-affected and is being reclaimed, the onset of sodicity is gradual and not readily detected until significant physical and chemical changes have occurred in soil profile. Regarding sodicity problem, he stressed that the cyclic use of tubewell water of poor quality with canal water of low salinity for irrigation of the same fields could cause the sodification of the irrigated soils.

This effort was continued in collaboration with CEMAGREF the French national research organization for agriculture, water and forests. This collaborative salinity/sodicity research conducted during 1996 at IIMI sample fields in southeastern Punjab, was supervised by Dr. Serge Marlet of the Centre for International Cooperation in Agricultural Research for Development (CIRAD) in Montpellier; he had spent five years in Niger doing similar salinity research. He has presented information on the geochemical processes and their effects on soil salinity and sodicity in his consultancy report titled, **"SALINIZATION OF THE IRRIGATED SOILS IN THE PUNJAB (PAKISTAN)"**. An M.S. student, Mr. Nicolas Condom, has reported the field research results in IIMI research report (R-22) titled, **"SALINIZATION, ALKALIZATION AND SODIFICATION ON IRRIGATED AREAS IN PAKISTAN"**.

During 1997, Jos van Dam from the Department of Water Resources, Wageningen Agricultural University, The Netherlands, undertaken a modeling study on soil salinity and sodicity processes using the UNSATCHEM model developed at the U.S. Salinity Laboratory during 1996. This study was undertaken using data collected by IIMI in Chistian Irrigation Sub-Division of Punjab. His findings were provided in the consultancy report titled, "SOIL SALINITY AND SODICITY IN RELATION TO IRRIGATION WATER QUALITY, SOIL TYPE AND FARMER MANAGEMENT". He mentioned that using tubewell water, sodicity, rather than salinity, 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.

The present report presents the results of a modeling study on soil salinity/sodicity processes using a soil moisture chemistry model, LEACHM (Leaching Estimation And solute transport Chemistry Model) developed at Cornell University, USA. This model was employed in order to develop predictive capabilities of soil moisture flow and solute transport in irrigated soils of four sample fields selected in the commands of Azim and Fordwah distributaries of Chishtian Irrigation Sub-division. This study also reveals that the use of tubewell water of sodic nature for irrigation is posing a soil sodification hazard, due to which the acreage of unproductive land will increase with time, which is a serious concern for long-term sustainability of irrigated agriculture in the study area. In the case of loamy soil, the entire soil profile would become sodic with the use of high residual sodium carbonate (RSC) tubewell water within the time frame of ten years.

This report culminates the research reporting for this subcomponent. We have finished describing the chemical processes occurring in the unsaturated soil profile. IIMI has benefited much from these efforts. Now, the salinity research program will focus on salinity control measures, including technologies that can be implemented by farmers.

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MODELLING SOIL SALINITY AND SODICITY PROCESSES IN AN UNSATURATED ZONE USING LEACHM: A CASE STUDY FROM THE CHISHTIAN IRRIGATION SUB-DIVISION

Chapter I

INTRODUCTION

Background

Proper management of salinity and sodicity problems in irrigated areas requires a comprehensive understanding of the processes that control the movement of water and salt through the root zone of irrigated soils. This detailed understanding requires the knowledge of chemical reactions taking place in the soil profile when irrigation water moves through the soil profile. These chemical reactions in the root zone of an irrigated soil affect soil salinity and sodicity and the quantity (load) of subsurface drainage water. The process of evaluating the chemical changes in the subsurface return flows as they move through the soil profile and are transported into the ground water reservoir is called soil moisture chemistry modeling. The primary objective of soil moisture chemistry simulation is to model soil moisture flow, the chemical reactions (cation exchange, precipitation and dissolution of gypsum and lime), and the transport of salts. For this purpose, many computer models have been developed.

The soil moisture chemistry and groundwater management modeling is a supportive subcomponent of the Salinity Management Component of the Dutch Phase II Project, *Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan*. The Salinity Management Component of the project has the objectives: (1) to assist in the establishment of the physical and chemical (salinity and sodicity) processes occurring in the unsaturated soil profile between the ground surface and the groundwater table and the spatial and temporal variation of salinity in the groundwater reservoir resulting from pumping, (2) to identify salinity management alternatives for the Rechna Doab in the Punjab, and (3) to assess potential opportunities for alleviating extreme conditions of waterlogging and salinity in the province of Sindh that would result in environmentally sustainable agricultural production.

The present study on modelling soil salinity and sodicity processes in irrigated soil profiles falls under the abovementioned soil moisture chemistry and groundwater management modeling supportive subcomponent of the Salinity Management Component of the Dutch Phase II Project. Soil moisture chemistry modeling provides the predictions of variations in the salinity and sodicity in the soil profile and of subsurface return flows entering the groundwater reservoir. Many computer models have been developed for simulating soil moisture flow and solute transport in the unsaturated soil profile considering the chemical reactions taking place in the root zone. For the present study, an existing soil moisture chemistry model, **LEACHM (Leaching Estimation And solute transport**

CHemistry Model) was employed in order to develop predictive capabilities of soil moisture flow and solute transport in irrigated soils of four sample fields selected in the commands of Azim and Fordwah distributaries of Chishtian Irrigation Sub-division.

Study Objectives

The main objectives of the study are:

- To apply a transient solute transport model for simulating water and solute transport in the unsaturated zone of irrigated soils;
- To predict temporal salinity/sodicity trends in soils under various irrigation management scenarios; and
- To evaluate LEACHM as a research tool to be used for IIMI's research work.

Chapter II

REVIEW OF LITERATURE ON WATER FLOW AND SOLUTE TRANSPORT MODELS

To study salt transport in soils, consideration should be given to both the water flow and the salt flow. Biggar and Nielsen (1967, p. 254) stated that

Such considerations become particularly important in irrigated agriculture when it is desirable to know the concentration and location of a dissolved constituent in the soil profile, the removal of undesirable constituents, the reactions of the constituents with each other, and the soil matrix during the displacement, and transport of water and solutes to plant roots.

Jury (1982) and Addiscot and Wagenet (1985) provided an excellent review of solute transport modeling approaches and discussed their utility and limitations depending on their degrees of complexity. They concluded that solute transport models differ greatly in complexity and utility, ranging from simple steady-state models which do not consider chemical reactions, to complex dynamic models which consider all major soil-solution reactions. The usefulness of solute transport models in making predictions of field conditions is limited by the inadequacy of water flow models in describing the spatial and temporal distribution of water flow. However, the solute transport model is a very valuable tool to study the relative behavior of different irrigation waters, different soil types, or different water management alternatives when a scenario for drainage ion composition is produced.

Various solute transport models have been developed for simulating soil water movement and salt transport through irrigated soil profiles. This chapter presents a detailed review of literature on these models.

Water Flow Models

The basic soil-water flow equation for non-steady vertical one-dimensional flow is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(\theta) \frac{\partial H}{\partial z} \right] + A(z, t) \quad (1)$$

where θ is the volumetric water content; t is time; z is depth; $K(\theta)$ is the hydraulic conductivity; H is soil hydraulic head; and $A(z, t)$ is the root-extraction term (sink term) representing water lost per unit time by transpiration. The above equation without the sink term is called the Richards Equation.

Equation 1 can be written in a more convenient form called the water content form as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[D(\theta) \frac{\partial \theta}{\partial z} + K(\theta) \right] + A(z, t) \quad (2)$$

where $D(\theta)$ is the soil water diffusivity. Equation 1 in pressure head form is given as:

$$\frac{\partial h}{\partial t} C(\theta) = \frac{\partial}{\partial z} \left[K(\theta) \frac{\partial H}{\partial z} \right] + A(z, t) \quad (3)$$

where h is the pressure head and $C(\theta)$ is the water capacity equal to $\partial \theta / \partial h$.

The above mentioned partial differential equation for water flow has been solved by many investigators using different techniques with or without considering the sink term. Some of these solutions are discussed below.

Analytic Solutions

The analytic solutions are very important in order to understand the different aspects of water flow in soils. They also provide a standard for comparison against which numerical models can be checked. Some of the analytic solutions are being reviewed below.

Brutsaert (1968a; 1968b) obtained an analytic solution to the Richards Equation by transforming this equation into an ordinary differential equation using the Boltzmann transformation technique. He developed functional forms for the conductivity and soil moisture characteristic and substituted an approximation for the transformed terms on the right-hand side of the equation. Then, he integrated the equation and got an analytic solution for soil moisture content with depth.

Gardner et al. (1970) solved the Richards Equation analytically for water redistribution. They solved the equation using a variable separation method by assuming functional forms for conductivity and diffusivity as power functions of water content, and that the matric potential is proportional to $\exp(-B\theta)$, where B is a constant and θ is water content. They obtained the solutions for redistribution with and without considering gravity terms and found a good agreement between the theory and experimental results.

Parlange (1971a; 1971b) derived an analytic representation for solution of the infiltration equation. He transformed the water content form of the Richards Equation into an equation with z as the dependent variable and approximated the water content profile by integrating while neglecting the unsteady term. The unsteady term was calculated using this approximation and was substituted into a differential equation which was integrated to get a second approximation. The soils were assumed as homogeneous and isotropic throughout the profile. He compared this water content profile with that calculated with a numerical method and found a complete numerical agreement.

Numerical Solutions

Though analytic solutions are very important for understanding the flow systems, most of the time the water flow equation offers great difficulty in being solved analytically because of complexities in the flow systems. For instance, no analytical solutions are possible for vertically heterogeneous soils or soils with strongly non-linear soil hydraulic characteristics. Also, the dynamic change of boundary conditions in the field is difficult to reproduce by analytical models. That is why investigators now use numerical techniques (more commonly the finite difference and finite element methods) in order to solve the water flow equation. Some of the numerical solutions with and without considering the sink term (root-extraction term) are discussed below.

Philip (1957) developed a partial differential equation to describe both horizontal and vertical infiltration of water. He also formulated the numerical methods for solving this equation for initial and boundary conditions corresponding to absorption or desorption in the horizontal and vertical columns. For vertical infiltration, the solution is given as an infinite series:

$$z = \sum_{n=1}^{\infty} f_n(\theta) t^{n/2} \quad (4)$$

where z is the depth to a particular water content and t is time. The coefficient $f_n(\theta)$ is calculated from diffusivity and conductivity functions.

Hanks and Bowers (1962) developed the most widely known numerical solution to the general water flow equation. They solved the pressure form of the equation, including a gravity term, for infiltration into a layered soil using a Crank-Nicolson (Crank and Nicolson, 1947) implicit technique. They considered the critical part of the solution of the difference equations system to be the selection of the hydraulic parameters (hydraulic conductivity and water capacity) and the time interval. They did not incorporate the sink term in the solution and considered the soil properties uniform through each layer. They found a good agreement between calculated and measured water content profiles for horizontal infiltration when compared with Philip's (1957) numerical analysis.

Whisler and Klute (1965) obtained a numerical solution of the soil-water flow for a system consisting of a vertical column of soil drained from saturation to equilibrium with a water table considering hysteresis. A thin layer of ponded water was assumed to be applied to the top end of the column. The solution of the equation simulated the time and depth distributions of water content and pressure head during the resulting infiltration.

Rubin (1967) formulated a numerical method to be applied to the basic water flow equation to analyze the post-infiltration redistribution of water in a semi-infinite vertical soil column assuming the soils to be homogeneous and isotropic throughout the profile. He

considered the effects of hysteresis of the soil moisture characteristic, which proved to be very important in analyzing the redistribution processes.

Wang and Lakshminarayana (1968) developed a numerical technique to solve the explicit-implicit difference scheme analogue for the parabolic nonlinear partial differential equation, which was used to simulate the water flow through unsaturated non-homogeneous soils. They used numerically average field data for the entire soil profile for the conductivity-water content relationship and the soil-water characteristics. Comparisons between computed and field measured water content profiles in a non-homogeneous soil were good.

Freeze (1969) developed a numerical solution using an implicit finite difference method for a mathematical model of one-dimensional, vertical, unsteady, unsaturated flow above a recharging or discharging ground-water flow system. He considered homogeneous and isotropic soils and the hysteresis of the soil moisture characteristic, but he did not take into account the sink terms. He presented the solutions in the form of pressure head, total head, and moisture content profiles and found that hysteresis is a very important factor to be considered in calculating infiltration, redistribution, and drainage through the soil.

Hanks et al. (1969) developed a numerical model using a finite difference technique for estimating one-dimensional infiltration, redistribution, evaporation, and drainage of water from unsaturated soil considering the hysteresis in the water content-pressure head relation. They assumed that unsaturated hydraulic conductivity is not affected by hysteresis, but is dependent on water content only. They did not include the sink term in the solution. They found a good agreement between measured and simulated values of infiltration, redistribution, and evaporation.

Staple (1969) solved the soil moisture movement equation using an explicit difference technique to compute the redistribution profiles taking into account the hysteresis in the soil moisture characteristic. He measured water redistribution in three soils following two different initial amounts of infiltration and then compared the computed redistribution profiles with measured redistribution profiles. He found a satisfactory agreement between the measured and computed redistribution profiles.

Bhuiyan et al. (1971) used a dynamic simulation language to develop a computer model for simulating the vertical one-dimensional water infiltration into unsaturated soil without considering the sink term. This model was based upon the principles of conservation of mass and Darcy's Law. The model gives a complete picture of the water intake characteristics of a soil by calculating water content profiles, infiltration rate and cumulative infiltration with time. The model gave an excellent comparison between the results obtained by this model and those obtained by Philip's numerical analysis (1957) under the same boundary and initial conditions.

Nimah and Hanks (1973a; 1973b) developed a model to predict water content profiles, evapotranspiration, water flow from or to the water table, root extraction, and root water potential under transient field conditions using the general one-dimensional flow equation given below:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(\theta) \frac{\partial H}{\partial z} \right] + A(z, t) \quad (5)$$

where θ is the volumetric water content; t is time; z is soil depth; K is the hydraulic conductivity; H is the hydraulic head, and $A(z, t)$ is the root extraction term defined as:

$$A(z, t) = \frac{[H_{\text{root}} + (RRES \cdot z) - h(z, t) - s(z, t)] [RDF(z) k(\theta)]}{(\Delta x \Delta z)} \quad (6)$$

where H_{root} is the soil water potential in the root at the soil surface; $RRES$ is a root resistance equal to $1 + R_c$; R_c is a flow coefficient in the plant root system assumed to be 0.05; $h(z, t)$ is the soil pressure head; $s(z, t)$ is the osmotic potential; $RDF(z)$ is the proportion of total active roots in depth increment Δz ; and Δx is the distance between the plant roots at the point in the soil where $h(z, t)$ and $s(z, t)$ are measured. They solved the model using a finite difference technique in which the root extraction term was also finite differenced and solved as part of the Richards Equation. The basic input data required for the solution of the model are hydraulic conductivity and soil water potential as a functions of water content, air dry and saturated water content, rooting depth, limiting root water potential, water content-depth at the beginning (initial conditions), potential evaporation and potential transpiration rate, osmotic potential of the irrigation water (boundary conditions) and osmotic potential-soil depth data (initial conditions), and presence or absence of a water table at the bottom of the soil profile (boundary condition).

Van der Ploeg and Benecke (1974) developed a computer model using a dynamic simulation language to predict vertical and horizontal infiltration processes in one, two and three dimensional infiltration problems. The model gave excellent comparisons for horizontal infiltration studies when compared with Philip's numerical analysis.

Haverkamp et al. (1977) made a comparison of six numerical simulation models for one-dimensional infiltration in terms of execution time, accuracy, and programming considerations. They found a good agreement between measured water content profiles and those predicted by six models and also among the results obtained with these models. They found an excellent correlation between water content distributions, infiltration rates and cumulative infiltration volumes obtained by the implicit finite difference solution and Philip's quasi-analytical solution. From their study, they concluded that the implicit finite difference approximation with implicit or explicit evaluation of the hydraulic conductivity and water capacity functions has the widest range of applicability for predicting water movement in both saturated and unsaturated soils.

Kabala and Milly (1990) presented a numerical model developed by solving Richards Equation using a finite element method to simulate the movement of water in unsaturated heterogeneous soils and made sensitivity analyses of the model. The model produced results that match with exact analytical or semi-analytical solutions.

Campbell (1991) developed a computer model to predict root water extraction and plant water status for a given soil-plant-atmosphere system. This model considers water uptake from a uniformly rooted soil layer and from a soil with spatially varying root density. This model gave good agreement between measured and predicted water uptake and soil water profiles.

Hanks et al. (1991) presented a numerical model called SOWATET (soil-water-crop atmosphere-irrigation management model) to simulate infiltration and redistribution of water in a uniform soil with a known initial water content profile and with different intensities of water added to the soil surface. This model gave a good agreement between the measured and predicted results of infiltration and redistribution and evaporation and drainage from a soil. This model is very sensitive to matric potential and hydraulic conductivity versus water content relations. If these relations change with time, and rainfall or water additions occur with high rates, the model will give incorrect results, unless the model is modified to consider these changes. That is why Hanks recommended that "Always keep one foot in the field" when using this model.

Solute Transport Models

The salt flow models can be categorized as: solute transport models without chemical reactions; chemical equilibrium models; and cation exchange models. These models are reviewed in the following sections.

Models Without Chemical Reactions

The solute movement through soil can take place by means of three processes: chemical diffusion in the liquid phase in response to an aqueous concentration gradient; if the chemical is volatile, diffusion in the gas phase can take place in response to a gradient in gas concentration; and physical convection (mass flow) of the chemical can occur as a result of the movement of the bulk phase (water) in which the chemical is dissolved. There may also be sources or sinks for the solute specie. Wagenet and Hutson (1987) expressed the physical convection and chemical diffusion, which when combined displace the solute in the soil, in an equation form which is called the convection-dispersion equation (CDE). This equation describes the salt transport process in the soil. The CDE in one dimension is:

$$\frac{\partial(\theta C)}{\partial t} = \partial[\theta D(\theta, q) \partial C / \partial z - qC] / \partial z + S \quad (7)$$

where θ is the volumetric moisture content, t is time, z is soil depth, $D(\theta, q)$ is the apparent diffusion that accounts for dispersion and diffusion which affect ion solute movement in the liquid phase; C is chemical concentration; q is water flux; and S is a sink term for chemical species. The solution of the CDE gives the estimation of salt transport.

Biggar and Nielsen (1962) considered the principal mechanisms of transport of dissolved ions to be convection within flowing soil water, dispersion of the solutes due to the variations in local soil water velocity, and diffusion of the dissolved solutes within the soil solution. Their model was tested in many laboratory experiments and found valid for isotropic and homogeneous porous media.

Nielsen and Biggar (1962) developed a miscible displacement (the process that occurs when one fluid mixes and displaces another fluid) model to describe miscible displacement in porous materials. They stressed experimental work to obtain the interactions between the velocity distribution and diffusion and then to include in the model the transport of solute through the soil more accurately. They considered that convection, dispersion, and diffusion are important processes for describing the solute transport in soils.

Miller et al. (1965) investigated the movement of chloride through the soil relative to the movement of water under field conditions using three soil water treatments. They found that chloride could be leached more effectively if the soil was kept unsaturated during water infiltration than if the surface was ponded.

Bresler (1967) developed a mathematical model based upon the law of mass conservation to predict the transport of noninteracting solutes. This is a linear model which considers the initial salinity, water-retention properties, moisture use in each soil layer, and the quantity and quality of water applied during each irrigation. Bresler compared the measured chloride profiles with those calculated by the model and found a good correlation between them.

Bresler and Hanks (1969) developed a numerical solute transport model by combining a water flow model presented by Hanks et al. (1969) and a salt flow model developed by Bresler (1967). This model, which does not take into account the diffusion and the source and the sink processes, can be used to predict the transport of noninteracting solutes in unsaturated soils under transient field conditions. The simulated solute profiles were found to be in good agreement with the measured solute profiles.

Rasheed (1970) developed a model based on plate theory to investigate solute transport in soils. In this model, the soil profile was divided into n layers of about 30 cm thickness each. The mass balance for a layer was given by the following equation:

$$C_e d_e + C_o d_o = C_i d_i + C_f d_f \quad (8)$$

where C is concentration; d is water depth; and e, o, l, and f are subscripts representing entering, initial, leaving, and final concentration and water depths. Water is allowed to flow only downwards after the water content reaches field capacity.

Terkeltoub and Babcock (1971) developed a model based on plate theory to study the movement of non-interacting salts through a soil profile having a uniform initial salinity concentration and water content. This model considers only mass flow and describes the flow type as a downward flow after the water content reaches field capacity in a soil layer. The input data required for the model are; the initial soil salinity, the initial and field capacity soil moisture contents, and the salinity of the irrigation water. There was a good agreement between predicted and measured concentration profiles.

Warrick et al. (1971) analytically solved the convection-diffusion equation for simultaneous salt and water flow. They assumed one-dimensional steady flow in homogeneous soils and used the finite difference technique developed by Hanks and Bowers (1962) to simulate the water infiltration. They tested the model in the field for the movement of the chloride ion by neglecting the sink-source terms. Good agreement was found between predicted and measured chloride profiles when a value for the dispersion coefficient was selected which was in excess of laboratory values measured at similar water velocities.

Bresler (1973) developed a numerical model to simulate transient one-dimensional simultaneous movement of noninteracting solute and water in unsaturated soils. He solved the water flow and convection-diffusion equations using a finite difference technique and tried to eliminate the effect of numerical dispersion. He did not consider the sink term in his model.

Bresler and Laufer (1974) developed a model to simulate nitrate in soils under transient unsaturated flow conditions. They solved the water and salt flow equations by a finite difference method. They found a reasonable agreement between predicted and measured water and nitrate distributions.

Hanks et al. (1974) developed a numerical model to simulate salt flow through the soil. They adapted the solution procedure developed by Bresler (1973) assuming unequal depth increments. They did not consider any precipitation or dissolution of salts within the profile.

Childs and Hanks (1975) developed a water flow-salt flow model to study solute transport in soils. In this model, the solute transport is estimated by solving the following equation by a finite difference method:

$$\frac{\partial C(\theta)}{\partial t} = \frac{\partial}{\partial z} \left[D(\theta, q) \frac{\partial C}{\partial z} \right] - \frac{\partial qC}{\partial z} \quad (9)$$

where C is the solute concentration; $D(\theta, q)$ is the diffusion; and q is the water flux. This model also included a dynamic root growth function, hourly evaporation and transpiration rates, relative crop yield, and considered salinity effects on crop growth and water uptake.

Davidson et al. (1975) solved the transport equation including a sink term for predicting simultaneous movement of water and adsorbed solutes through a soil profile under transient flow conditions. The soil moisture movement equation was solved by using an implicit-explicit finite difference method and the solute flow equation was approximated using an explicit finite difference technique. There was a good agreement between the predicted and measured water and solute distributions.

Jury (1975a; 1975b) developed a model for estimating solute travel times and effluent water quality for tile-drained soil profiles for cases of ponded and unsaturated infiltration. This model, based on purely convective flow in a steady state-system, describes a characteristic travel time which allows a determination to be made of the relationship between solute input and drain output as a function of time or discharge. The comparison of measured tile-drained effluents and solute flux with those predicted by the model showed good agreement.

Smajstrla et al. (1975) developed a numerical simulation model for predicting the movement of water and solute through homogeneous and isotropic unsaturated porous media. The water flow component of the model was based on the law of conservation of mass and Darcy's law and was solved by a finite difference method, whereas the salt component (convective-dispersion equation) was solved by characteristic and finite difference methods.

The comparison of predicted results with analytic results and other simulated results from the literature showed good agreement.

