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ASSESSMENT OF LEACHM-C MODEL FOR SEMI-ARID SALINE IRRIGATION

by

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**A thesis submitted to the Faculty of Graduate
Studies and Research, in partial fulfilment
of the requirements for the degree of
Master of Science**

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ABSTRACT

Arid and semi-arid countries are facing the exhaustion of their water resources and are being forced to use saline water (brackish groundwater and drainage water) for irrigated agriculture. The result is often disastrous as extensive productive regions become salinized. Nevertheless, there is potential to expand irrigated agriculture through the increasing use of saline waters for irrigation. Two kinds of evidence are given to support this contention. Literature is cited to document the successful use of saline waters for irrigation around the world. Results of numerous field tests demonstrate the feasibility of using saline waters for irrigation through the development of new crop/water management strategies and practices.

This study presents an analysis of the performance of a transient state model for numerical simulation of water and solute transport, known as LEACHM-C. It is assessed for areas where saline water may be an option for crop production. The model estimates the salt and water balance of a soil profile given certain irrigation and crop rotation strategies.

First, the predictive capability of the model was successfully tested using one year of data from a field experiment in a dry region of India. Comparison between observed and predicted values of soil profile salinity (0-120 cm) was performed by graphical display techniques and by using four statistical indices: root mean square error (RMSE), coefficient of residual mass (CRM), coefficient of determination (CD) and modeling efficiency (EF). Based on the statistics, as well as the graphical displays, initial model simulations were marginal. The model over-estimated the measured values. RMSE results ranged from 28 to 70%. Agreement was improved when water retention parameters a and b were adjusted using regression equations for calculating retentivity reported in Appendix D. The RMSE values, following adjustment of the water retention parameters, ranged from 26 to 36%,

indicating the importance of obtaining accurate values of soil parameters for optimum model performance.

Second, potential usefulness of the LEACHM-C model as a tool in the planning of reclamation activities was examined for a semi-arid basin in Syria. Three management scenarios fitted to an ongoing research program in Syria were simulated. Two different water qualities and two water management schemes were used for reclamation. Predicted soil salinity rose to a pre-determined threshold value of 4 dS m^{-1} , noted for the semi-arid basins of Syria, at the end of the three-year simulations.

Despite some differences between observed and simulated EC_e values, the LEACHM-C model does predict accurate trends. In absolute terms, the model is not precise, but it is capable of indicating the appropriate salt built-ups. Results from this study may not be sufficient to assess the model's field validation and its application for semi-arid saline irrigation. Additional testing with field data is required.

RESUME

Les pays arides et semi-arides font face à l'épuisement de leurs ressources hydriques et doivent utiliser des eaux salines (eaux souterraines saumâtres et eaux de drainage) pour irriguer les cultures. Les résultats sont souvent désastreux alors que des régions de production intensive se salinisent. Malgré tout, on peut envisager d'étendre la superficie irriguée, en augmentant l'utilisation d'eaux salines pour l'irrigation. Plusieurs arguments supportent cette thèse. On trouve dans la littérature de nombreux cas où l'eau saline est utilisée avec succès pour l'irrigation. Plusieurs expériences au champ montrent qu'il est possible d'irriguer avec des eaux salines en utilisant de nouvelles pratiques et stratégies de gestion des cultures et de l'eau.

Cette étude présente l'analyse de la performance de LEACHM-C, un modèle de simulation numérique en régime transitoire du transport de l'eau et des matières dissoutes. Le modèle a été évalué pour les conditions qui existent dans des régions où l'eau saline pourrait être utilisée pour l'irrigation. Le modèle estime les bilans hydrique et de salinité des sols pour différentes stratégies d'irrigation et de rotations des cultures.

Les tests avec une année de données provenant d'un champ expérimental d'une région sèche de l'Inde ont montré que le modèle a une bonne capacité de prédiction. La comparaison de valeurs observées et prédites de salinité des sols (entre 0 et 120 cm) a été faite avec des méthodes graphiques et par le calcul de 4 indices statistiques (erreur quadratique moyenne, RMSE; coefficient de valeurs cumulées résiduelles, CRM; coefficient de détermination, CD; et efficacité de modélisation, EF). Si on se fie à la méthode graphique et aux indices statistiques, les résultats des simulations initiales furent plutôt mitigés. Les valeurs calculées par le modèle étaient surestimées. RMSE allait de 28 à 70%. Les valeurs prédites et observées se sont rapprochées lorsque les paramètres de rétention de l'eau, a et b , ont été ajustés grâce à des équations de régression présentées à l'annexe D. Les

valeurs d'erreur quadratique, après ajustement, allaient de 26 à 36%, ce qui montre l'importance d'obtenir des données de sol précises.