Hillel et al. (1976) presented a dynamic numerical model based on the transport equations for water and noninteracting solutes in soils for computing the water and salt flow through soils considering an active root system. The input data required for the model are soil and root system hydraulics, initial water content and solute concentration, density and distribution of active roots in the soil profile, and the evapotranspiration rate.

Jury et al. (1976) developed a one-dimensional simulation model based on mass balance for nitrate and chloride movement through the soil. The physical processes modeled were dispersion, convection, plant uptake, nitrification, and mineralization. Predicted and measured nitrate concentrations in lysimeter drainage were in good agreement when the nonuniform infiltration pattern was included into the model.

Elprince and Day (1977) made an effort to improve the convection-dispersion model to investigate the solute transport through aggregated soils where a simple model could not predict solute transport accurately. They divided the water volume into a mobile region and an exclusion volume where water is stagnant and salt is excluded.

Van de Pol et al. (1977) investigated solute and water movement under steady-state conditions in a field soil and they found the pore water velocity and apparent diffusion coefficient log-normally distributed and consequently a log-normal variation in salt concentration at a given soil depth.

Van Genuchten et al. (1977) developed an analytical model for the movement of chemicals through unsaturated sorbing media. In this model, the liquid phase in the soil is divided into mobile and immobile regions, where the diffusion transfer between two liquid regions is assumed to be proportional to the concentration difference between the mobile and immobile liquids. The comparison between the predicted and measured effluent concentration distributions gave a good correlation.

Wierenga (1977) made a comparison between a steady-state model (water content and flux are constant during irrigation with time or depth) and a transient model (water content and flux are variable with time and depth) for simultaneous movement of water and salts in soil profiles. He used the following convective-dispersion equation to describe the movement of noninteracting solutes through soil with constant water content and pore water velocity:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - V \frac{\partial C}{\partial x} \quad (10)$$

where C is the solute concentration; V is the average pore velocity; D is the dispersion coefficient; x is the distance; and t is time. The above CDE has been solved analytically for specific initial and boundary conditions. The comparison between the results obtained by these two models showed that both models give comparable output data when the solute concentrations are plotted against cumulative drainage. Wierenga concluded that the steady-state model could be used successfully to predict solute transport in field soils.

Dagan and Bresler (1979) presented a theory for investigating noninteracting solute dispersion in heterogeneous fields from a macroscopic point of view and proposed that solute transport be modeled stochastically.

Beese and Wierenga (1980) developed a transient solute transport model and a steady-state solute transport model for predicting the movement of water and salt through soil profiles with and without adsorption and with and without root water uptake. They compared the solute distribution profiles obtained with the transient water and solute flow model to those obtained with the steady state model called the constant infiltration transport

model. They found that for soil profiles underlying both bare and cropped fields, and also for both adsorbing and nonadsorbing chemicals, when the solute concentration in the drainage water is plotted against the cumulative drainage depth, smooth concentration distributions are obtained and that these smooth concentration distributions can also be simulated by the steady state model, which requires the average water content in the soil profile, the average drainage rate, the root distribution, the adsorption coefficient, and the dispersion coefficient.

James and Rubin (1986) studied the Cl^- ion transport in an unsaturated soil by using miscible displacement methods. They compared the measured unsaturated Cl^- concentration profiles with those calculated with a model based on convection-dispersion theory and obtained good agreement between them. They concluded that the chemical process of anion exclusion should be included in the solute transport model to predict the movement of anions in the unsaturated soils.

Kapoor and Pal (1986) used two models, a miscible displacement model and a cation exchange model, to predict the accumulation of total salts and exchangeable sodium in a sandy loam soil after redistribution and evaporation, resulting from irrigations with either saline sodic water or rain. There was a good agreement between measured and predicted values of electrical conductivity, EC, and exchangeable sodium percentage, ESP.

Elrick et al. (1987) developed the approximations to convert an exact analytic solution of one-dimensional solute transport during infiltration into the simplest approximate solution applicable to field models. The simplest model gave absorption and infiltration profiles of salts reasonably comparable with experimental results.

Knighton and Wagenet (1987a; 1987b) developed a simulation model called CTMP based on a continuous time Markov process (stochastic approach) to predict solute movement through the soil under steady-state water flow conditions. This model included chemical and biological degradation, crop uptake, and adsorption as processes that affect the probability of movement of solutes between adjacent soil layers. This model gave comparable results for noninteracting solutes with those measured in the laboratory under steady-state water flow conditions. They extended this model to transient water conditions under fallow and cropped field soils and obtained good results.

Jardine et al. (1988) studied the transport of cations and anions through large undisturbed soil columns from two watersheds. The solute transport equation for convection-dispersion was used to describe the movement of both nonreactive and reactive solutes.

Russo et al. (1989a; 1989b) investigated the transport of nonreactive solutes under transient water flow considering hysteresis, soil heterogeneity, and the immobile effect on solute transport. They found that under transient water flow, when the hysteresis effect is

significant and the soil profile is nonhomogeneous, transient models ignoring hysteresis and soil profile heterogeneity could overestimate solute velocity because both hysteresis and soil heterogeneity change the water content profile and consequently retard the solute transport relative to that simulated if the soil water system is considered as homogeneous and non-hysteretic. They used a modified two-component, mobile-immobile soil moisture model to study the immobile water effect on solute transport and found that the results obtained by the transient two-component model were significantly different from those predicted by the steady-state model.

Jury et al. (1990) developed a transient solute transfer function model called TFM to simulate the transient solute transport for transient water flow under field conditions. This model represents macroscopic solute dispersion and convection in terms of the field-average drainage past the depth of observation. The drainage function is developed from a field-scale water-balance model, which is interfaced with a solute transport and dispersion model obtained from assuming steady-state conditions. The model produced a good representation of the field data.

Saleh et al. (1990) evaluated the convection-dispersion model, the micropore-macropore, and the mobile-immobile zone model to describe the transport of nonsorbed chemicals in the subsurface environment. They also modified an existing mobile-immobile zone model assuming that the molecule transport between the mobile-immobile zone is reversible and that the flow partitioning coefficient is dependent on many variables, among which are flow velocity and the soil specific surface area. This model could be used to predict the transport of nonsorptive solutes under a variety of experimental conditions.

Bresler (1991) stressed the stochastic modeling approach for porous media flow and solute transport of inert salts in heterogeneous soils because a stochastic model can represent the spatially variable soils realistically, whereas traditional models do not represent the actual field conditions in non-homogeneous soils.

Hanks and Cui (1991) presented a numerical model called SOWATSAL (SOil Water, solute Transport, SALT) by including salt flow and its effects on plant growth into the model called SOWATET developed by Hanks et al. (1991) to predict salt flow with soil water flow in the soil profile. This model considers root uptake of pure water leaving salt behind, as well as salt flow to or from the water table but does not take into account chemical exchange, precipitation or dissolution reactions. There was a good agreement between measured and predicted results.

Cation Exchange Models

Cation transport through a soil profile with negatively charged mineral surfaces is more complex than anion transport because of exchange adsorption. Many investigators have studied the transport of the main cations (Ca, Mg, Na and K) in irrigation water because of their significance in the reclamation of irrigated soils by leaching. The exchange equations

can be evaluated as the equilibrium relationship given by the following equation (Robbins, 1979):

$$\frac{[N^{+b}]_b^1}{[M^{+a}]_a^1} = K \frac{X_b^1}{X_a^1} \quad (11)$$

where M and N are either cation solution concentrations or activities depending on the derivation definitions; K is the selectivity coefficient; a and b are the ionic charges of ions M and N respectively; and X_M and X_N are the exchangeable cation concentrations. For example, selectivity coefficient (K₂) for Na-Ca cations for equilibrium between their solution activities and the exchangeable concentrations can be calculated by the expression:

$$K_2 = \frac{(Na) X_{Ca}}{(Ca)^{1/2} X_{Na}} \quad (12)$$

where (Ca) and (Na) are the Ca and Na solution activities and X_{Ca} and X_{Na} are the Ca and Na exchangeable concentrations. Some of the cation exchange models are reviewed in the following sections.

Sommerfeldt (1962) made a study to determine the effect of anion environment on the amounts of cations adsorbed by soils and found that the adsorption capacity of soil material did not remain constant with anions in the system. Thus, total exchangeable cations, exchangeable sodium, and exchangeable calcium plus magnesium were greatly affected by the anions in the soil. They concluded that it is important to consider precipitation for obtaining cation concentrations for estimating the values of the selectivity coefficients.

Babcock and Schulz (1963) studied the effect of anions on the sodium-calcium exchange in soils. They concluded that the calculation of exchangeable sodium percentage should be based on activities rather than concentrations in order to consider the effect of anions on cation-exchange reactions.

Dutt and Doneen (1963) developed a computer model to predict exchangeable Ca^{2+} , Mg^{2+} , and Na^+ concentrations in saturated extracts from soils undergoing salinization with waters containing Cl^- and SO_4^{2-} salts of one or more of the cations, Ca^{2+} , Mg^{2+} , and Na^+ . The model predictions of cation concentrations were in good agreement with those obtained by experiment.

Dutt and Anderson (1964) evaluated the procedures previously developed to predict the ionic composition of the soil solution in the moisture range between field capacity and permanent wilting when waters containing various salts are added to soils.

Clark (1966) found a constant value of 1.06 for the Ca-Mg exchange selectivity coefficient in Wyoming bentonite for a pH range of 3.5 to 9.2. There is, however, a pH dependent charge component of the cation exchange capacity in some exchange materials found in soils.

Rao et al. (1968) estimated the values of the selectivity coefficients for a given system by changing the anion ratios and concentrations, when ionic strength and ion pair formation corrections were applied to the solution cation activities.

Lai and Jurinak (1971) developed a cation exchange model to study the cation exchange process in soil columns during the miscible displacement of cation solutions by assuming equilibrium between the cation adsorbed and cation in solution. They solved the material balance equation which describes the miscible displacement of cations and involves an exchange function using a finite difference technique. They found good agreement between the predicted and measured results and they concluded that equilibrium in a soil column is dependent not only on the flow velocity of the percolating fluid, but also on the cation exchange properties of the soil.

Dutt et al. (1972) developed a water flow-salt flow model which considered the processes of dissolution, precipitation, ion pair formation, and changes due to chemical and biological processes. They also considered the processes of cation exchange for Ca, Mg, and Na. They employed the following equation to estimate exchangeable Ca:

$$X_{Ca} = \frac{CEC}{\left[\frac{(Ca)^{\frac{1}{2}} K_2}{(Na)} + \frac{(Mg) K_1}{(Ca)} + 1 \right]} \quad (13)$$

where X_{Ca} is the exchangeable Ca concentration; CEC is the cation exchange capacity; K_1 and K_2 are the selectivity coefficients for the Ca-Mg and Na-Ca exchange relationships, respectively; and (Na), (Ca), and (Mg) are the sodium, calcium, and magnesium activities in solution. They obtained the value of the exchangeable Na concentration, X_{Na} , by Eq. 13 for (Ca) and (Na) and then they estimated the value of exchangeable Mg concentration X_{Mg} by the following expression:

$$X_{Mg} = CEC - X_{Ca} - X_{Na} \quad (14)$$

Jury et al. (1979) performed a lysimeter study to reclaim saline-sodic soils by ponded or unsaturated leaching following a saline irrigation. They used a chromatographic displacement model consisting of standard cation exchange equilibrium equations to describe the exchangeable Na reduction as a function of the leaching pore volume and another model

to calculate exchangeable Mg reductions. The predicted reductions in exchangeable Na and Mg concentrations were in good agreement with those measured in the experiment.

Cho (1985) developed a mathematical model to study the transport of two ions in an exchange material solving numerically two simultaneous transport equations for ion A and ion B. He studied the changes in the concentration distributions by using different values of selectivity coefficients for ion exchange reactions, valences of A and B, the amount of incoming concentration, and CEC under a constant flow rate of soil solution and a constant dispersion coefficient. He found that the cation exchange capacity, CEC, selectivity coefficient, and concentration of the displacing solution are very important for obtaining the shape of the distribution curves for both displacing and displaced ions.

Bond and Phillips (1990a; 1990b) obtained analytical solutions for the transport of reactive solutes during the unsteady flow of water in unsaturated porous media. The developed solutions could be applied to solutes which undergo adsorption reactions including ion exchange, specific adsorption, or negative adsorption. There was a good agreement between measured and predicted concentration distributions.

Chemical Equilibrium Models

In the following section, some of the models developed to study the chemistry of soil systems which included gypsum and lime equilibria and cation exchange reactions will be discussed.

Dutt and Tanji (1962) developed a computer model to predict the concentrations of solutes in the water leached through soils containing gypsum and exchangeable Ca^{2+} and Mg^{2+} . There was a reasonable correlation between the predicted and measured solutes concentrations.

Tanji et al. (1967) developed a model to compute the solute concentrations in the waters percolating through a moist layered soil column by modifying the solute transport model developed by Dutt and Tanji (1962), which was originally designed to simulate salt concentrations in water percolating through an initially air-dry, non-layered soil column. This model considered the solubility and dissociation of gypsum and cation exchange. Water content during percolation and solute transport were reasonably estimated.

Bower et al. (1968) developed a chemical model involving CO_2 , CO_3 , HCO_3 , and pH interactions to estimate lime CaCO_3 precipitation or dissolution and its effects on the sodium adsorption ratio, SAR, and the exchangeable sodium percentage, ESP.

Nakayama (1969) discussed in detail the $\text{Ca-SO}_4\text{-HCO}_3\text{-CO}_3$ interactions in solution and provided an overview of the combined lime CaCO_3 and gypsum $\text{CaSO}_4\cdot 2\text{H}_2\text{O}$ interactions in soil-water systems.

Tanji (1969) developed a computer model to predict ion association and gypsum solubility in simple and mixed aqueous electrolyte systems. The input data required for the model to predict equilibrium concentrations are nonequilibrium solute concentrations, solubility product of gypsum and the dissociation constant for CaSO_4^0 , MgSO_4^0 , and NaSO_4^- . There was a good agreement between the predicted and measured cationic activities and gypsum solubility.

Oster and McNeal (1971) developed three solute models for estimating the change in soil solution composition and electrical conductivity, EC, as the moisture content changes due to evaporation or transpiration in unsaturated soils. They used laboratory data on the composition of the soil-saturated extract, the soil cation exchange capacity, the percent water at saturation, the field water content, and the partial pressure of CO_2 at laboratory atmosphere to compute the concentrations and activity coefficients of ion and ion pairs and the degree of super-saturation with respect to calcite and gypsum. They obtained good agreement between predicted and measured EC values.

Tanji et al. (1972) developed a steady-state land reclamation leaching model to approximate chemical changes in salt-affected profiles undergoing reclamation leaching. This model considered cation exchange and gypsum solubility, but did not consider lime.

King and Hanks (1973) devised a detailed salt transport model which combined the water and salt flow model of Bresler and Hanks (1969) and the chemistry model of Dutt et al. (1972). They modified the moisture flow model of Hanks et al. (1969) by adding a plant root extraction term. They also included the reactions of the dissolution or precipitation of gypsum, the formation of undissociated Ca and Mg sulfate, the dissolution or precipitation of lime, and the cation exchange reactions for Ca, Mg, and Na. The comparison of measured and predicted salt concentrations was found to be better for total dissolved solids, TDS, than for individual ions.

Oster and Rhoades (1975) developed a computer simulation model to predict the equilibrium chemical composition (the values of Ca, Mg, Na, SO_4 , HCO_3 , SAR, and EC) of irrigation drainage water by using the input data on irrigation water composition, leaching fraction, and the CO_2 partial pressure within the soil profile. Equilibrium speciation (chemical composition) of drainage water was estimated by successive calculations of the concentrations of each chemical ion using appropriate equilibrium constants. The comparison of predicted and measured drainage water speciations gave a good agreement. The model was employed to predict the salinity, sodicity, and pollution hazards of irrigation waters in terms of minimum leaching fractions required for maintaining satisfactory salinity and sodicity levels.

Shaffer (1976) developed a detailed model based on the law of the conservation of mass to simulate irrigation water return flow salinity and nutrient movement in the plant-soil-aquifer system. This model simulates unsaturated and saturated water flow, solute transport,

and biological and chemical processes occurring in the soil. At transient conditions the model simulates concentrations of Ca^{2+} , Mg^{2+} , Na^+ , HCO_3^- , CO_3^{2-} , Cl^- , SO_4^{2-} , NO_3^- , NH_4^+ , organic-N, and urea using chemical equilibrium and chemical kinetic theories for chemical reactions. This model has been verified in laboratory and field studies.

Melamed et al. (1977) developed a salt flow model by including a source-sink term in the model presented by Childs and Hanks (1975) to predict chemical precipitation and dissolution during the movement of the solute in the soil. This model was tested under both laboratory and field conditions.

Jury et al. (1978a; 1978b) coupled a water flow-salt flow model with a chemical equilibrium model to study the transient changes in soil solution concentrations and salt precipitation rates with saline irrigation water in order to estimate the effect of soil water concentration on plant roots, and to estimate the salt balance and environmental impact of the drainage water. The transient soil solution concentrations and salt precipitation rates were shown to be affected by the ion composition and concentration of the applied water and soil exchange complex, the water uptake distribution, and infiltration rate.

Glas et al. (1979a; 1979b) developed a model to simulate the dissolution and transport of gypsum in soils using two approaches. The first approach is based on equilibrium principles and a mixing-cell concept and the second approach is based on a combination of the one-dimensional convection-dispersion equation and a kinetic expression for the dissolution process. They concluded from the comparison between experimental results and model predictions that the gypsum dissolution reaction depended on time and could not be controlled by solubility product relationships.

Jury and Pratt (1980) used a proportional model, a steady-state model, and a transient model to predict the salt concentrations and mass emissions of irrigation drainage water below irrigated fields. The proportional model characterizes irrigation management in terms of an average ratio of drainage volume to irrigation volume and considers no reactions within the soil solution. The steady-state model assumes that water and salt concentrations have reached steady-state throughout the root zone for a given leaching fraction and it also requires chemical equilibrium between ions in both the solution and the soil solid phase. The steady-state model calculates ion pairing and precipitation-dissolution reactions of the major ions in irrigation drainage waters, whereas the transient model combines solute transport with cation exchange, ion pairing, and precipitation-dissolution reactions to consider the transient behavior of the system. A major conclusion was that the proportional and steady-state models were not suitable for calculating the salt burden of irrigation drainage waters.

Ayars et al. (1981) modified the solute transport model by Dutt et al. (1972), which was then applied to the Grand Valley in western Colorado, U.S.A. They found that the chemistry model predicted total dissolved solids, TDS, better than the individual chemical ions.

Wagenet and Hutson (1987) developed a solute transport model called LEACHM (Leaching Estimation And CHemistry Model) to study water and solute flow in the soil. This model includes ion pair formation, ionic strength, precipitation-dissolution and cation exchange reactions. They solved the water flow and salt flow equations using a numerical finite difference method. In the present study, it is required that the chemistry portion of the transport model calculate: (a) the dissolution or precipitation of gypsum and or lime; and (b) the cation exchange reactions for cations present in the soils of the study area. LEACHM was used in the present research because this model estimates all these required reactions in the soil. A detailed discussion about this model can be found in Chapter III.

Mansell et al. (1990) developed a finite difference model for predicting the transport of multiple-species cation transport coupled with ion exchange during unsteady water flow in unsaturated soils. The approach used in the model requires consecutive solutions of the Richards Equation to obtain water pressure head and convective-dispersion equation for each major cation to obtain the aqueous-phase concentration for each ion. They validated the cation-transport portion of the model using the measured data for steady water flow in saturated soil and validated the water flow and salt transport portions of the model using data for unsteady flow in unsaturated soil. They concluded from cation transport predictions under unsteady, unsaturated flow in sandy loam that the exchange selectivity has great significance for leaching native ions by invading ions.

Robbins (1991) developed a combined salt transport-chemical equilibrium model by coupling a chemical precipitation-dissolution model and a cation exchange model with a water flow-salt flow model to predict EC, SAR, and Ca, Mg, Na, K, Cl, SO_4 , and HCO_3 concentrations in the soil solution. This model was used under field conditions and it was found that both the chemical and cation exchange models were important for satisfactory EC and SAR predictions.

Dudley and Hanks (1991) developed a computer model called SOWACH (a model of soil water flow and salt transport with an equilibrium chemistry routine) to simulate salt flow in the soils. This model considers chemical exchange, precipitation or dissolution reactions of gypsum and lime in soil profile.

Suarez and Simunek (1997) developed a one-dimensional solute transport model, UNSATCHEM, which simulates variably saturated water flow, heat transport, carbon dioxide production and transport, and solute transport with major ion equilibrium and kinetic chemistry developed at U.S. Salinity Laboratory, USDA, ARS, Riverside, California. In UNSATCHEM, Richard's equation governs the water movement, and convection dispersion equation (CDE) describes the solute transport through 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. 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 numerical solution or minimize 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, NO_3 , H_4SiO_4 , 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 and never included into an equilibrium system. Other dissolution-precipitation reactions considered include gypsum, hydromagnesite, nesquehonite, and sepiolite. considers the effects of solution chemistry (chemical composition) on hydraulic conductivity.

UNSATCHEM also models the production and transport of CO_2 . It is assumed that CO_2 (one-dimensional) transport in the unsaturated zone can occur in both the liquid and gas phases. It is also considered that the CO_2 concentration in the soil is governed by two transport mechanisms, convective transport and diffusive transport in both gas and aqueous phases, and by CO_2 production and /or removal. The CO_2 production model considers the effect of moisture content, temperature, changes in CO_2 concentration and changes in oxygen concentration in the soil atmosphere and salinity on CO_2 production.

Chapter III

THE SOIL MOISTURE CHEMISTRY MODEL: LEACHM

This chapter presents a detailed description of a water movement-salt transport chemistry model, **LEACHM (Leaching Estimation And solute transport CHemistry Model)** that was developed by Wagenet and Hutson (1987). This model was applied for use in the present study for simulating water flow, equilibrium chemistry, and solute transport in one dimension in the unsaturated zone of irrigated soils from the soil surface to the groundwater table. LEACHM has five versions, namely, **LEACHW**, **LEACHN**, **LEACHP**, **LEACHB**, **LEACHC**:

- LEACHW describes water regimes only,
- LEACHN describes nitrogen transport and transformation,
- LEACHP simulates pesticide displacement and degradation,
- LEACHB describes microbial population dynamics in the presence of a single growth-supporting substrata and
- LEACHC describes transient movement of inorganic ions (Ca, Mg, Na, K, SO₄, Cl, CO₃, and HCO₃), which is being used in the present study.

LEACHM is organized on a modular basis. A main program reads input data, initializes variables, calls different subroutines, performs mass balancing and prints output (simulation) results. Subroutines deal with time step calculations, evapotranspiration, water flow, solute transport, soil chemistry, cover and root growth. A schematic diagram of LEACHC is provided in Figure 1, while the flow chart which describes the operation of the LEACHC program is presented in Figure 2.

Modeling Water Flow In Soils

In LEACHC, the one-dimensional transient soil moisture movement in the vertical direction is described using the Richards Equation in the form:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(\theta) \frac{\partial H}{\partial z} \right] + A(z, t) \quad (15)$$

where θ is the volumetric water content; t is time; z is the soil depth; $K(\theta)$ is the hydraulic conductivity; H is the soil hydraulic head; and $A(z, t)$ is a root-extraction term given by Eq. 6. In LEACHM, to simulate soil moisture movement in soil, Eq. 15 is solved by a finite difference numerical technique in which the soil profile is discretized into a number of horizontal segments and the total time period is divided into short time intervals. The finite difference equation for the matric head form of Eq. 15 is provided in Appendix A.

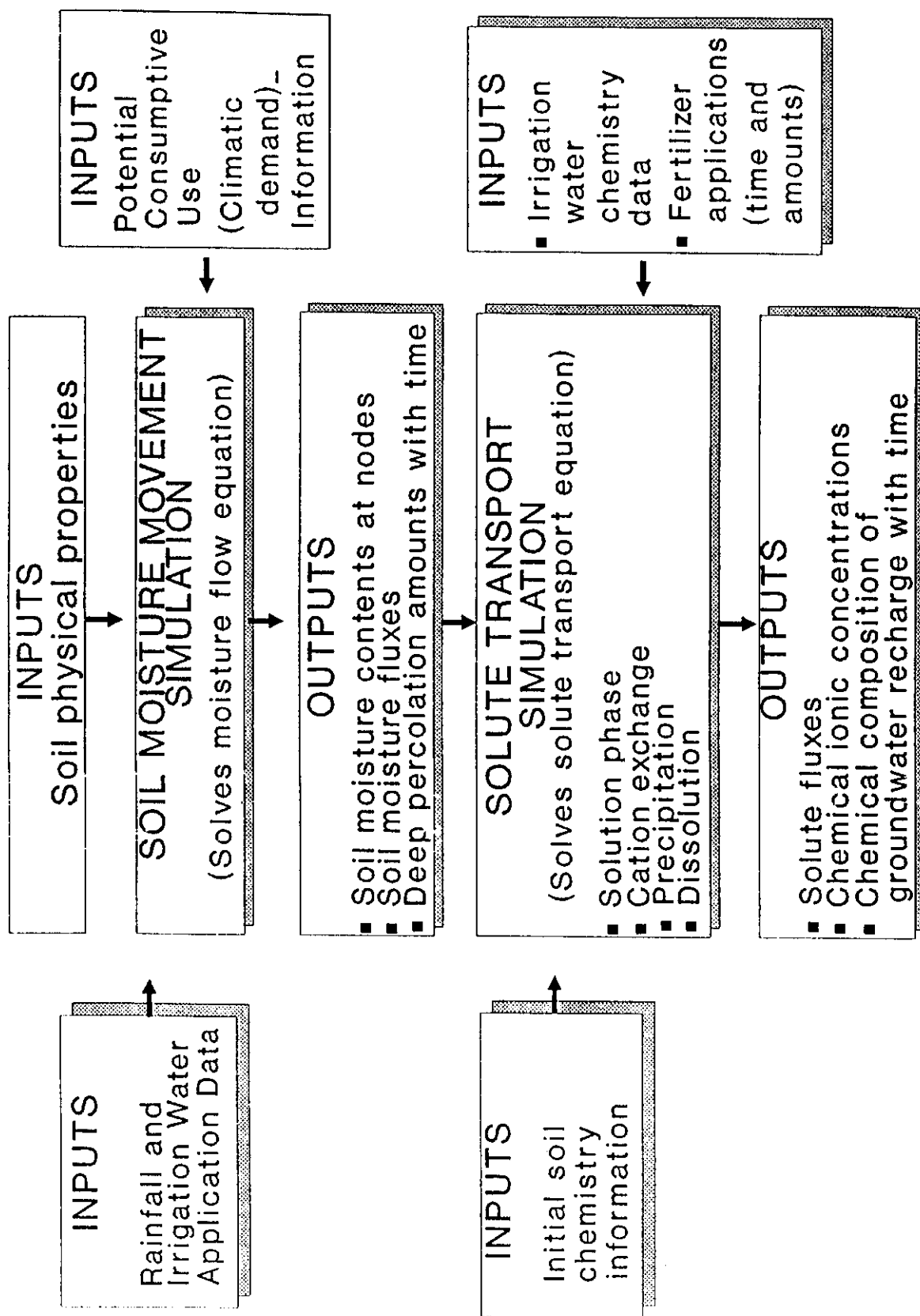


Figure 1 Schematic Diagram of the LEACHAM Soil Moisture Chemistry Model.

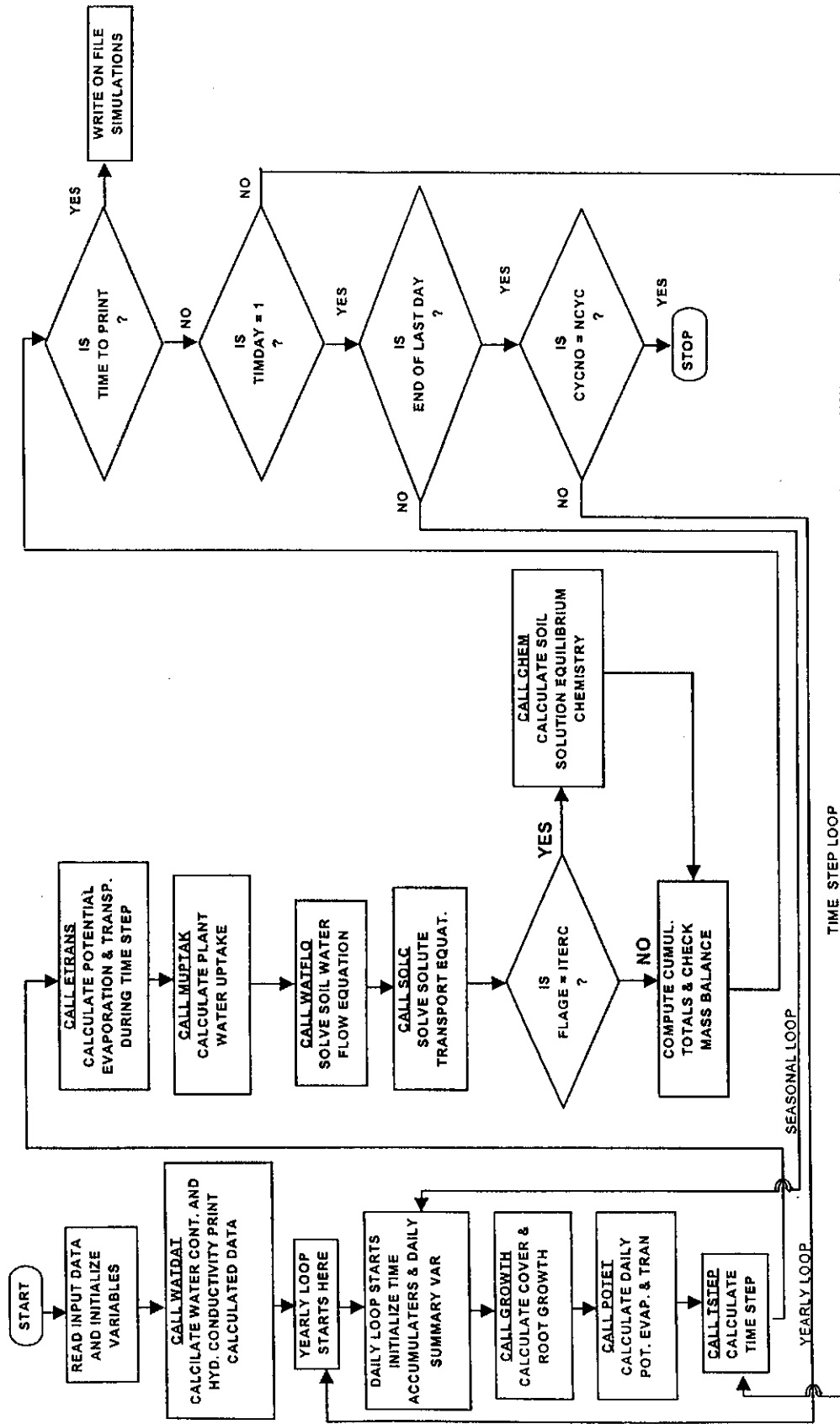


Figure 2. Flow Chart of the LEACHAM Soil Moisture Chemistry Model.

Top Boundary Condition

In LEACHM, the surface boundary conditions (ponded infiltration or non-ponded infiltration, evaporation or zero flux conditions) are simulated by adjusting the value of matric potential of the top node (surface node).

For the ponded case that occurs in a flooded irrigated basin, the matric potential of the top node is set equal to zero, thereby simulating the saturated surface condition.

The flux surface boundary condition during rainfall or sprinkler irrigation, evaporation and zero flux is simulated by calculating g_i using the following formula:

$$g_i = 2\Delta z_i \left[\left(\frac{W_i^{j-1/2}}{\Delta t} - K_{i+1/2}^{j-1/2} \right) / K_{i+1/2}^{j-1/2} \right] + h_2^{j-1} - h_i^{j-1} \quad (16)$$

where W is the surface flux. After determining the value of g_i , a value of h_i^j is calculated to simulate the surface flux condition using the following expression:

$$g_i = h_i^j - h_2^j \quad (17)$$

Bottom Boundary Condition

The bottom boundary condition, which may be the potential or flux condition, is simulated by adjusting the potential of the bottom node K . A water table bottom boundary condition is simulated by setting the bottom node matric potential to a fixed value.

For simulating a freely draining profile, which requires a unit hydraulic potential gradient, the value of bottom node matric potential, h_k^j , is calculated by the following expression:

$$h_k^j = \left[\frac{g_{k-1} - h_k^{j-1} + h_{k-1}^{j-1}}{1 - m_{k-1}} \right] \quad (18)$$

The zero flux condition, which requires that the hydraulic potential gradient be equal to zero, is simulated by calculating the bottom node potential using the following formula:

$$h_k^j = \left[\frac{g_{k-1} + h_{k-1}^{j-1} - h_k^{j-1} + 2\Delta z}{1 - m_{k-1}} \right] \quad (19)$$

Calculating Root Extraction

In the LEACHM model, the value of the root extraction for each depth and time increment is calculated by Eq. 6, which shows that root extraction is a function of the root water potential at the soil surface, the resistance to flow in the root, the matric and osmotic potentials, and the hydraulic conductivity. The model finds the value of Hroot through successive iterations. A value for Hroot is selected so that the sum of the root extraction over the root profile is equal to the potential transpiration.

Modeling Solute Transport In Soils

The one-dimensional salt transport process in LEACHM is described by the following convection-diffusion equation (CDE):

$$\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z} \left[D(\theta, v) \frac{\partial c}{\partial z} - qc \right] \quad (20)$$

where θ is volumetric water content; c is the solute concentration; t is time; z is the soil depth; q is the volumetric solution flux; and $D(\theta, v)$ is the combined diffusion and hydrodynamic dispersion coefficient given by:

$$D(\theta, v) = D_o a e^{b\theta} + \lambda |v| \quad (21)$$

where v is the average flow velocity (q/θ); D_o is the diffusion coefficient for pure water; a , b are diffusion constants; and λ is a dispersion constant.

A second-order finite difference solution of Eq. 20 simulates the solute transport process in the soil. This second-order finite difference equation for salt flow is given in Appendix B.

Top Boundary Condition

For the case when irrigation or rainfall occurs and the water flux across the top boundary is positive (infiltration event), the surface boundary is the concentration of the solutes in the irrigation water, c_{iw} . Also diffusion is not allowed to take place at the surface. This surface boundary condition is expressed as follows:

$$c_1^j = c_{iw}; \quad D_{1+1/2}^{j+1/2} = 0; \quad q_{1+1/2}^{j+1/2} > 0$$

For the case when evaporation takes place and water flux is negative, the solute flow across the surface boundary is assumed equal to zero. This surface boundary conditions is expressed by the following equation:

$$c_i^j = 0; \quad q_{i+1/2}^{j+1/2} = 0; \quad D_{i+1/2}^{j+1/2} = 0$$

For the zero flux case, the surface boundary condition is simulated by the following expressions:

$$c_i^j = 0; \quad q_{i+1/2}^{j+1/2} = 0; \quad D_{i+1/2}^{j+1/2} = 0$$

Bottom Boundary Condition

For the case when there is no water flow across the bottom boundary (zero flux boundary condition), the solute flow is assumed equal to zero. This condition is expressed by the following relations:

$$q_{k-1}^{j+1/2} = 0; \quad D_{k-1/2}^{j+1/2} = 0; \quad D_k^{j+1/2} = 0$$

For the case when there is a water table at the bottom boundary, the solute concentration at node KK is assumed constant and equal to that in the groundwater. This condition is expressed as follows:

$$c_k = c_{gw}; \quad D_{k-1/2}^{j+1/2} = 0$$

For simulating a freely draining profile (unit hydraulic gradient condition), a constant solute concentration at the bottom node is assumed as expressed below:

$$c_k = \text{constant}; \quad D_{k-1/2}^{j+1/2} = 0$$

Modeling Soil Chemistry

In LEACHC, to simulate the chemical reactions in the soil profile during transient transport conditions, the solute transport model is used to transport a chemical ion in solution as a non-reactive species. After independent movement of Ca, Mg, Na, K, Cl, and SO₄ ions as individual species, the chemistry model, CHEM and cation exchange model, XCHANG are used to bring the solution species into chemical equilibrium with lime and gypsum, and to adjust the exchange equilibria. These submodels (CHEM and XCHANG) are discussed in the following sections.

Chemistry Submodel, Chem

The CHEM submodel calculates new solution concentrations of Ca, Mg, Na, K, Cl, and SO₄ and the precipitation or dissolution of CaCO₃ and CaSO₄. In this submodel, the electrical conductivity of the soil solution is calculated by the formula (McNeal et al., 1970) given below:

$$EC = \sum K_o c^b \quad (22)$$

where EC is the electrical conductivity in mS/cm; c is the ionic concentration in me/l; K_o and b are the coefficients for the solution species. The EC is used in the calculation of the ionic strength, which in turn is used to calculate the activity coefficients for the mono- and divalent chemical species.

The ionic strength of the soil solution is calculated by the expression:

$$I = 0.0127 EC \quad (23)$$

where I is the ionic strength of the solution in moles/l. The mono- and divalent ion activity coefficients, γ_1 and γ_2 , are estimated using the Davies formula:

$$\log \gamma_i = -0.509 Z_i^2 \left[\frac{I^{1/2}}{1.0 + I^{1/2}} - 0.3 I \right] \quad (24)$$

where Z_i is the ionic charge. The ionic activities are approximated by the following relationship:

$$a_i = \gamma_i m_i \quad (25)$$

where a_i is the activity of the ith ion in solution; γ_i is the activity coefficient of the ith ion; and m_i is the molar concentration of ith ion in the solution. The activities of the hydrogen ion (H), bicarbonate (HCO_3), and carbonate (CO_3) are calculated by the following expressions:

$$(H) = \sqrt{\frac{P_{\text{CO}_2} K_H K_{a1} K_{a2} (Ca)}{K_{\text{SP}2}}} \quad (26)$$

$$(\text{HCO}_3) = \frac{P_{\text{CO}_2} K_H K_{a1}}{(H)} \quad (27)$$

$$(\text{CO}_3) = \frac{K_{a1} K_{a2} K_H P_{\text{CO}_2}}{(H)^2} \quad (28)$$

where () indicate ion activity; P_{CO_2} is the partial pressure of CO_2 ; K_{a1} and K_{a2} are the first and second dissociation constants of carbonic acid, H_2CO_3 ; K_H is the constant in Henry's law; $K_{\text{SP}2}$ is the solubility product of CaCO_3 ; and (Ca) represents Ca activity.

The ion activities in solution are corrected for ionic strength and ion-pair formation. The ion pairs considered important in the soil system are NaSO_4° , NaCO_3° , CaCO_3° , CaHCO_3^+ , CaOH^+ , CaSO_4° , MgCO_3° , MgHCO_3^+ , MgOH^+ and MgSO_4° . The equation used to calculate the activity of Na corrected for ionic strength and ion-pair formation is derived as

follows. The total sodium concentration in solution, Na_T , is equal to the concentration of sodium that exists as a free ion, Na , plus the concentration of sodium that exists as ion pairs, $NaCO_3^-$ and $NaSO_4^-$.

$$[Na_T] = [Na^+] + [NaCO_3^-] + [NaSO_4^-] \quad (29)$$

where $[]$ denote concentration (moles/l). The activity of each ion pair is written in terms of its stability constant and component ions as follows:

$$\gamma_1 [NaCO_3^-] = (NaCO_3^-) = \frac{(Na)(CO_3)}{K_{d1}} \quad (30)$$

$$\gamma_1 [NaSO_4^-] = (NaSO_4^-) = \frac{(Na)(SO_4)}{K_{d2}} \quad (31)$$

where K_{d1} and K_{d2} are the stability constants. Substituting Eq. 30 and Eq. 31 into Eq. 29 gives:

$$[Na_T] = (Na) \left[\frac{1}{\gamma_1} + \frac{(Na)(CO_3)}{K_{d1} \gamma_1} + \frac{(Na)(SO_4)}{K_{d2} \gamma_1} \right] \quad (32)$$

Substituting Eq. 28 into Eq. 32 and rearranging gives the following form of the equation to calculate the corrected activity of Na :

$$(Na) = [Na_T] \div \left[\frac{1}{\gamma_1} + \frac{P_{CO_2} K_{a1} K_{a2} K_H}{\gamma_1 (H)^2 K_{d1}} + \frac{(SO_4)}{K_{d2} \gamma_1} \right] \quad (33)$$

The same approach is used to develop the equations for Ca , Mg , K , CO_3 , HCO_3 and SO_4 to calculate the ionic activities corrected for ion-pairing. These corrected cation activities are also used in the cation exchange calculations.

In LEACHM, using the corrected (Ca) and (CO_3) or (SO_4) , values and the appropriate solubility product, K_{sp} , the amount of slightly soluble salt, X , that must be added or removed from the soil solution to bring the system into equilibrium is calculated by:

$$(CAT - X)(AN - X) = K_{sp} \quad (34)$$

where CAT is the solution cation activity and AN is the solution anion activity.

Cation Exchange Submodel, XCHANG

The XCHANG submodel equilibrates the solution and exchangeable cation concentrations during water and salt movement. There are two options available in the model for the initial conditions. Either initial values for ions in the exchange are calculated using a relationship between a selectivity coefficient, the cation exchange capacity, and concentrations of ions in solution, or exchangeable ion concentrations are provided in the input data.

After the transport, precipitation and dissolution calculations, the soil solution is no longer in equilibrium with the exchangeable ions. The new concentrations of exchangeable cations are estimated by employing the equations which describe the relationship between the cation exchange capacity, selectivity coefficients, and solution ionic activities.

In XCHANG, it is assumed that the cation exchange capacity is equal to the sum of the exchangeable cations as given below:

$$CEC = X_{Ca} + X_{Mg} + X_{Na} + X_K \quad (35)$$

where CEC is the cation exchange capacity in me/100 g of soil and X_{Ca} , X_{Mg} , X_{Na} , and X_K are the exchangeable cations in me/100 g. The selectivity coefficients, K_1 through K_6 , for the equilibrium between the cations in solution and the exchangeable cations are calculated by the following expressions:

$$K_1 = \frac{(Ca) X_{Mg}}{(Mg) X_{Ca}} \quad (36)$$

$$K_2 = \frac{(Na) X_{Ca}}{(Ca)^{1/2} X_{Na}} \quad (37)$$

$$K_3 = \frac{(K) X_{Ca}}{(Ca)^{1/2} X_K} \quad (38)$$

$$K_4 = \frac{(K) X_{Mg}}{(Mg)^{1/2} X_K} \quad (39)$$

$$K_5 = \frac{(Na) X_{Mg}}{(Mg)^{1/2} X_{Na}} \quad (40)$$

and

$$K_6 = \frac{(Na) X_K}{(K) X_{Na}} \quad (41)$$

In the XCHANG submodel, the concentrations of exchangeable cations are calculated by the following formulae:

$$X_{Ca} = CEC \div \left[\frac{(Mg) K_1}{(Ca)} + \frac{(Na)}{(Ca)^{1/2} K_2} + \frac{(K)}{(Ca)^{1/2} K_3} + 1 \right] \quad (42)$$

$$X_{Mg} = CEC \div \left[\frac{(Ca)}{(Mg) K_1} + \frac{(Na)}{(Mg)^{1/2} K_5} + \frac{(K)}{(Mg)^{1/2} K_4} + 1 \right] \quad (43)$$

$$X_{Na} = CEC \div \left[\frac{(Ca)^{1/2} K_2}{(Na)} + \frac{(Mg)^{1/2} K_5}{(Na)} + \frac{(K) K_6}{(Na)} + 1 \right] \quad (44)$$

and

$$X_K = CEC \div \left[\frac{(Ca)^{1/2} K_3}{(K)} + \frac{(Mg)^{1/2} K_4}{(K)} + \frac{(Na)}{(K) K_6} + 1 \right] \quad (45)$$

Model Inputs

To run the model, the required input data are read from a data file which consists of nine sections. The **first section** of the input data file contains the input values of program flow parameters. The **second part** of the input data file contains the initial values of the water potential in kpa, hydrological constants (air entry value, AEV in mm H₂O, Exponent in Campbell's equation, BCAM1) required for calculating soil moisture content and hydraulic conductivity, soil bulk density in Mg/m³, saturated hydraulic conductivity in mm/day, and root fractions with soil depth.

The **third section** has crop data, i.e., days from planting to seedling emergence, days from planting to crop maturity, root growth parameters, and cover growth parameters. The **fourth section** of the input data file provides the initial concentrations of soluble cations and anions with depth in the soil profile.

The *fifth part* of the input data file contains the initial concentrations of exchangeable cations (X_{Ca} , X_{Mg} , X_{Na} , X_K) and initial values of the cation exchange capacity for the soil, CEC with soil depth. The *sixth section* provides the values of the selectivity coefficients (K_1 , K_2 , K_3 , K_4 , K_5 , and K_6) for appropriate cation exchange reactions. This data is required by the XCANG submodel. This section also has information on partial pressure of CO_2 , the mass fractions of lime ($CaCO_3$) and gypsum ($CaSO_4$) with depth in the soil profile.

The *seventh section* contains data about fertilizer applications (i.e., time of application and amount of application). Input data about irrigation/rainfall frequency, duration, and rate on a daily basis and chemical composition of the irrigation water is supplied by the *eighth part* of the input data file. The *ninth section* of the input data file provides the pan evaporation (mm) on a weekly basis. A sample input file for the present study is presented in Appendix C.

Model Outputs

The LEACHM model provides the different simulation results at specified print intervals (days) in the form of four output tables. *Table 1* has the information about soil moisture content and hydraulic conductivity with soil depth corresponding to the soil water matric potentials of 0, -3, -10, -30, -100, and -1500 kPa. *Table 2* provides cumulative totals and mass balances of water and solutes (Ca, Mg, Na, K, Cl, and SO_4). This table provides information about the amounts of water (mm) and salts ($mmol/m^2$) initially present in the soil profile, currently in the profile, the simulated change, additions, losses, and an overall mass error.

The output printed on *Table 3* is the volumetric water content, matric potential (kPa), water flux between soil layers (mm/day), evapotranspiration (mm), Cl, SO_4 , HCO_3 , CO_3 , sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), electrical conductivity (EC in mS/m) and soil pH with depth in the soil profile.

Table 4 provides a summary of root density (m/m^2), concentrations of exchangeable cations (X_{Ca} , X_{Mg} , X_{Na} , and X_K) in me/kg, solution cations (Ca, Mg, Na, K) concentrations ($mmol/l$), solution anion (SO_4) concentration ($mmol/l$), and total concentration of dissolved cations (me/l) with soil depth. A sample output file for the present study is presented in Appendix D.

Model Limitations

The LEACHM model has the following limitations:

- Uses only equal depth increments;
- Does not predict runoff water quantity or quality;
- Does not simulate CO_2 concentration, which has a direct influence on chemical equilibria;
- 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 solute.

Chapter IV

APPLICATION OF LEACHM TO CHISHTIAN IRRIGATION SUB-DIVISION

Description Of The Study Area

The Chishtian Sub-division is located in the south-east of Punjab Province and is part of the Fordwah/Eastern Sadiqia area, where currently, a multi-disciplinary team of IIMI is conducting research on inter-related aspects of irrigation, salinity/sodicity and agricultural production at different levels of the irrigation system (field level, farm level, tertiary level, secondary and primary canal level) in order to devise irrigation management interventions for sustainable irrigated agriculture. It is a 70,000 ha irrigation scheme receiving its surface water from the Fordwah Branch Canal (Figure 3).

The Chishtian Sub-division is comprised of about 470 watercourses and out of which in eight sample watercourses (four on Azim Distributary and four on Fordwah Distributary) IIMI is conducting research on the field and farm level. The four sample fields used in the present field-level study are located in two of the eight sample watercourses, two in Fordwah 62-R and two in Azim 111-L. (Figure 4). In May 1994, IIMI-Pakistan started a detailed monitoring of these four sample fields in the Chishtian Sub-division (IIMI, 1995). The four sample fields with their watercourses and field codes are provided in Table 1.

Table 1. Four sample fields with their field codes.

watercourse	field code
Fordwah 62-R	1: 351/15/17
Fordwah 62-R	2: 351/10/21
Azim 111-L	3: 173/15/22
Azim 111-L	4: 173/11/07

The Chishtian Sub-division has an arid climate with annual evaporation of 2400 mm far exceeding annual rainfall of 260 mm. The agricultural year can be divided into two seasons: kharif-season (summer), from June till December; and rabi-season (winter), from January till May. The monsoon period comprises July and August, and rainfall can amount upto 85 mm per month. The Chishtian Sub-division is located in the cotton-wheat agro-ecological zone of the Punjab. The major crops in kharif and rabi are cotton and wheat, respectively. The cropping intensity is 130 %.

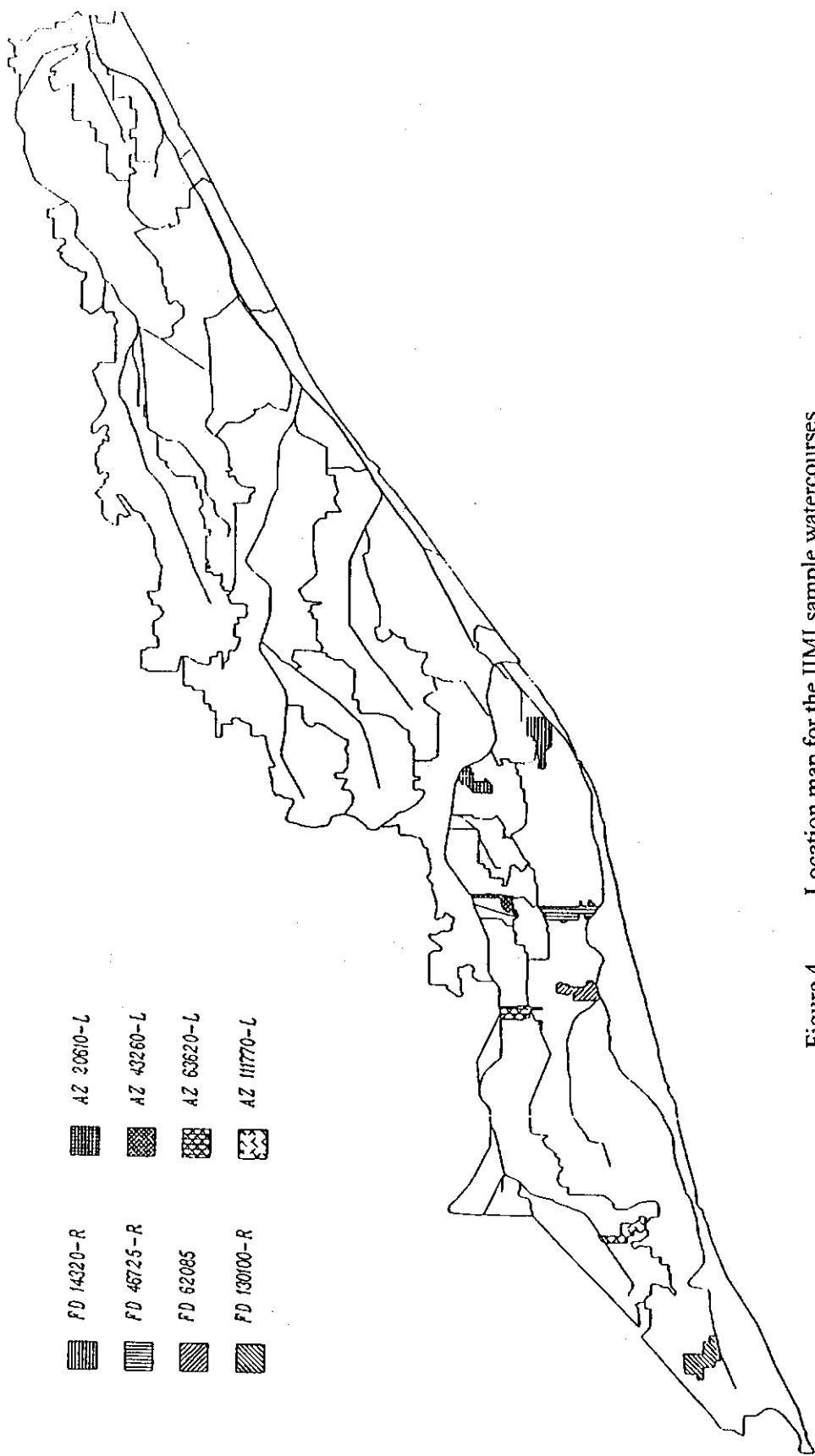


Figure 4. Location map for the IIMI sample watercourses.

The Chishtian Sub-division is located in the tail of Fordwah Branch Canal off-taking from Fordwah Main Canal, starting from Suleimanki Headworks on the Sutlej River (Figure 3). Annually an amount of 420 million m³ is diverted to the Chishtian Sub-division. The irrigation system in the Chishtian sub-division is an odd mixture of perennial and non-perennial distributary canals. Two sample fields are located in the perennial watercourse Fordwah-62 (taking off from Fordwah distributary) and the other two fields are located in the non-perennial watercourse Azim-111 (taking off from Azim distributary). Due to inadequate, inequitable, and unreliable canal water supply, farmers augment their canal water supplies with pumped groundwater from their private tubewells (about 12 per 100 ha) (Smets, 1996).

The soils in the area are a mixture of alluvial and eolian depositions. Silty alluvia, containing a substantial amount of fine sands, and sandy deposits of eolian origin have mixed into thick uniform deposits of silt to fine sandy textures. The textural classes for the four sample fields are provided in Table 2. Field 1 is classified as a Jhang soil series consisting of a loamy sand top soil, underlain by a sandy subsoil. Field 2 is less sandy and is classified as a Rasulpur soil series, with a sandy loam top soil, underlain by a loamy sand subsoil. Field 3 is classified as a Sultanpur soil series consisting of a loamy top soil, underlain by a sandy loam subsoil. Field. Field 4 has a somewhat higher silt content and a lower clay content than Field 3 and is classified as a Harunabad soil series. The soil consists of a (silty) loam topsoil, underlain by a loamy sand subsoil. The four sample fields having different soil types, represent the most common soil types (loamy sand to silty clay loam) in the Chishtian Sub-division.

Soils in Chishtian Sub-division are moderately calcareous with 5% < CaCO₃ < 15% (SSP and IIMI, 1996).

Table 2. Textural classes for four sample fields (Smets, 1996).

Field	15 cm	30 cm	60 cm	90 cm	120 cm	150 cm	200 cm
1	SL	LS	SL	LS	LS	S	S
2	L	SL	SL	L	SL	LS	LS
3	L	L	SiCL	L	LS	LS	LS
4	L	L	SiL	SiL	SL	LS	LS

S : sand

LS : loamy sand

SL : sandy loam

L : loam

SiL : silt loam

SiCL : silty clay loam

Data Collection

The above mentioned four fields were monitored during Kharif'94, Rabi'94/95 and Kharif'95. The data collected for these sample fields consisted of:

- **Soil data** (soil texture, soil salinity/sodicity: EC, SAR, pH, Ca, Mg, Na, CO₃, Cl, SO₄) The E_{Ce} and SAR of Adilpur soil series measured in the Chishtian Sub-division vary in the following ranges (van dam and Aslam, 1997):
 $1 < E_{Ce} < 14 \text{ dS/m}$
 $8 < SAR < 75 (\text{mmol/l})^{1/2}$
- **Agronomical data** (cropping pattern, length of growing seasons, etc.)
- **Meteorological data** (temperature, wind speed, relative humidity, rainfall)
- **Irrigation data** (no. of irrigations, timings and amounts, quality: EC, SAR, RSC)

Typically, farmers in the Chishtian Sub-division apply one rauni of 13 cm depth and five irrigations of 6.5 cm each for the wheat crop and two raunis (6.5+8.7 cm) and eight irrigations of 6.8 cm each for the cotton crop. This results in a total irrigation application of 45.5 cm for wheat and 69.6 cm for cotton (Van Dam and Aslam, 1997).

Model Input Data

For successful soil moisture chemistry modeling, detailed soil physical and chemical data and water chemistry data are required, but the adequate data bases are lacking in the study area. Due to this reason, model was not calibrated, but the simulations of soil salinity and sodicity processes were performed using more general data rather than the field specific data of any particular field from four sample fields. The input data used for running LEACHC, in order to simulate water flow and solute transport through unsaturated zone are described in the following sections.

Soil Physical And Chemical Data

In the present study, soil considered was loam for which soil profile of one meter depth was divided into 25 soil layers of 4 cm thickness each. The soil physical and chemical data are provided in Tables 3 through 5. The initial profiles of soluble ions Ca, Na, Cl, SO₄ and HCO₃ and exchangeable cations, Ca, Mg, Na, and K are presented in appendices E and F, respectively. The 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 determined, 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 were used as initial condition. In this way the water and solute amounts (except for precipitation) over a year hardly change, only seasonal changes occur.

Table 3. Soil physical data.

DS	AEV	BCAM	P	RHO	IMC	KS	RF	DIS	TEMP
1	-.2544	5.38	1.0	1.48	.200	249.6	.08	50	25.
2	-.2544	5.38	1.0	1.48	.200	249.6	.078	50	25.
3	-.2544	5.38	1.0	1.48	.200	249.6	.066	50	25.
4	-.2544	5.38	1.0	1.48	.228	249.6	.065	50	25.
5	-.2544	5.38	1.0	1.48	.228	249.6	.053	50	25.
6	-.2544	5.38	1.0	1.48	.242	249.6	.052	50	25.
7	-.2544	5.38	1.0	1.48	.242	249.6	.05	50	25.
8	-.2544	5.38	1.0	1.48	.242	249.6	.048	50	25.
9	-.2544	5.38	1.0	1.48	.242	249.6	.047	50	25.
10	-.2544	5.38	1.0	1.48	.242	249.6	.045	50	25.
11	-.2544	5.38	1.0	1.48	.242	249.6	.044	50	25.
12	-.2544	5.38	1.0	1.48	.242	249.6	.042	50	25.
13	-.2544	5.38	1.0	1.48	.242	249.6	.04	50	25.
14	-.2544	5.38	1.0	1.48	.235	249.6	.039	50	25.
15	-.2544	5.38	1.0	1.48	.235	249.6	.037	50	25.
16	-.2544	5.38	1.0	1.48	.222	249.6	.036	50	25.
17	-.2544	5.38	1.0	1.48	.222	249.6	.034	50	25.
18	-.2544	5.38	1.0	1.48	.222	249.6	.032	50	25.
19	-.2544	5.38	1.0	1.48	.170	249.6	.031	50	25.
20	-.2544	5.38	1.0	1.48	.170	249.6	.028	50	25.
21	-.2544	5.38	1.0	1.48	.136	249.6	.027	50	25.
22	-.2544	5.38	1.0	1.48	.136	249.6	.026	50	25.
23	-.2544	5.38	1.0	1.48	.136	249.6	.0	50	25.
24	-.2544	5.38	1.0	1.48	.136	249.6	.0	50	25.
25	-.2544	5.38	1.0	1.48	.136	249.6	.0	50	25.

DS = depth segment

AEV = air-entry value (kPa) in Campbell's water retention equation

(Campbell's water retention equation, $h = AEV(\theta/\theta_s)^{-BCAM}$ where h is the pressure potential, θ is the volumetric moisture content and θ_s is the saturated volumetric moisture content)

- BCAM= exponent in Campbell's equation.
P = Pore interaction parameter (P) in Campbell's conductivity equation (Campbell's conductivity equation, $K(\theta) = KS (\theta/\theta_s)^{2BCAM+2+P}$ where $K(\theta)$ is the hydraulic conductivity at a moisture content θ)
RHO = soil bulk density (g/cm^3).
IMC = initial soil moisture content (volumetric)(Source: Van Dam and Aslam, 1997).
KS = soil saturated hydraulic conductivity (mm/day).
RF = root fraction.
DIS = dispersivity (mm).
TEMP = temperature (degree C)

Table 4. Initial profile data - soluble cations and anions.

(Source: van Dam and Aslam, 1997).

Depth Segment	Ca	Mg	Na	K	Cl	SO4	Alkalinity
	(mmol/l)						(mmol/l)
1	0.05	0.14	13.1	0.095	1.7	1.99	8.5
2	0.05	0.14	13.1	0.095	1.7	1.99	8.5
3	0.064	0.19	14.0	0.111	1.94	2.4	9.
4	0.095	0.042	16.95	0.151	2.	3.	11.4
5	0.095	0.042	16.95	0.151	2.	3.	11.4
6	0.097	0.054	21.9	0.231	2.96	4.0	14.85
7	0.097	0.054	21.9	0.231	2.96	4.0	14.85
8	0.097	0.054	21.9	0.231	2.96	4.0	14.85
9	0.084	0.084	30.85	0.42	3.86	5.45	19.6
10	0.084	0.084	30.85	0.42	3.86	5.45	19.6
11	0.044	0.263	60.0	1.21	10.	13.99	35.9
12	0.044	0.263	60.0	1.21	10.	13.99	35.9
13	0.044	0.263	60.0	1.21	10.	13.99	35.9
14	0.044	0.263	60.0	1.21	10.	13.99	35.9
15	0.044	0.263	60.0	1.21	10.	13.99	35.9
16	0.044	0.263	60.0	1.21	10.	13.99	35.9
17	0.044	0.263	60.0	1.21	10.	13.99	35.9
18	0.044	0.263	60.0	1.21	10.	13.99	35.9
19	0.21	0.285	95.0	2.0	11.84	15.00	37.0
20	0.21	0.285	95.0	2.0	11.84	15.00	37.0
21	0.21	0.285	95.0	2.0	11.84	15.00	37.0
22	0.18	0.25	85.0	1.6	11.5	14.	30.0
23	0.21	0.285	95.0	2.0	11.84	15.00	37.0
24	0.12	0.19	80.0	1.2	10.	10.50	29.0
25	0.1	0.16	79.0	1.0	9.	8.00	21.0

Table 5. Exchangeable cations and exchange capacity (CEC).

(Source: van Dam and Aslam, 1997).

Depth segment	Ca	Mg	Na	K	CEC
	(mmol _c /kg)*				
1	39.2	67.8	42.6	0.345	149.945
2	39.2	67.8	42.6	0.345	149.945
3	39.2	67.8	42.6	0.345	149.945
4	53.2	36.2	60.1	0.52	150.02
5	53.2	36.2	60.1	0.52	150.02
6	45.9	36.	67.4	0.69	149.99
7	45.9	36.	67.4	0.69	149.99
8	45.9	36.	67.4	0.69	149.99
9	35.41	36.0	77.49	1.04	149.94
10	35.41	36.0	77.49	1.04	149.94
11	24.2	36.0	88.2	1.66	150.06
12	24.2	36.0	88.2	1.66	150.06
13	24.2	36.0	88.2	1.66	150.06
14	14.91	35.8	96.99	2.45	150.15
15	14.91	35.8	96.99	2.45	150.15
16	7.71	36.7	111.5	3.7	159.61
17	7.71	36.7	111.5	3.7	159.61
18	7.71	36.7	111.5	3.7	159.61
19	7.71	36.7	111.5	3.7	159.61
20	7.71	36.7	111.5	3.7	159.61
21	9.4	39.8	115.	4.2	168.4
22	9.4	39.8	115.	4.2	168.4
23	9.4	39.8	115.	4.2	168.4
24	9.4	39.8	115.	4.2	168.4
25	9.4	39.8	115.	4.2	168.4

* millimoles of charge per kilogram of soil

The information about the selectivity coefficients for appropriate cation exchange reactions is required by the XCANG submodel. The values of the required selectivity coefficients were calculated in the model using the option that solution and exchangeable cations are in equilibrium, calculate selectivity coefficients. Further, PCO₂ was increased linearly from 0.00033 at the soil surface to 0.02 at the root zone bottom. The mass fractions of lime and gypsum (0.05 and 0.00, respectively) were kept constant throughout the entire soil profile.

Crop data

In the present study two major crops grown in the study area, wheat and cotton were considered for rabi (growth period: from 1 January to 30 April) and kharif (growth period:

from 1 June to 15 December). The relative root distribution decreases linearly between 0 and 100 cm depth, as shown in Table 3.

Irrigation and rainfall data

Input data about irrigation/rainfall timings, application depths and chemical composition (Ca, Mg, Na, K, Cl, SO₄ and Alkalinity) of the irrigation water is provided in Appendix C (Section 8). Figure 5 shows 19 irrigation events for the whole year (rabi+kharif seasons). There are two canal water rauni irrigations of 6.5 and 8.7 cm depths on 123 and 137 julian days for cotton and one rauni of 13 cm depth for wheat on Julian day 357. In addition to raunis, 5 irrigations (6.5cm/irrigation) for wheat and 8 irrigations (6.8 cm/irrigation) for cotton were provided as used by Van Dam and Aslam, 1997. Total rainfall of 18 cm was divided into three rainfall events 6 cm each on Julian days 192, 206 and 230 in order to simulate monsoon rainfall. All other irrigations were done using tubewell water. The chemical quality of canal and tubewell water is provided in Table 6. The chemical composition of tubewell water is equal to measured values in watercourse Fordwah 130 (Mr. Muhammad Yaqoob). The quality of this water belongs to the worst category.

Table 6. Quality of irrigation water.

Water type	EC	SAR	RSC	Water composition (mmol/l)						
				Ca	Mg	Na	K	Cl	SO ₄	Alkalinity
Canal	0.19	0.2	-0.4	0.350	0.45	0.200	0.100	0.400	0.150	7.500
Tubewell	1.51	11.5	6.6	0.600	0.600	12.60	0.100	1.900	2.650	9.800

EC = electrical conductivity (dS/m).

SAR = sodium adsorption ratio (mmol/l)^{1/2}.

RSC = residual sodium carbonate (meq/l).

Potential Evapotranspiration (PET) data

The weekly values of potential evapotranspiration are also needed to run the model. The daily values of PET from Smets (1996) were converted into weekly totals, which are presented in Figure 6.

Model Simulation Results

As discussed in Chapter III, the solute transport model consists of two submodels; namely, moisture flow submodel and salt transport (chemical) submodel. The simulations results obtained from the moisture flow and chemical submodels are discussed separately in the following section.

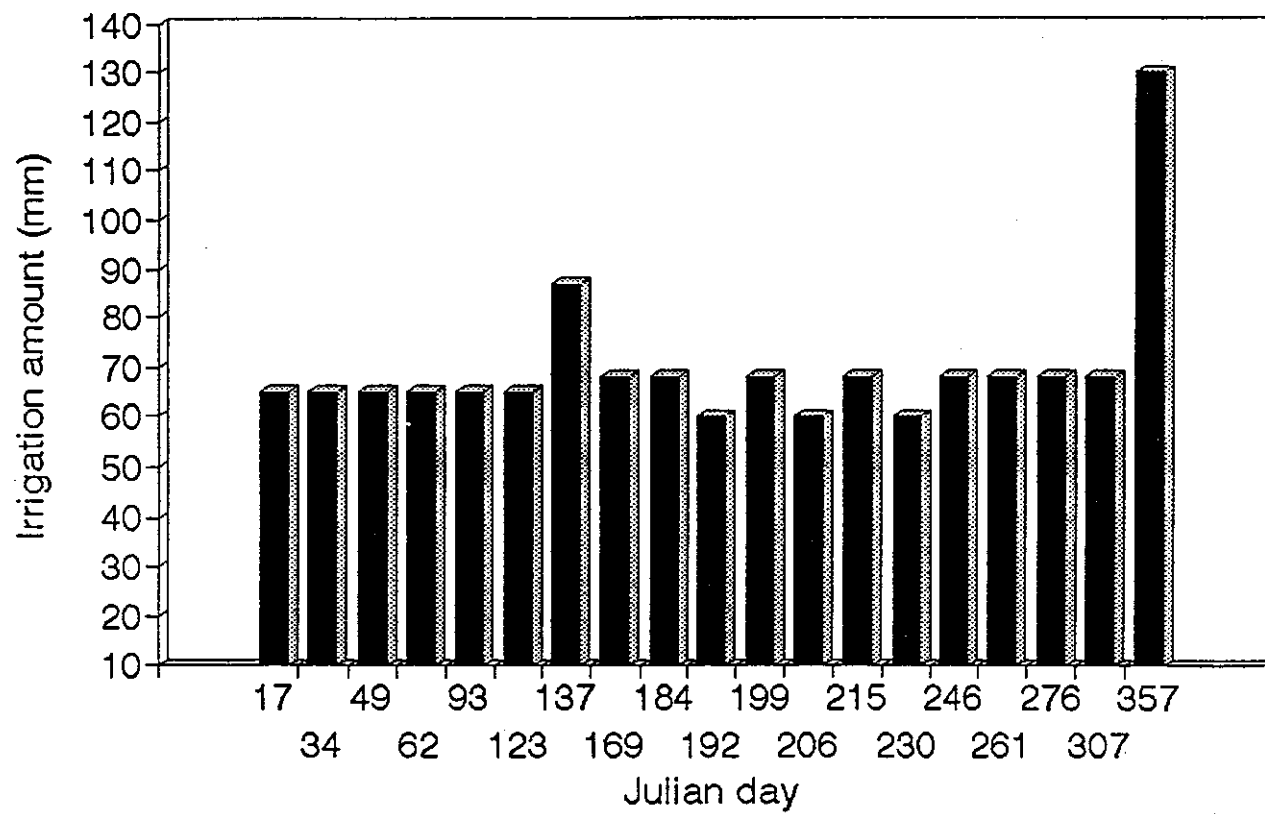


Figure 5. Irrigation Schedules.

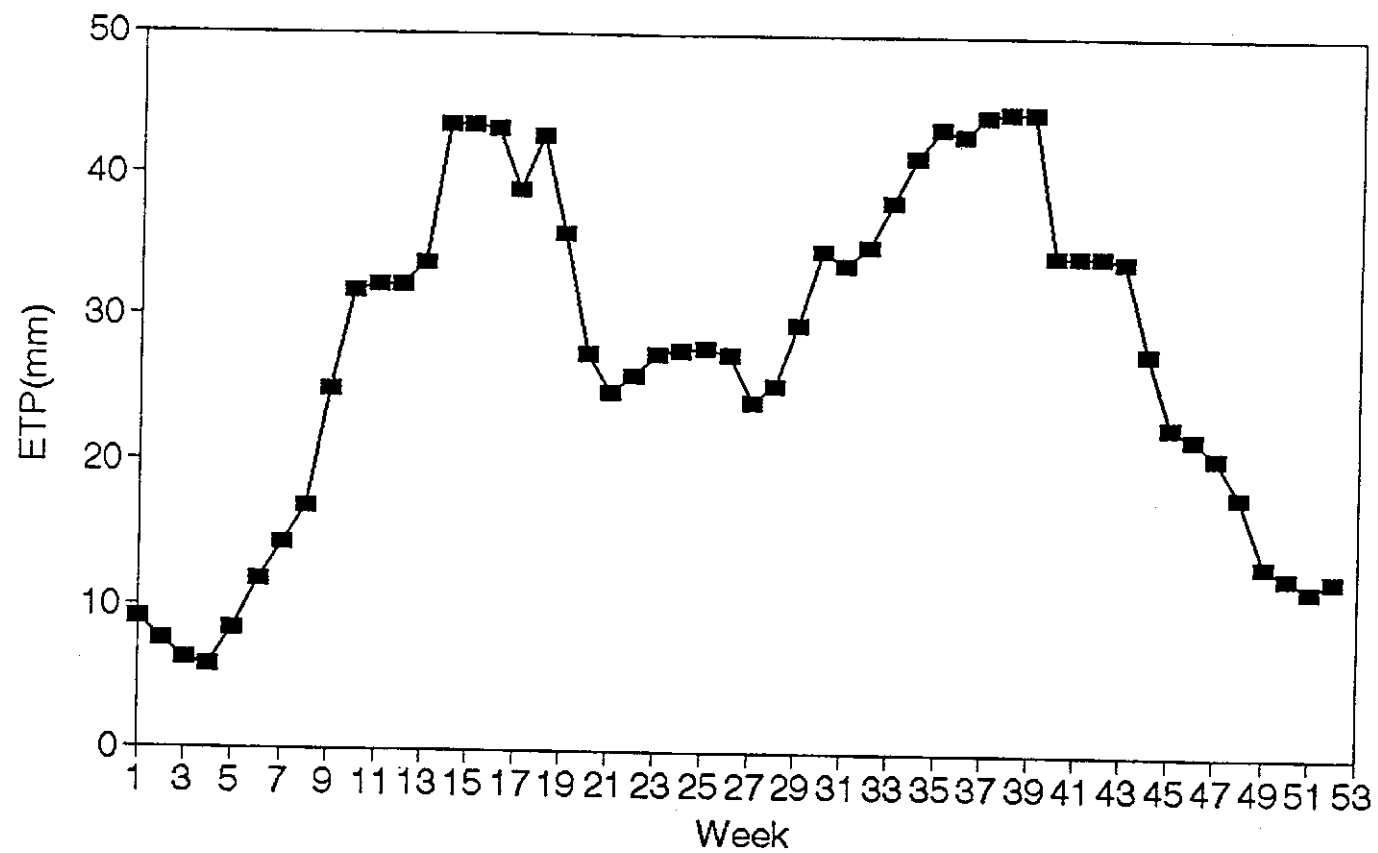


Figure 6. Potential Evapotranspiration Data (weekly totals).

Moisture Flow Simulations

Employing the required input data, the model was run for the whole year (rabi+kharif seasons) in order to simulate the soil moisture movement through the unsaturated soil profile. The simulated moisture content profiles for days 120 (end of rabi season for wheat), 150 (start of kharif season for cotton), 273 (end of monsoon), 349 (end of kharif season for cotton) and 365 (start of rabi season for wheat) are plotted in Figure 7. Clearly, at the start of the wheat and cotton growing seasons, pre-irrigations moisten the soil profile considerably until 80 to 90 cm depth, while at the end of these seasons, the soil dries to about a moisture content of 0.13. The monsoon rainfall of 180 mm is not effective in moistening the soil profile.

Salt Transport Simulations

Using the required input data, the model provides output on salt mass balance, Ca, Mg, Na, K, Cl, SO_4 , HCO_3 , CO_3 , electrical conductivity (EC), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), and soil pH with depth in the soil profile.

The model simulation results are plotted in Figures 8 through 14. Figure 8 shows the salt mass balance over a period of one year. It can be seen that Na salt in the soil profile is initially greater than Ca salt and though over one year period Na has reduced, but, still it is greater than Ca. It is also interesting to know that HCO_3 has increased in the soil profile at the end of a year that reflects the use of high RSC tubewell water for irrigation which causes precipitation of calcite.

The simulated Ca and Na profiles for days 120 (end of rabi season for wheat), 150 (start of kharif season for cotton), 273 (end of monsoon), 349 (end of kharif season for cotton) and 365 (start of rabi season for wheat) are plotted in Figures 9 and 10. Clearly, Ca concentrations are less at the start of the wheat and cotton growing seasons as compared to those at the end of these seasons. In the upper portion of the soil profile, the increase in Ca concentrations (peak concentrations) results from the concentrating effect of evapotranspiration of the applied irrigation water. Evapotranspiration removes pure water from the soil solution and leaves the salts. The net effect is an increase in the concentration of salts.

In the deeper layers of soil, the decrease in Ca concentrations results from the accumulation of HCO_3 , causing the precipitation of lime. The effectiveness of the monsoon rainfall in reducing the Ca concentration profile can also be seen from Figure 9. This effectiveness results from the fact that rain water contains no salts and the additional water maintains a larger water content in the soil profile, which contributed to the redistribution of the water and transport of Ca. Figure 10 shows the Na profiles simulated at days 120, 150, 273, 349 and 365. Na concentrations increase continuously in the soil profile with depth and reach a maximum value just above the bottom of the root zone. This case is opposite to Ca case which will cause higher values of SAR in the lower portions of the soil profile.

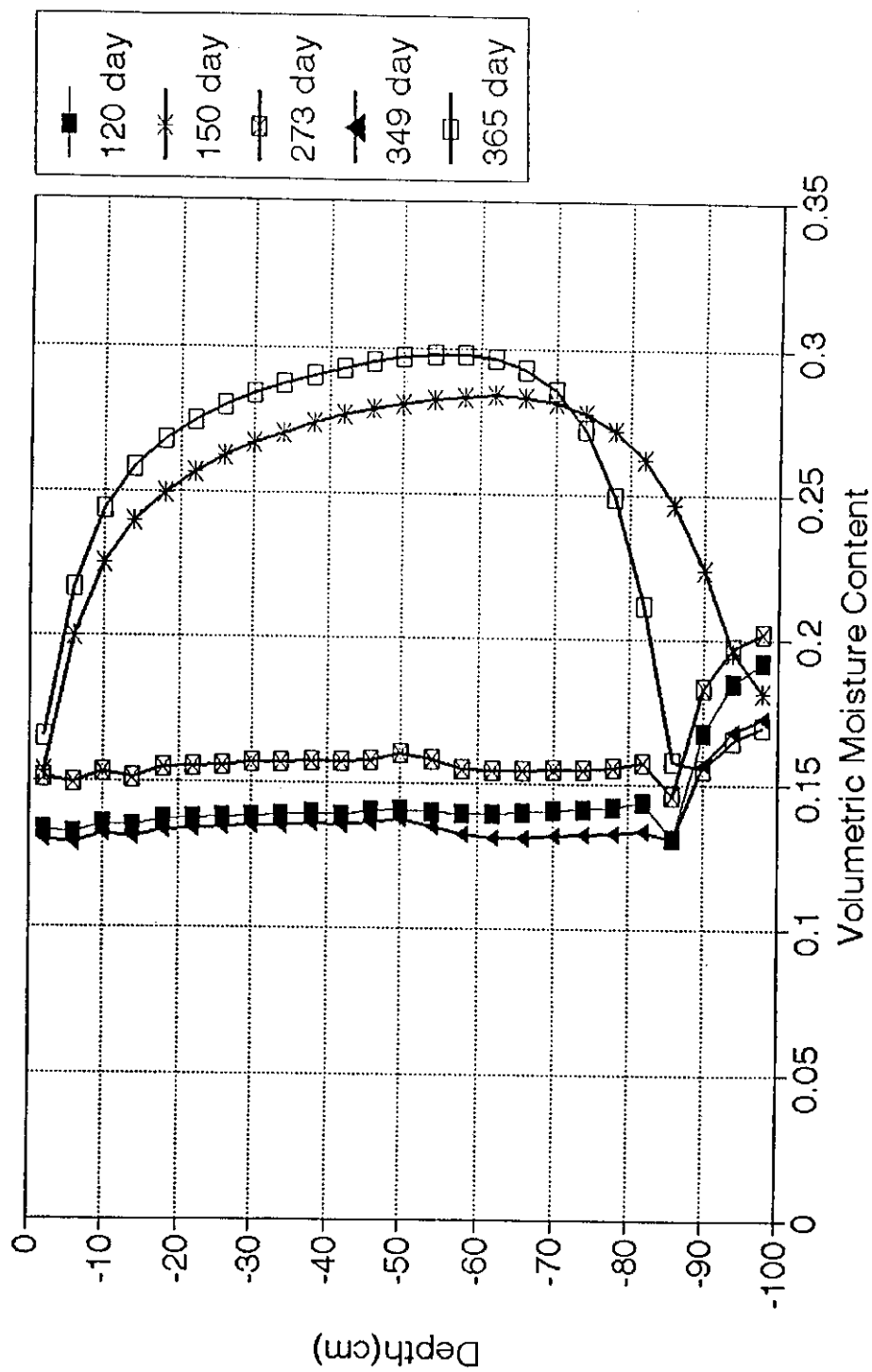


Figure 7. Simulated moisture content profiles for days 120, 150, 273, 349 and 365.

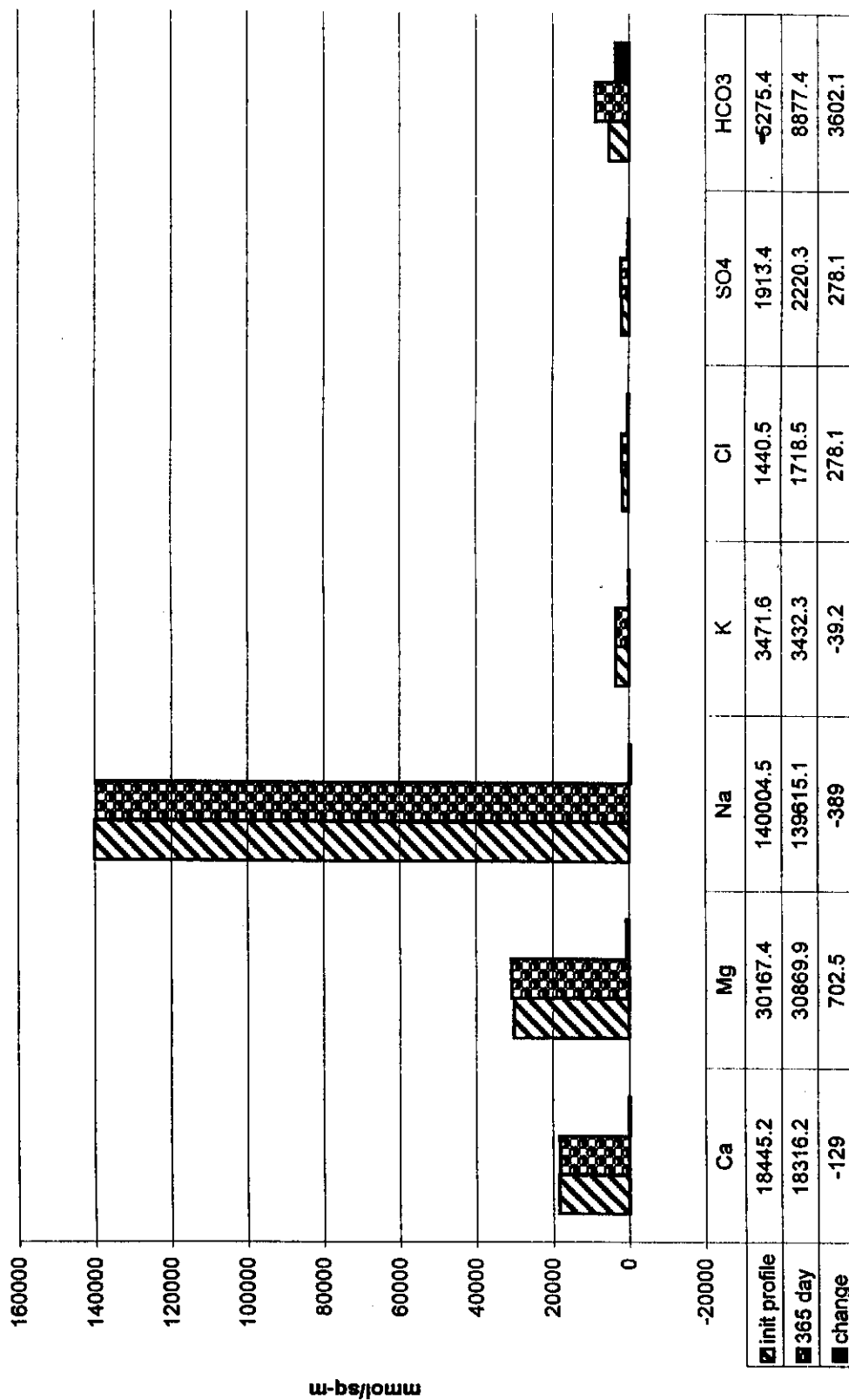


Figure 8. Simulated salt mass balance.

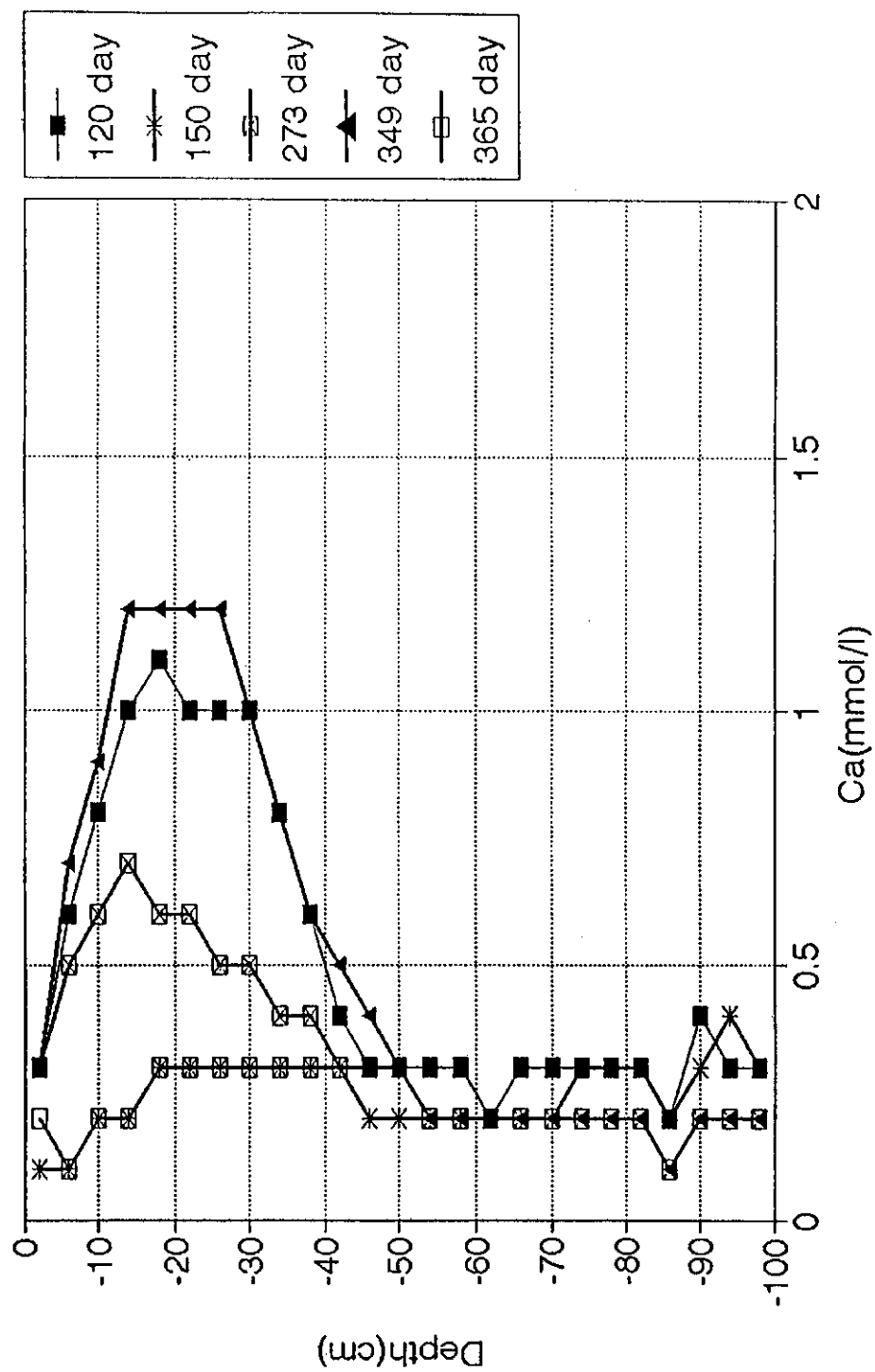


Figure 9. Simulated Ca concentration profiles for days 120, 150, 273, 349 and 365.

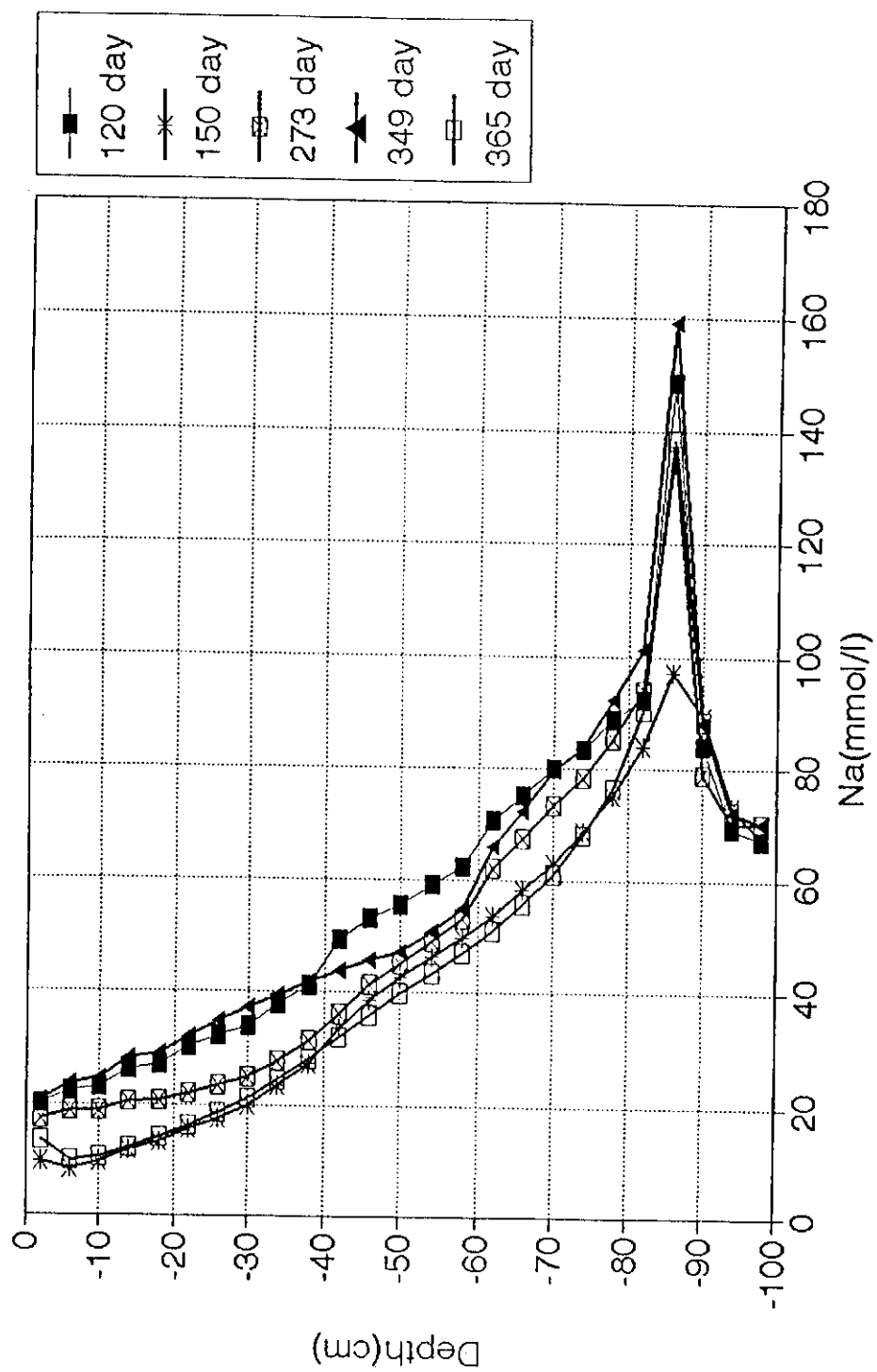


Figure 10. Simulated Na concentration profiles for days 120, 150, 273, 349 and 365.

Figure 11 presents the simulated EC profiles for days 120, 150, 273, 349 and 365. This figure also reveals that EC values are smaller at the beginning of growing seasons as compared to those at the end of seasons. The simulated values of EC (2-17 dS/m) fall within the range of 2 to 28 dS/m measured in the soils of Chishtian Irrigation Sub-division. The SAR profiles simulated for the same times are plotted in Figure 12, which shows that SAR values ($20 \text{ to } 135 \text{ mmol/l}^{1/2}$) increase continuously in the soil profile with depth and reach a maximum value at the bottom of the root zone.

Interesting to note is that SAR values hardly change at various times (wetting and drying) of the year. This phenomenon is explained by the fact that the amounts of cations in the soil solution are less as compared to the amounts of adsorbed cations, which determines to a large extent the ions ratios in the soil solution. Without considering adsorption, dilution would cause a decrease of the SAR value. However, due to exchange with the adsorbed cations, the SAR value hardly change (van Dam and Aslam, 1997).

Figure 13 presents the simulated ESP profiles at the beginning and end of the wheat and cotton growing seasons as well as at the end of monsoon period. It can be seen from the Figure 13 that ESP ranges from about 30 to 55 % within top 40 cm of the soil profile and 55 to 70 % in the lower 60 cm of root zone. It indicates that overall entire soil profile is sodic as ESP is greater than 15 %. But in the top 40 cm, the EC value is less than 4 dS/m and in the lower 60 cm of soil, EC is greater than 4 dS/m (Figure 11), therefore, the top of 40 cm soil may be classified as sodic, and the lower 60 cm of soil as saline-sodic according to USSLS, 1954 (U.S. Salinity Laboratory Staff, 1954) soil quality criteria. Overall high ESP in the soil profile results from the use of very bad quality tubewell water for irrigation.

The soil pH profiles simulated for days 120, 150, 273, 349 and 365 are given in Figure 14, which shows that soil pH varies from about 8.3 to 9.0 within top 40 cm of soil and is about 8.3 in the lower 60 cm of the soil profile. The top soil profile can be classified as alkali soil having both the high sodicity and high pH (ESP > 15 % and pH > 8.3) and containing soluble bicarbonate and carbonate. In the alkali soils swelling and dispersion increase as both ESP and pH increase and soil solutions with Na and $\text{HCO}_3 + \text{CO}_3$ predominant ions tend to have low salinities and high pH values. The pH of a sodic soil can be either greater or less than 7 and such soils can be either saline or non-saline (Agassi, 1996). In the present case, the lower portion of soil profile can be classified as saline-sodic soil.

Scenario Analysis

Sodification rate

A long - term simulation for a period of ten years on SAR was made in order to investigate the speed of soil sodification process assuming that the soil was originally irrigated with canal water for last ten years and now being irrigated with bad quality tubewell water mentioned under model input data section. The same assumption was used by Van Dam and Aslam (1997). The SAR profiles for this simulation are presented in Figure 15. It can be seen from the Figure 15 that SAR values vary in the ranges of 0.4 to 2, 1 to 10, 1 to 22, 2 to 34 and 10 to 75, at the start, at the end of first year, third year, fifth year and tenth year, respectively. These results reveal that SAR increases with time in the soil profile and the entire soil profile becomes sodic within a time frame of ten years, which reflects the gradual build-up of sodicity in the soil profile due to use of high RSC tubewell water for irrigation.

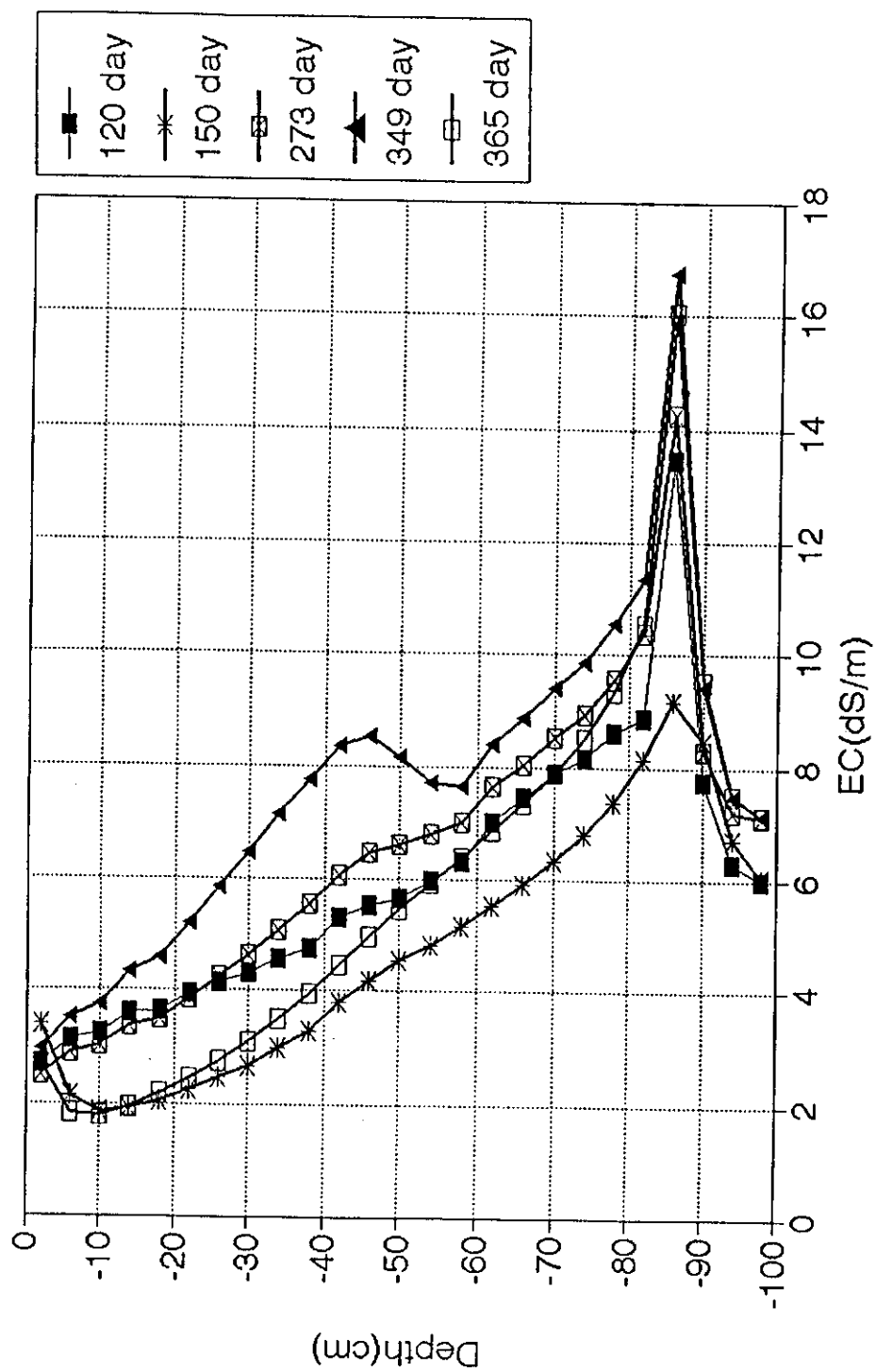


Figure 11. Simulated EC profiles for days 120, 150, 273, 349 and 365.

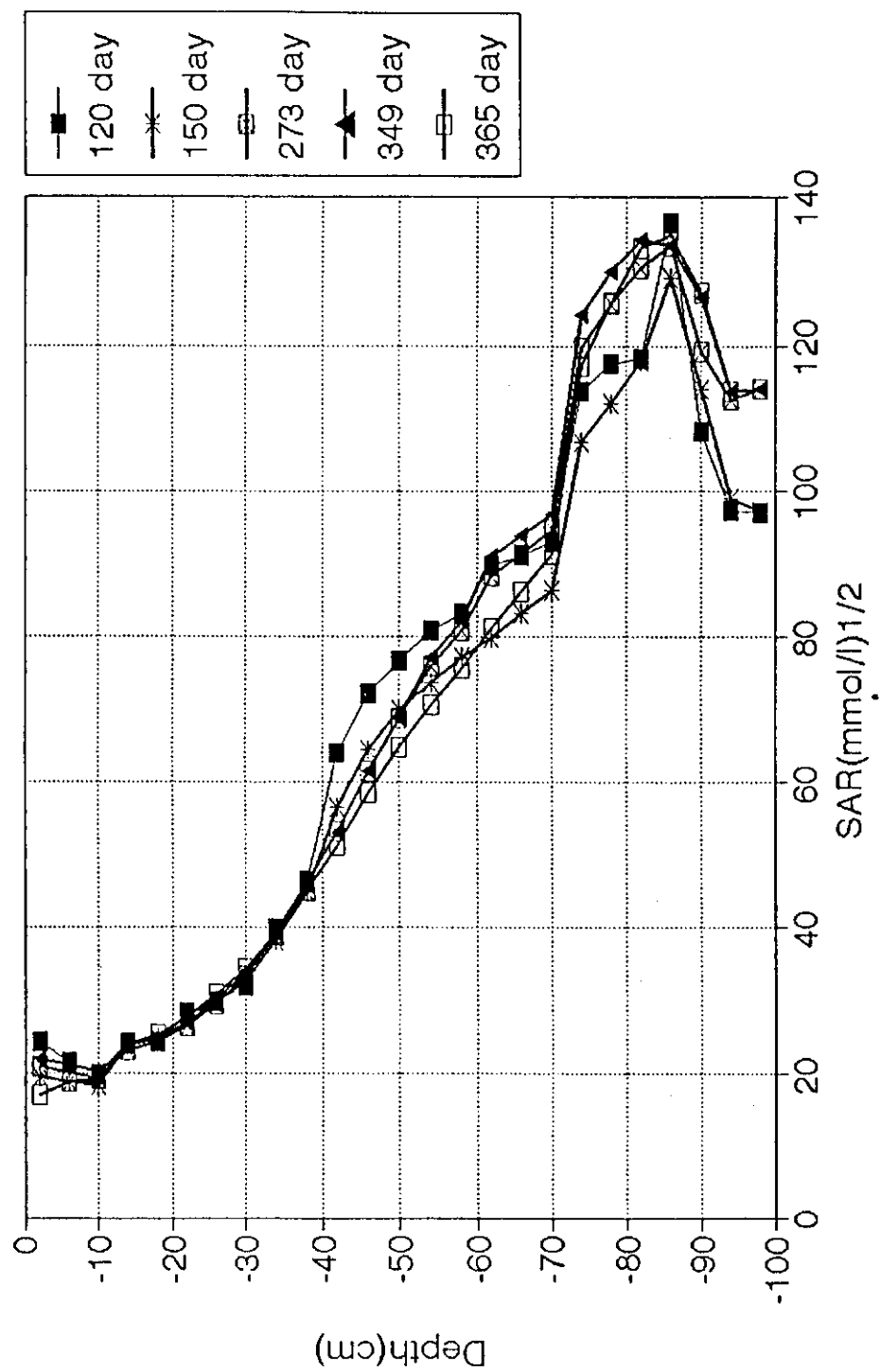


Figure 12. Simulated SAR profiles for days 120, 150, 273, 349 and 365.

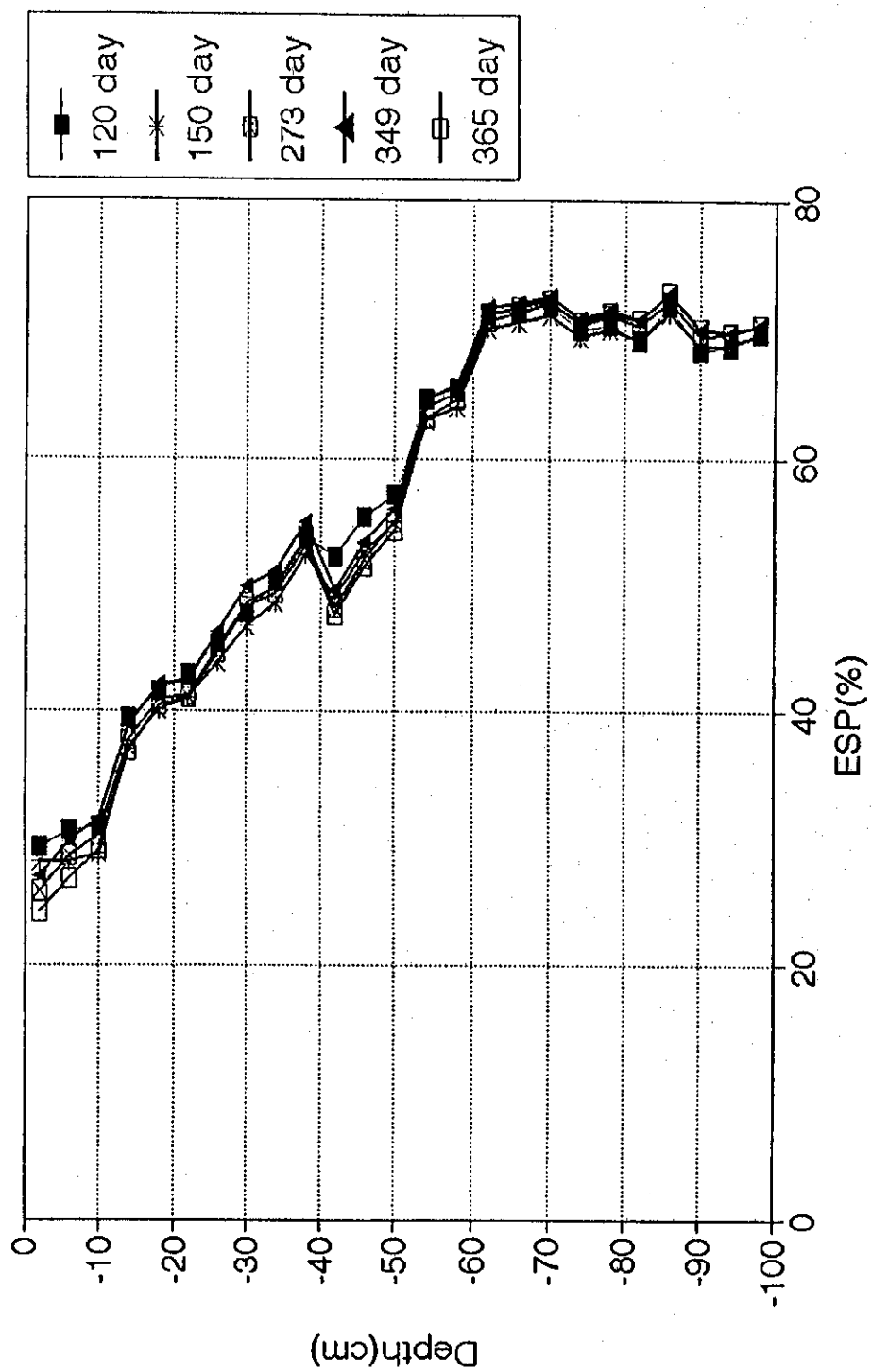


Figure 13. Simulated ESP profiles for days 120, 150, 273, 349 and 365.

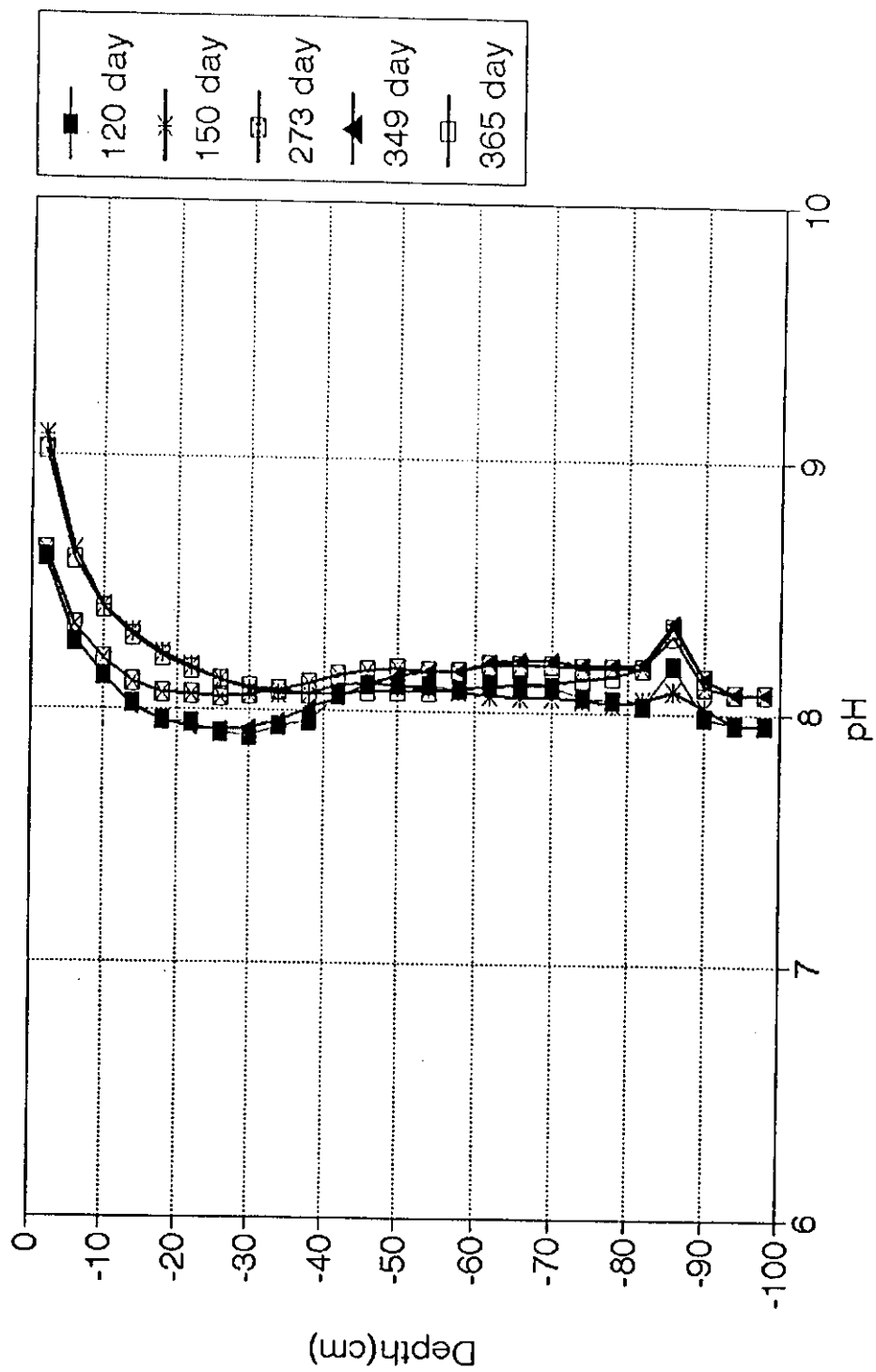


Figure 14. Simulated soil pH profiles for days 120, 150, 273, 349 and 365.

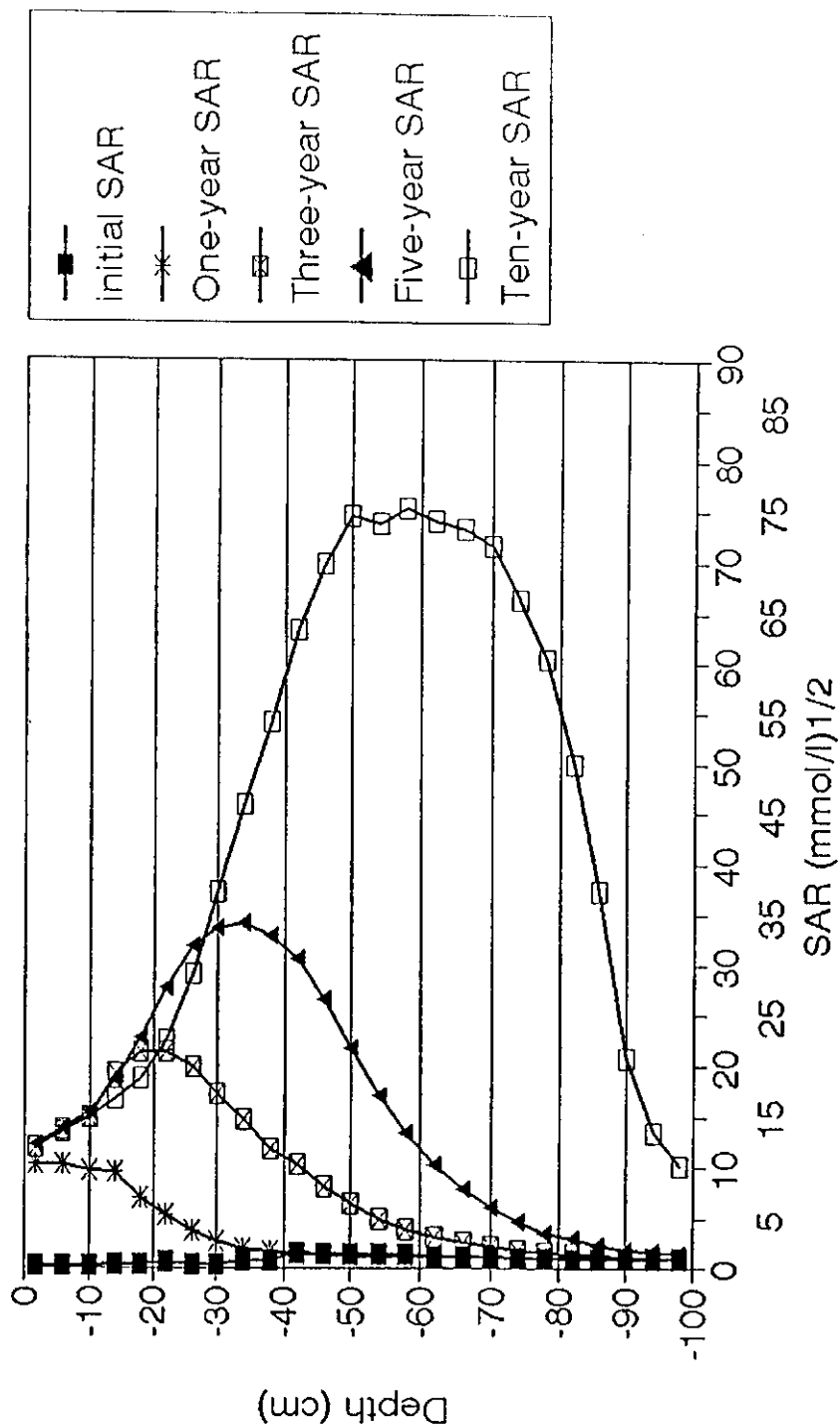


Figure 15. SAR profiles over a 10-year period, due to a change from canal water to tubewell water for irrigation.

Gypsum application

Gypsum, either incorporated into the soil or left on the surface, is the Ca source most commonly used to reclaim sodic soils and to improve soil water infiltration that has been decreased by low salinities. The exchange phase of the soil, in the presence of gypsum, is an effective sink for Ca, which replaces exchangeable Na, resulting in reduction in ESP. Modeling results (SAR) for reclamation with gypsum (2 tons per acre) of the study soil are plotted in Figure 16. In order to evaluate the effectiveness of gypsum in reclaiming sodic soil, simulations on SAR were performed at days 151 and 365 with and without gypsum application. Figure 16 shows that SAR profiles do decrease 5 and 12 months after gypsum application.

Still, upper soil profile is sodic and lower one is saline-sodic. This simulation has shown that gypsum causes reclamation of sodic soils. For proper soil reclamation, the farmers in the study area should get recommendations on the amount of gypsum required for their soils from the District Soil Chemistry Laboratories.

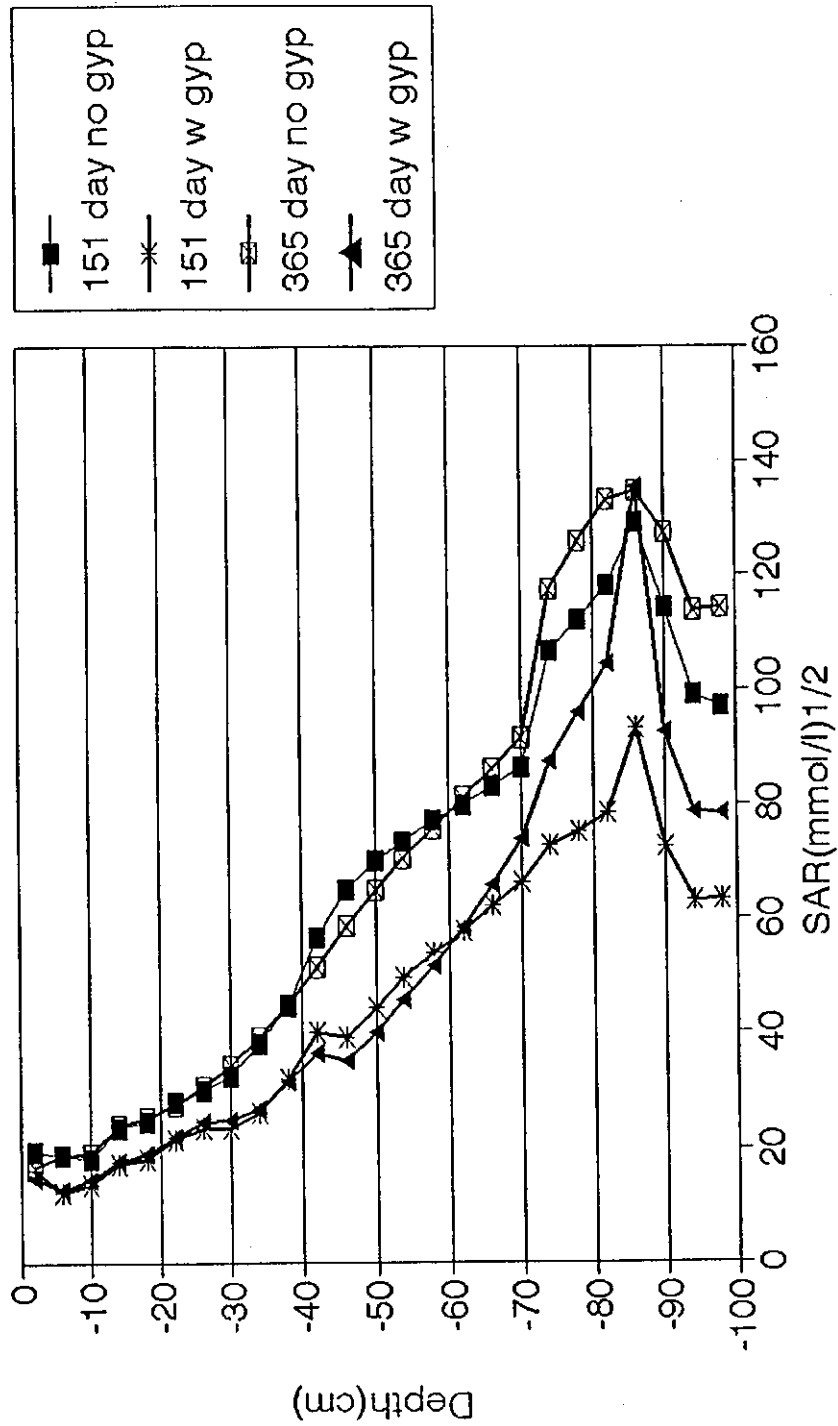


Figure 16. SAR profiles with and without gypsum application simulations.

Chapter V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Irrigated agriculture has always been affected by salinity problem. Large areas of agricultural land are going out of production in arid and semi-arid regions of the world. The salinization of soils of an irrigated area is the result of the salt concentrating effect due to evapotranspiration. In most cases, soil salinity is caused by shallow saline groundwater, but use of poor quality groundwater also converts productive agricultural lands into salt-affected lands. For sustained agricultural productivity, it is imperative that salinity should be controlled and managed in a proper way, for which it is necessary to understand the salinity and sodicity processes taking place in the irrigated soils.

Mathematical simulation and predictive models are an attractive and efficient method for analyzing salinity problems and evaluating various management alternatives for salinity control. Model predictions regarding the effectiveness of management measures which have proved to be reliable are preferred to educated guesses and costly trial- and-error. However, successful application of a computer model requires an adequate data base for its operation; acquiring an adequate data base can be a major task for modeling studies.

The focus of the present study was the evaluation of a numerical model which could be used to characterize the salt transport occurring in the soils of the Chishtian Irrigation Sub-division. A numerical salt transport model, LEACHM, developed at Cornell University, USA, was selected for use in the study. The soil water chemistry simulation model simulates the movement of soil water and solute transport through the unsaturated soil profile, taking into account various physical and chemical processes, such as evaporation, transpiration, cation exchange, precipitation and dissolution of salts, while considering soil equilibrium chemistry.

LEACHM considers eight chemical ions, such as Ca, Mg, Na, Cl, SO_4 , HCO_3 , and CO_3 , which are commonly found in irrigation water. The soil water and soil chemistry and irrigation data used in the evaluation of the model was derived from data collected by IIMI at four sample fields in the commands of Azim and Fordwah distributaries offtaking from Fordwah Branch of Chishtian Sub-division Irrigation System.

The main conclusions derived from the present study are:

- The simulated moisture content profiles and Ca and Na concentration profiles and EC, SAR and ESP profiles indicate that the moisture movement and salt transport through the soils in the Chishtian Sub-division could be adequately modeled with LEACHM;
- Intensive and reliable field data on soil physical and chemical properties and irrigation water chemistry are essential for reliable model simulations regarding soil salinity and sodicity processes occurring in the soil profile;

- A sound knowledge of computer model capabilities and limitations is essential in order to obtain useful and valuable results from the model studies;
- Field experience about the various aspects of salinity and sodicity problems adds accuracy and increases the confidence in the model simulated results on soil salinity and sodicity processes;
- The use of tubewell water of sodic nature for irrigation is posing a soil sodification hazard, due to which the acreage of unproductive land will increase with time. This is a serious concern for long-term sustainability of irrigated agriculture in the study area;
- Though the results of the model study are more general due to the lack of specific data for input and calibration, the simulation results fulfill the study objective of analyzing and managing salinity and sodicity processes taking place in the unsaturated zone of the soils in the study area; and
- In the case of loam soil, entire profile would become sodic with the use of high RSC tubewell water within the time frame of ten years.

The following recommendations have been drawn from this study:

- Presently, for the model calibration and validation, and the long-term predictions on salinity and sodicity build-up trends in the soil profile, detailed soil physical and chemical data are lacking in the study area. There is a definite need to obtain a better data base through an extensive and intensive field data collection in order to use the solute transport model successfully. The concentration profiles of, Ca, Mg, Na, K, Cl, SO₄, HCO₃ and CO₃ and profiles of PCO₂, CEC, lime and gypsum and the concentration profiles of exchangeable cations Ca, Mg, Na, and K should be obtained. The irrigation water chemistry needed for the model includes concentrations of Ca, Mg, Na, K, Cl, SO₄, HCO₃ and CO₃, should also be determined;
- Though farmers seem to have an idea about soil sodicity caused by using sodic groundwater, they are not able to mitigate this problem because farmers are not aware of chemical amendments and leaching requirements without which they will get low crop yields from the affected lands or they will have to abandon those lands from cultivation permanently. Farmers should be made aware of using chemical amendments and leaching for improving tubewell water quality and reclaiming salt-affected lands.
- A clear procedure should be developed for assessing tubewell water suitability for irrigation. Current irrigation water quality criteria as used by WAPDA, do not take into account soil type, leaching fraction, and crop characteristics. LEACHM may be valuable for developing such a procedure.

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APPENDICES

Appendix A. Finite Difference Form Of The Richards Equation (Eq. 15).

$$\left[\frac{h_i^j - h_i^{j-1}}{\Delta t} \right] C_i^{j-1/2} = K_{i-1/2}^{j-1/2} \left[\frac{h_{i-1}^{j-1} + h_{i-1}^j - h_i^{j-1} - h_i^j + 2\Delta z_1}{2\Delta z_1 \Delta z_3} \right] \quad (15a)$$

$$- K_{i+1/2}^{j-1/2} \left[\frac{h_i^{j-1} + h_i^j - h_{i+1}^{j-1} - h_{i+1}^j + 2\Delta z_2}{2\Delta z_2 \Delta z_3} \right] - A_i^{j-1/2}$$

where i is a depth subscript and j is a time superscript; h is the matric head; Δt is a time interval ($t^j - t^{j-1}$); $C_i^{j-1/2} = C(\theta)$ is the water capacity ($= \partial\theta / \partial h$) for depth i and time $j-1, j$; $K_{i-1/2}^{j-1/2} = K(\theta)$ is the average hydraulic conductivity for depth $i, i-1$ and time $j-1, j$; $K_{i+1/2}^{j-1/2} = K(\theta)$ is the average hydraulic conductivity for depth $i, i+1$ and time $j-1, j$; $\Delta z_1, \Delta z_2$, and Δz_3 are depth increments where $\Delta z_1 = z_i - z_{i-1}$; $\Delta z_2 = z_{i+1} - z_i$; and $\Delta z_3 = (z_{i+1} - z_{i-1})/2$.

Equation 15a is rewritten for each time step j in the following form:

$$\alpha_i(h_{i-1}^j) + \beta_i(h_i^j) + \gamma_i(h_{i+1}^j) = \delta_i \quad (15b)$$

The expressions for $\alpha_i, \beta_i, \gamma_i$, and δ_i from Eq. 15a are obtained as follows:

$$\alpha_i = \frac{K_{i-1/2}^{j-1/2}}{\Delta z_1} \quad (15c)$$

$$\beta_i = \frac{C_i^{j-1/2} \Delta z_3}{\Delta t} + \alpha_i + \gamma_i \quad (15d)$$

$$\gamma_i = \frac{K_{i+1/2}^{j-1/2}}{\Delta z_2} \quad (15e)$$

$$\delta_i = C_i^{j-1/2} \Delta z_3 h_i^{j-1} / \Delta t + \alpha_i [h_{i-1}^{j-1} - h_i^{j-1} + \Delta z_1] \quad (15f)$$

$$+ \gamma_i [h_{i+1}^{j-1} - h_i^{j-1} - \Delta z_2] + \Delta z_3 A_i^{j-1/2}$$

All of the terms contained in the coefficients α_i , β_i , γ_i and δ_i are either known or estimated values. After specifying the initial and boundary conditions, Eq. 15b results in a tri-diagonal matrix that is solved by the Gaussian elimination method. The model simulates the soil moisture movement by calculating h_i^j values in two steps. In the first step, it calculates the g and m (parameters required to calculate h_i^j) values. Initial values of g_i and m_i are selected to meet the desired surface boundary conditions. In the second step, the model calculates the values of h_i^j starting at the bottom of the profile by substituting the boundary value h^j into the following expression, and working towards the surface:

$$h_i^j = g_i + m_i h_{i+1}^j \quad (15g)$$

$$g_i = \left[\frac{\delta_i + \alpha_i g_{i-1}}{\beta_i - \alpha_i m_{i-1}} \right] \quad (15h)$$

and

$$m_i = \left[\frac{\gamma_i}{\beta_i - \alpha_i m_{i-1}} \right] \quad (15i)$$

Appendix B. Finite Difference Form of Convection-Diffusion Equation (Eq. 20).

$$\begin{aligned}
 & \frac{[\theta_i^{j+1} c_i^{j+1} - \theta_i^j c_i^j]}{\Delta t} - \frac{\Delta t v_i^{j+1/2} [\theta_i^{j+1} - \theta_i^j]}{8 \Delta z_3} \\
 & \left[\frac{v_{i-1/2}^{j+1/2}}{\Delta z_1} (c_{i-1}^{j+1} + c_{i-1}^j - c_i^{j+1} - c_i^j) - \frac{v_{i+1/2}^{j+1/2}}{\Delta z_2} (c_i^{j+1} + c_i^j - c_{i+1}^{j+1} - c_{i+1}^j) \right] = \\
 & \frac{D_{i-1/2}^{j+1/2}}{\Delta z_1 \Delta z_3} (c_{i-1}^{j+1} + c_{i-1}^j - c_i^{j+1} - c_i^j) \\
 & - \frac{D_{i+1/2}^{j+1/2}}{\Delta z_2 \Delta z_3} (c_i^{j+1} + c_i^j - c_{i+1}^{j+1} - c_{i+1}^j) + \beta_1 q_{i-1/2} (c_{i-1}^j + c_{i-1}^{j+1}) / \Delta z_3 \\
 & - \beta_2 q_{i+1/2} (c_i^j + c_i^{j+1}) / \Delta z_3 + \beta_3 q_{i+1/2} (c_{i+1}^j + c_{i+1}^{j+1}) / \Delta z_3 \\
 & - \beta_4 q_{i-1/2} (c_i^j + c_i^{j+1}) / \Delta z_3
 \end{aligned} \tag{20a}$$

Rewriting Eq. 20a, the following new form of Eq. 20a is obtained:

$$\begin{aligned}
& c_{i-1}^{j+1} [-AB_i - B_1 CB_i] \\
& + c_i^{j+1} \left[\frac{\theta_i^{j+1}}{\Delta t} + AB_i + BB_i + \beta_2 DB_i - \beta_4 CB_i \right] \\
& + c_{i+1}^{j+1} [-BB_i + B_3 DB_i] \\
& = c_{i-1}^j [AB_i + \beta_1 CB_i] \\
& + c_i^j \left[\frac{\theta_i^j}{\Delta t} - AB_i - \beta_2 DB_i + \beta_4 CB_i - BB_i \right] \\
& + c_{i+1}^j [BB_i - \beta_3 DB_i]
\end{aligned} \tag{20b}$$

where

$$AB_i = \frac{D_{i-1/2}^{j+1/2}}{\Delta z_1 \Delta z_3} + \frac{\Delta t v_i^{j+1/2} (\theta_i^{j+1/2} - \theta_i^j)}{8 \Delta z_3} \frac{v_{i-1/2}^{j+1/2}}{\Delta z_1} \tag{20c}$$

$$BB_i = \frac{D_{i+1/2}^{j+1/2}}{\Delta z_2 \Delta z_3} - \frac{\Delta t v_i^{j+1/2} (\theta_i^{j+1/2} - \theta_i^j)}{8 \Delta z_3} \frac{v_{i+1/2}^{j+1/2}}{\Delta z_2} \tag{20d}$$

$$CB_i = \frac{q_{i-1/2}}{\Delta z_3} \tag{20e}$$

$$DB_i = \frac{q_{i+1/2}}{\Delta z_3} \tag{20f}$$

To solve Eq. 20b, it is rearranged in the following form:

$$A1_i(c_{i-1}^{j+1}) + B1_i(c_i^{j+1}) - C1_i(c_{i+1}^{j+1}) = D1_i \quad (20g)$$

where

$$A1 = -AB_i - \beta_1 CB_i \quad (20h)$$

$$B1 = \frac{\theta_i^{j+1}}{\Delta t} + AB_i + BB_i + \beta_2 DB_i - \beta_4 CB_i \quad (20i)$$

$$C1 = -BB_i + \beta_3 DB_i \quad (20j)$$

$$D1 = c_{i-1}^j [AB_i + \beta_1 CB_i] + c_i^j \left[\frac{\theta_i^j}{\Delta t} - AB_i - \beta_2 DB_i + \beta_4 CB_i - BB_i \right] \\ + c_{i+1}^j [BB_i - \beta_3 DB_i] \quad (20k)$$

After specifying the initial and boundary conditions, Eq. 20g produces a tri-diagonal matrix, which is solved by using a Gauss elimination technique.

Appendix C. Sample Input Data File For LEACHM

Section 1

2 <Date format (1: month/day/year; 2: day/month/year)
010194<Starting date. No date in the input data should precede this date
365 <Ending date or day number. The starting date is day 1
0.05 <Largest time interval within a day (0.1 day or less)
0.10 <Maximum water flux per time step
1 <Number of repetitions of rainfall, crop and chemical application data
1000 <Profile depth (mm), preferably a multiple of the segment thickness
40 <Segment thickness (mm)
2 <Lower boundary condition: 1:fixed depth water table; 2:free drainage, 3:zero flux
1300 <If the lower boundary is 1 or 5: initial water table depth (mm)
50 <Time intervals between calls to chemical equilibration subroutine
0. <Molecular diffusion coefficient in water (mm²/day)
0.001 <Adjustment in Bresler's equation
10 <Adjustment in Bresler's equation
1 <Number of output files: 1: OUT only; 2: OUT + SUM; 3: OUT + SUM + BTC

For the *.OUT file:

<Units for depth data: 1: ug/kg, 2: mg/m² per segment
1 <Node print frequency (print data for every node (1), alternate nodes (2)
3 <Print options: 1, 2 or 3. To select one of the following 3 options
1 <Option 1: Time steps/print (not practical for most applications!)
5.00 <Option 2: Print at fixed time intervals (days between prints)
5 <Option 3: No. of prints (the times for which are specified below)
3 <Tables printed: 1: mass balance; 2: + depth data; 3: + crop data

For the *.SUM file:

1.00 <Summary print interval (d)
000 <Surface to [depth 1?] mm
000 <Depth 1 to [depth 2?] mm
00 <Depth 2 to [depth 3?] mm

For the *.BTC (breakthrough) file:

1.0 <Incremental depth of drainage water per output (mm)
List here the times at which the *.OUT file is desired for print option 3.
The number of records must match the 'No. of prints' under option 3 above.

Date or Time of day (At least one must be specified
Day no. (to nearest tenth) even if print option is not 3)

120 1. (These dates can be past the last day)
151 1.
273 1.
350 1.
365 1.

Section 2

SOIL PHYSICAL PROPERTIES

Retentivity model 0 uses listed Campbell's retention parameters, otherwise the desired particle size-based regression model is used.

Soil layer no.	Clay %	Silt %	Organic carbon %	Retention model	Starting theta (kPa)	or pot'l (relative)	Roots (for no growth)	Starting temp (C)
1	21.	48.	1.0	0	.200	-1500.	.04	25.
2	21.	48.	1.0	0	.200	-1500.	.04	25.
3	21.	48.	1.0	0	.228	-1500.	.04	25.
4	21.	48.	1.0	0	.228	-1500.	.04	25.
5	21.	48.	1.0	0	.228	-1500.	.04	25.
6	21.	48.	1.0	0	.242	-1500.	.04	25.
7	21.	48.	1.0	0	.242	-1500.	.04	25.
8	21.	48.	1.0	0	.242	-1500.	.04	25.
9	21.	48.	1.0	0	.242	-1500.	.04	25.
10	21.	48.	1.0	0	.242	-1500.	.04	25.
11	21.	48.	1.0	0	.242	-1500.	.04	25.
12	21.	48.	1.0	0	.242	-1500.	.04	25.
13	21.	48.	1.0	0	.235	-1500.	.04	25.
14	21.	48.	1.0	0	.235	-1500.	.04	25.
15	21.	48.	1.0	0	.235	-1500.	.04	25.
16	21.	48.	1.0	0	.222	-1500.	.04	25.
17	21.	48.	1.0	0	.222	-1500.	.04	25.
18	21.	48.	1.0	0	.170	-1500.	.04	25.
19	21.	48.	1.0	0	.170	-1500.	.04	25.
20	21.	48.	1.0	0	.170	-1500.	.04	25.
21	21.	48.	1.0	0	.136	-1500.	.04	25.
22	21.	48.	1.0	0	.136	-1500.	.04	25.
23	21.	48.	1.0	0	.136	-1500.	.04	25.
24	21.	48.	1.0	0	.136	-1500.	.04	25.
25	21.	48.	1.0	0	.136	-1500.	.04	25.

1 < Use listed water contents (1) or potentials (2) as starting values.

Particle density: Clay 2.65 Silt and sand 2.65 Organic matter (kg/dm3) .01184

For a uniform profile: Any non-zero value here will override those in the table below (only if retentivity model is 0).

Section 2 (continued)

1.48	<Soil bulk density (kg/dm ³)
-0.863	<'Air-entry value' (AEV) (kPa)
1.31	<Exponent (BCAM) in Campbell's water retention equation
249.6 -0.00	<Conductivity (mm/day) and corresponding matric potential (kPa)
1.0	<Pore interaction parameter (P) in Campbell's conductivity equation
.50	<Dispersivity (mm)

Soil Seg. no.	Soil retentivity parameters		Bulk density	K	Matric pot'l	P	Dispersivity
	AEV	BCAM	kg/dm ³	mm/d	kPa		mm
	kPa						
1	-1.00	3.00	1.30	1000	-00.	1.0	50.
2	-1.00	3.50	1.32	1000	-00.	1.0	50.
3	-1.00	4.00	1.40	1000	-00.	1.0	50.
4	-1.00	4.50	1.48	1000	-00.	1.0	50.
5	-1.50	5.00	1.50	1000	-00.	1.0	50.
6	-2.00	5.50	1.51	1000	-00.	1.0	50.
7	-2.40	6.00	1.51	1000	-00.	1.0	50.
8	-2.70	6.40	1.52	1000	-00.	1.0	50.
9	-2.90	6.70	1.53	1000	-00.	1.0	50.
10	-3.00	7.00	1.55	1000	-00.	1.0	50.
11	-3.00	7.00	1.57	1000	-00.	1.0	50.
12	-1.00	3.00	1.30	1000	-00.	1.0	50.
13	-1.00	3.50	1.32	1000	-00.	1.0	50.
14	-1.00	4.00	1.40	1000	-00.	1.0	50.
15	-1.00	4.50	1.48	1000	-00.	1.0	50.
16	-1.50	5.00	1.50	1000	-00.	1.0	50.
17	-2.00	5.50	1.51	1000	-00.	1.0	50.
18	-2.40	6.00	1.51	1000	-00.	1.0	50.
19	-2.70	6.40	1.52	1000	-00.	1.0	50.
20	-2.90	6.70	1.53	1000	-00.	1.0	50.
21	-3.00	7.00	1.55	1000	-00.	1.0	50.
22	-3.00	7.00	1.57	1000	-00.	1.0	50.
23	-1.00	3.00	1.30	1000	-00.	1.0	50.
24	-1.00	3.50	1.32	1000	-00.	1.0	50.
25	-1.00	4.00	1.40	1000	-00.	1.0	50.

Section 3

CROP DATA

 Data for at least one crop must be specified, even if no crop is desired
 For fallow soil, set flag below to 0, or germination past the simulation end date

- 1 <Plants present: 1 yes, 0 no. This flag overrides all other crop data
- 2 <No. of crops (>0), even if bypassed. Dates can be past last day of simulation
- 1 <Growth: 1:No(use root data specified above, crop cover below); 2:Yes
- 1500 <Wilting point (soil) kPa.
- 3000 <Min.root water pot'l(kPa).
- 1.1 <maximum ratio of actual to potential transpiration (dry surface).
- 1.05 <Root resistance

Crop No.	Germination Date or Day no	Emergence	Maturity Root	Harvest Plant	Rel. root depth	Crop cover fraction	Pan factor	Annual N uptake kg/ha
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1	1	15	91	100	121	1.00	1.0	1.00	102
2	122	167	213	274	365	1.00	1.0	1.00	167

Section 4

INITIAL PROFILE DATA - SOLUBLE CATIONS AND ANIONS

Depth segment	Ca	Mg	Na	K	Cl	SO4	Alkalinity
		mmol/l				mmol/l	
1	0.07	0.19	13.9	0.11	2.01	2.81	8.95
2	0.07	0.20	14.5	0.12	2.01	2.81	9.61
3	0.10	0.04	17.5	0.15	2.31	3.22	11.5
4	0.10	0.05	17.9	0.16	2.31	3.22	11.9
5	0.10	0.05	18.2	0.16	2.31	3.22	12.3
6	0.10	0.06	22.9	0.24	3.01	4.20	15.1
7	0.10	0.06	23.0	0.24	3.01	4.20	15.2
8	0.09	0.09	31.3	0.42	4.3	6.00	20.1
9	0.09	0.09	31.3	0.42	4.3	6.00	20.1
10	0.09	0.09	31.4	0.42	4.3	6.00	20.2
11	0.12	0.28	58.3	1.15	10.6	14.60	31.0
12	0.12	0.29	58.8	1.16	10.6	14.60	31.5
13	0.05	0.28	63.3	1.62	10.6	14.60	36.3
14	0.05	0.28	63.3	1.62	10.6	14.60	36.3
15	0.05	0.28	63.3	1.62	10.6	14.60	36.3
16	0.02	0.27	68.6	2.25	10.6	14.60	42.2
17	0.02	0.27	69.3	2.28	10.6	14.60	42.9
18	0.05	1.13	136.0	4.67	18.0	20.00	49.3
19	0.05	1.12	136.0	4.67	18.0	20.00	49.4
20	0.05	1.12	136.0	4.67	18.0	20.00	49.4
21	0.07	1.23	135.0	5.04	18.0	20.00	49.3
22	0.07	1.23	135.0	5.04	18.0	20.00	49.3
23	0.07	1.23	135.0	5.04	18.0	20.00	49.3
24	0.07	1.23	135.0	5.04	18.0	20.00	49.3
25	0.07	1.23	135.0	5.04	18.0	20.00	49.3

Section 5

EXCHANGEABLE CATIONS AND EXCHANGE CAPACITY

Depth segment	Ca	Mg	Na	K	CEC
			mmol _c /kg		
1	39.13	67.8	42.66	0.35	149.94
2	39.23	67.8	42.57	0.34	149.94
3	53.13	36.2	60.17	0.52	150.02
4	53.20	36.2	60.10	0.52	150.02
5	53.26	36.2	60.04	0.52	150.02
6	45.90	36.0	67.40	0.69	149.99
7	45.91	36.0	67.39	0.69	149.99
8	35.40	36.0	77.50	1.04	149.94
9	35.41	36.0	77.49	1.04	149.94
10	35.42	36.0	77.48	1.04	149.94
11	23.20	36.0	89.12	1.75	150.07
12	23.31	36.0	89.01	1.74	150.06
13	14.91	35.8	96.99	2.45	150.15
14	14.92	35.8	96.99	2.45	150.16
15	14.92	35.8	96.98	2.45	150.15
16	8.74	36.7	110.58	3.59	159.61
17	8.87	36.7	110.45	3.59	159.61
18	7.73	36.5	111.61	3.77	159.61
19	7.74	36.5	111.61	3.77	159.62
20	7.74	36.5	111.60	3.77	159.61
21	9.41	39.62	115.16	4.22	168.41
22	9.41	39.62	115.16	4.22	168.41
23	9.41	39.62	115.16	4.22	168.41
24	9.41	39.62	115.16	4.22	168.41
25	9.41	39.62	115.16	4.22	168.41

Section 6

SELECTIVITY COEFFICIENTS pCO2 Calcite Gypsum
Depth Seg. Mg/Ca Ca/Na Ca/K (atm) (mass fraction)

1	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
2	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
3	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
4	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
5	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
6	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
7	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
8	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
9	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
10	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
11	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
12	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
13	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
14	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
15	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
16	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
17	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
18	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
19	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
20	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
21	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
22	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
23	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
24	.1E+01	.2E+01	.2E+01	.003	0.05	0.00
25	.1E+01	.2E+01	.2E+01	.003	0.05	0.00

Section 7

CHEMICAL AMENDMENT APPLICATIONS

1 < Number of broadcast applications. (At least 1. Can be past last date.)

Date Incorporation Ca Mg Na K Cl SO4 HCO3 CO3
or day number (segments, >0) -----mol/sq.m-----

370 1 50.0 00.0 00.0 00.0 00.0 50.0 00.0 00.0

Section 8

RAIN/IRRIGATION AND WATER COMPOSITION

1 < Water flow: Richards (1), modified Addiscott (2), steady-state (3)

-5 < For Addiscott : matric potential at field capacity (kPa)

-200< division between mobile and immobile water (kPa)

0.4 < For steady-state: Water content in uniform column (theta)

19 < Number of water applications, some or all can be past last day

Start time	Time	Amount	Surface flux	Water composition (can be 0)						
Date or	day		density	Ca	Mg	Na	K	Cl	SO4	Alkalinity
Day no.		mm	mm/d							
17	.0	65.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
34	.0	65.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
49	.0	65.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
62	.0	65.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
93	.0	65.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
123	.0	65.	999.9	0.35	0.45	00.20	0.10	0.40	0.150	7.500
137	.0	87.	999.9	0.35	0.45	00.20	0.10	0.40	0.150	7.500
169	.0	68.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
184	.0	68.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
192	.0	60.	999.9	0.35	0.45	00.20	0.10	0.40	0.150	7.500
199	.0	68.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
206	.0	60.	999.9	0.35	0.45	00.20	0.10	0.40	0.150	7.500
215	.0	68.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
230	.0	60.	999.9	0.35	0.45	00.20	0.10	0.40	0.150	7.5
246	.0	68.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
261	.0	68.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
276	.0	68.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
307	.0	68.	999.9	0.60	0.60	12.60	0.10	1.90	2.650	9.800
357	.0	130.	999.9	0.35	0.45	00.20	0.10	0.40	0.150	7.5

Section 9

POTENTIAL ET (WEEKLY TOTALS, mm),

Week no	ET	Week no.	ET
1	9.17	28	5.41
2	7.70	29	29.60
3	6.32	30	34.73
4	5.82	31	33.82
5	8.41	32	35.12
6	11.89	33	38.25
7	14.40	34	41.37
8	16.92	35	43.37
9	24.92	36	42.96
10	31.79	37	44.33
11	32.18	38	44.52
12	32.20	39	44.52
13	33.81	40	34.44
14	43.47	41	34.44
15	43.47	42	34.44
16	43.34	43	34.13
17	38.93	44	27.64
18	42.78	45	22.74
19	35.95	46	21.84
20	27.43	47	20.71
21	24.86	48	18.06
22	26.02	49	13.35
23	27.53	50	12.52
24	27.69	51	11.70
25	27.85	52	12.36
26	27.47	53	9.17
27	24.25		

Appendix D. Sample Output File From LEACHM.

Table 1. Predicted retentivity and conductivity data (uniform soil profile)

Depth (mm)	Water content, theta (Conductivity mm/day)					
	Satrn	-3 kPa	-10 kPa	-30 kPa	-100 kPa	-1500 kPa
20.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
60.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
100.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
140.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
180.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
220.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
260.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
300.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
340.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
380.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
420.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
460.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
500.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
540.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
580.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
620.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
660.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
700.	.441	.171	.068	.029	.012	.001

Table 1 (continued)

	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
740.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
780.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
820.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
860.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
900.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
940.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11
980.	.441	.171	.068	.029	.012	.001
	.250E+03	.119E+01	.680E-02	.611E-04	.349E-06	.314E-11

Table 2. Cumulative totals and mass balance

TIME 120.0000 DAYS

DATE 30/ 4/94

	WATER	Ca	Mg	Na	K	Cl	SO4
mm	-----mmol/sq.m-----						
Initially in profile:	204.7	18240.5	29226.9	144885.4	3748.7	1827.7	2294.3
Currently in profile:	23.4	18870.1	29331.2	133956.5	3228.7	681.3	948.0
Change:	-181.3	629.6	104.3	-10928.9	-520.0	-1146.4	-1346.3

Added:

i) Infiltration:	325.0	27.6	195.0	4095.2	32.5	617.5	861.3
ii) As amendment:	.0	.0	.0	.0	.0	.0	.0
iii) From calcite/gyp	612.3						
iv) From CO2:							

Lost:

i) In drainage:	186.2	10.3	90.7	15024.0	552.5	1763.9	2207.5
ii) Tran/plant uptake :	319.9	.0	.0	.0	.0	.0	.0
iii) To calcite/gypsum :	.0				.0		
iv) Evaporation/to CO2:							

Mass error:	.2	.1	.0	.1	.0	.0	.0
-------------	----	----	----	----	----	----	----

Table 3.

Node	Theta	Potnl	Flux	ET	Cl	SO4	HCO3	CO3	SAR	ESP	EC	pH
mm		kPa	mm	mm	-----	mmol/l	-----				mS/m	
20.	.0237	-40.	325.01	19.66	17.7	24.7	4.7	.1	16.2	29.1	713.2	7.84
60.	.0236	-40.	312.34	25.68	22.4	31.3	4.5	.1	17.5	30.0	873.7	7.81
100.	.0236	-40.	293.69	25.50	25.6	35.7	4.4	.1	24.0	39.0	964.5	7.80
140.	.0236	-40.	276.36	24.37	28.4	39.6	4.5	.1	26.0	40.5	1054.8	7.81
180.	.0236	-40.	260.16	22.81	30.9	43.1	4.6	.1	28.7	42.0	1134.6	7.82
220.	.0235	-40.	245.52	21.38	33.4	46.6	5.3	.1	35.5	44.5	1211.2	7.88
260.	.0236	40.	232.86	19.87	35.4	49.3	5.6	.1	39.2	46.5	1272.3	7.90
300.	.0236	40.	221.70	18.15	37.3	52.0	7.1	.2	51.2	50.3	1333.2	8.01
340.	.0232	-41.	212.27	16.40	38.5	53.7	7.6	.2	55.3	52.0	1371.1	8.04
380.	.0243	39.	204.61	14.42	36.0	50.2	8.8	.2	60.3	53.5	1299.8	8.10
420.	.0226	42.	198.89	12.60	36.9	51.5	14.0	.6	81.6	56.5	1364.3	8.30
460.	.0236	40.	195.06	10.80	31.3	43.7	18.3	1.0	86.7	57.5	1219.3	8.42
500.	.0242	39.	192.99	9.20	26.5	37.0	24.1	1.6	98.6	62.9	1117.9	8.54
540.	.0233	41.	192.22	8.39	25.7	35.8	26.8	2.0	100.8	63.5	1117.9	8.59
580.	.0232	41.	192.29	7.84	25.9	36.1	29.9	2.5	102.2	64.1	1155.5	8.64
620.	.0231	-41.	192.92	7.44	26.3	36.6	37.6	4.2	113.3	68.9	1245.5	8.74
660.	.0231	-41.	193.43	7.08	26.6	37.0	44.2	6.0	113.0	69.1	1330.7	8.81
700.	.0231	-41.	194.30	6.76	26.9	37.5	69.0	16.8	95.7	67.7	1682.2	8.99
740.	.0231	-41.	193.42	6.47	27.3	37.9	75.2	20.8	93.4	68.0	1795.5	9.03
780.	.0231	-41.	192.82	6.24	27.6	38.4	80.4	24.6	91.2	68.3	1898.1	9.06
820.	.0231	-41.	192.45	6.07	28.0	38.8	86.8	30.2	84.6	67.2	2040.8	9.09
860.	.0231	41.	190.89	5.93	28.4	39.3	90.6	33.8	83.2	67.4	2130.1	9.11
900.	.0232	-41.	189.48	5.80	28.6	39.5	93.6	36.9	82.1	67.6	2203.1	9.12
940.	.0231	-41.	188.19	5.65	28.6	39.5	95.8	39.2	81.4	67.7	2252.4	9.13
980.	.0232	-41.	187.06	5.41	28.2	38.9	96.7	40.0	81.1	67.7	2255.2	9.13

Drainage flux :186.16

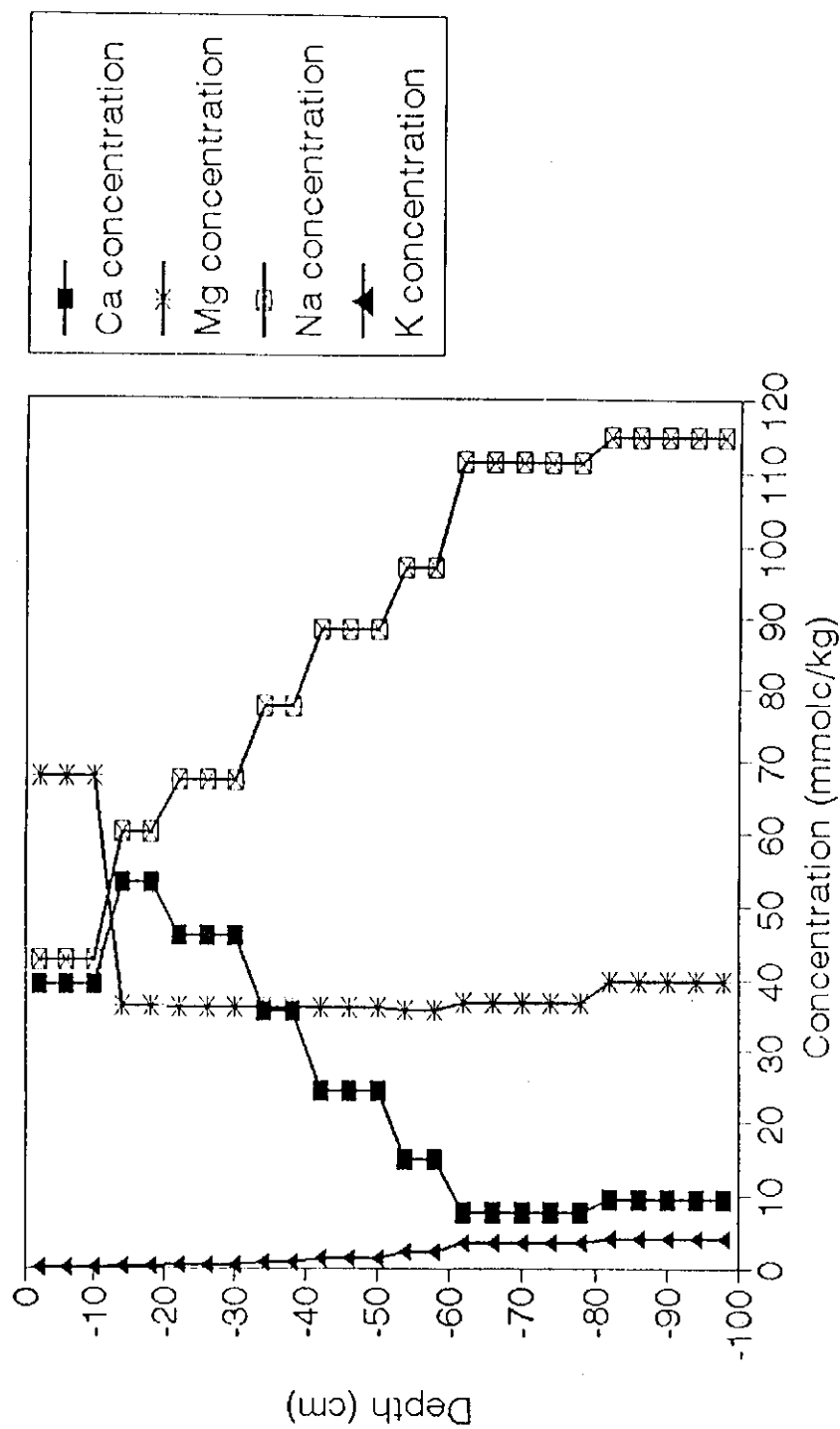
Table 4.

Crop root data, exchangeable and dissolved cations

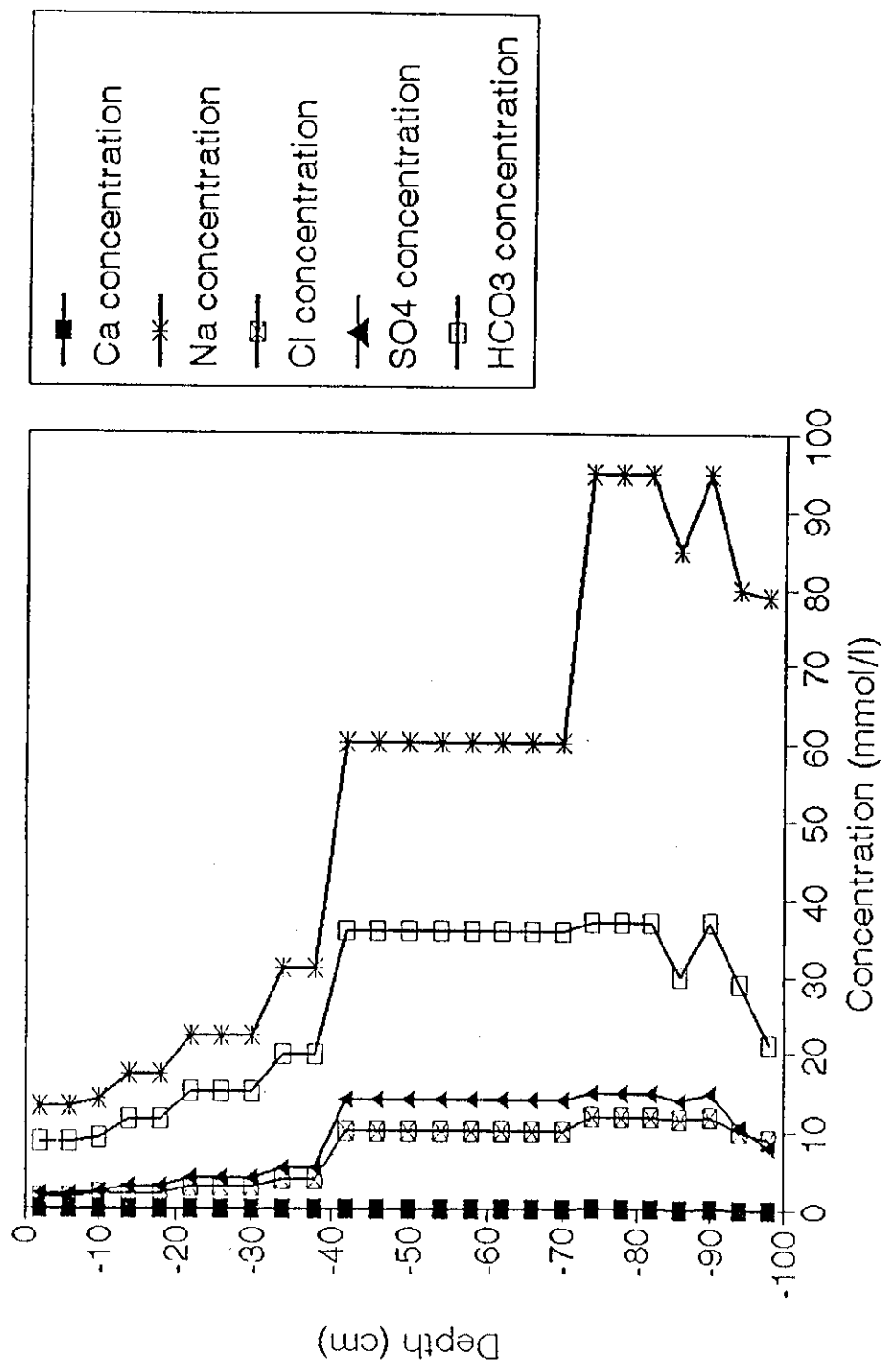
Time: 120.000 Days

Node	Roots	Ca		Mg		Na		K		Dissolved
Depth	fraction	Exch	Soln	Exch	Soln	Exch	Soln	Exch	Soln	cations
mm		me/kg	mmol/l	me/kg	mmol/l	me/kg	mmol/l	me/kg	mmol/l	me/l
20.	.040	35.79	4.1	70.18	2.3	43.61	41.3	.36	.3	54.5
60.	.040	36.04	5.1	68.63	3.1	44.91	50.6	.35	.4	67.4
100.	.040	52.95	5.8	38.02	.8	58.56	62.3	.49	.5	76.1
140.	.040	51.79	5.9	36.89	1.0	60.83	69.3	.51	.6	83.8
180.	.040	50.04	5.8	36.43	1.1	62.99	76.5	.55	.7	91.1
220.	.040	46.55	4.6	36.08	1.1	66.73	86.4	.63	.9	98.9
260.	.040	43.50	4.3	36.02	1.2	69.76	92.8	.71	1.0	104.7
300.	.040	37.63	2.7	36.00	1.2	75.42	102.6	.90	1.3	111.7
340.	.040	35.03	2.4	35.99	1.3	77.93	107.0	.99	1.4	115.8
380.	.040	32.59	1.8	35.99	1.1	80.25	102.8	1.12	1.5	109.9
420.	.040	27.87	.7	35.97	1.1	84.79	112.8	1.44	2.0	118.5
460.	.040	26.30	.5	35.92	.9	86.23	103.1	1.60	2.0	107.9
500.	.040	17.84	.3	35.85	.7	94.43	97.5	2.04	2.2	101.5
540.	.040	16.77	.2	35.79	.7	95.39	98.4	2.21	2.4	102.7
580.	.040	15.81	.2	35.73	.8	96.21	102.9	2.39	2.6	107.5
620.	.040	9.77	.2	36.81	.8	109.93	114.3	3.10	3.3	119.6
660.	.040	9.31	.2	36.79	1.0	110.24	124.7	3.28	3.8	130.9
700.	.040	11.79	.2	36.38	2.8	108.08	167.2	3.37	5.2	178.4
740.	.040	11.14	.2	36.39	3.5	108.59	180.7	3.50	5.8	193.8
780.	.040	10.59	.2	36.40	4.2	109.00	192.7	3.61	6.3	207.7
820.	.040	12.09	.2	39.30	5.8	113.15	208.0	3.87	7.0	226.8
860.	.040	11.65	.2	39.32	6.6	113.47	218.2	3.97	7.4	239.1
900.	.040	11.28	.2	39.33	7.3	113.76	226.7	4.04	7.8	249.4
940.	.040	11.02	.2	39.32	7.8	113.98	232.6	4.09	8.0	256.6
980.	.040	10.90	.2	39.32	7.9	114.07	233.6	4.12	8.1	258.0

Appendix E. Initial concentration profiles of exchangeable cations, Ca, Mg, Na And K.



Appendix F. Initial concentration profiles of soluble ions, Ca, Na, Cl, SO₄, and HCO₃.



IIMI-PAKISTAN PUBLICATIONS

RESEARCH REPORTS

Report No.	Title	Author	Year
R-1	Crop-Based Irrigation Operations Study in the North West Frontier Province of Pakistan Volume I: Synthesis of Findings and Recommendations	Carlos Garces-R D.J. Bandaragoda Pierre Strosser	June 1994
	Volume II: Research Approach and Interpretation	Carlos Garces-R Ms. Zaigham Habib Pierre Strosser Tissa Bandaragoda Rana M. Afaq Saeed ur Rehman Abdul Hakim Khan	June 1994
	Volume III: Data Collection Procedures and Data Sets	Rana M. Afaq Pierre Strosser Saeed ur Rehman Abdul Hakim Khan Carlos Garces-R	June 1994
R-2	Salinity and Sodicty Research in Pakistan - Proceedings of a one-day Workshop	J.W. Kijne Marcel Kuper Muhammad Aslam	Mar 1995
R-3	Farmers' Perceptions on Salinity and Sodicty: A case study into farmers' knowledge of salinity and sodicty, and their strategies and practices to deal with salinity and sodicty in their farming systems	Neeltje Kielen	May 1996
R-4	Modelling the Effects of Irrigation Management on Soil Salinity and Crop Transpiration at the Field Level (M.Sc Thesis - published as Research Report)	S.M.P. Smets	June 1996
R-5	Water Distribution at the Secondary Level in the Chishtian Sub-division	M. Amin K. Tareen Khalid Mahmood Anwar Iqbal Mushtaq Khan Marcel Kuper	July 1996
R-6	Farmers Ability to Cope with Salinity and Sodicty: Farmers' perceptions, strategies and practices for dealing with salinity and sodicty in their farming systems	Neeltje Kielen	Aug 1996
R-7	Salinity and Sodicty Effects on Soils and Crops in the Chishtian Sub-Division: Documentation of a Restitution Process	Neeltje Kielen Muhammad Aslam Rafique Khan Marcel Kuper	Sept 1996
R-8	Tertiary Sub-System Management: (Workshop proceedings)	Khalid Riaz Robina Wahaj	Sept 1996
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R-10	Canal Water Distribution at the Secondary Level in the Punjab, Pakistan (M.Sc Thesis published as Research Report)	Steven Visser	Oct 1996
R-11	Development of Sediment Transport Technology in Pakistan: An Annotated Bibliography	M. Hasnain Khan	Oct 1996

Report No.	Title	Author	Year
R-12	Modeling of Sediment Transport in Irrigation Canals of Pakistan: Examples of Application (M.Sc Thesis published as Research Report)	Gilles Belaud	Oct 1996
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