On a aussi examiné la possibilité d'utiliser LEACHM-C comme outil de planification des activités d'amendement des sols d'un bassin semi-aride de Syrie. On a simulé trois situations qui sont reliées à un projet de recherche présentement en cours en Syrie. Deux stratégies de gestion ont été examinées. Après une simulation avec 3 années de données, les valeurs prédites de salinité des sols ont atteint la limite maximale de 4 dS m^{-1} qui avait été observée dans des bassins semi-arides de Syrie.

Malgré certaines différences entre les valeurs prédites et observées de conductivité électrique (EC_e), le modèle LEACHM-C peut prédire adéquatement les tendances. En termes absolus, le modèle n'est pas précis mais est capable de calculer adéquatement les accumulations de sels. Les résultats de cette étude ne suffisent pas à valider le modèle et ne permettent pas de se prononcer sur une éventuelle utilisation pour planifier les irrigations avec de l'eau saline en milieu semi-aride. Des travaux additionnels, avec des données expérimentales, sont nécessaires.

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LIST OF SYMBOLS

a	air entry potential
An^{n-}	anion of negative charge
b	empirical constant related to soil texture
c	solute concentration
C	temperature degree, Celsius
Ca	calcium
Cat^{m+}	cation of positive charge
CD	coefficient of determination
CEC	cation exchange capacity
cm	centimeter
CRM	coefficient of residual mass
C_w	differential water capacity
$dS\ m^{-1}$	decisiemens per meter
$D(\theta, q)$	apparent diffusion coefficient
DW	drainage water
EC	electrical conductivity
EC_{DW}	EC of drainage water
EC_e	EC of saturated soil paste extract
EC_{IW}	EC of irrigation water
EF	modeling efficiency
ESP	exchangeable sodium percentage
ET	evapotranspiration
ha	hectare
h_c	potential at point of intersection (kPa)
h	soil water pressure head
H	hydraulic head
IW	irrigation water

LIST OF SYMBOLS CONT'D

K	hydraulic conductivity
K_{a1}	first dissociation constant of H ₂ CO ₃
K_{b2}	second dissociation constant of H ₂ CO ₃
K_d	distribution coefficient
K_f	stability constant for ion pairs
kg	kilogram
K_G	Gapon selectivity coefficient
K_H	Henry's Law constant
k Pa	kilopascal
K_{sp1}	solubility product of gypsum
K_{sp2}	solubility product of calcite
K_s	saturated hydraulic conductivity
l	litre
LF	leaching fraction
LR	leaching requirement
mmol kg⁻¹	millimol per kilogram
mmol l⁻¹	millimol per litre
mg	milligram
Mg	magnesium
Na	sodium
O_i	observed value
$\bar{O}$	mean observed value
OM	organic matter
OP	osmotic pressure, bars
pH_s	pH of saturated paste
P_i	predicted value
q	water flux density
RMSE	root mean square error

LIST OF SYMBOLS CONT'D

SAR	sodium adsorption ratio
SUM	summary file
t	time
TDS	total dissolved solids
U	absorption of water by plant
z	depth
θ	volumetric water content
θ_c	water content at point of intersection
θ_i, θ_s	initial and saturated water contents, respectively
ϕ	sink term
Δt	time step
Δz	thickness of soil layer
ρ_b	soil bulk density
ε	fractional air-filled porosity

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1. INTRODUCTION

1.1 BACKGROUND

While the earth's renewable water resources are finite, the earth's population is projected to double from the present 5.6 billion to about 10 billion by the year 2050 (U.N. Population Fund, 1993). Most of this increase will occur in arid and semi-arid regions, where close to 80% of the world's population is located (Ghassemi et al., 1995). Moreover, supplies of good quality water for irrigation are expected to decrease in the future because the development of new water supplies is not expected to keep pace with the increasing water needs of industries and municipalities. Thus, conservation of fresh irrigation water through efficient conveyance and irrigation practices and use/reuse of the drainage effluent or other relatively poor quality water for irrigating crop lands is essential.

In many arid and semi-arid regions good agricultural land has either gone out of production due to waterlogging and salinity problems or the fresh water resources available are not sufficient for achieving profitable crop production. As stated by Von Hoyningen Huene (1993), throughout history, great civilisations have flourished in these regions of the world by setting up sizeable irrigation projects. However, in the past, many of these projects eventually failed due to the problems created by irrigation. Rising water tables, combined with increasing salinity, rendered many low-lying areas useless for agriculture. The resultant loss of land severely reduced the quantity of arable land available and that, in turn, lowered the standard of living of the people depending on irrigation for their livelihood.

Water resources problems are considered a crucial matter in arid and semi-arid regions. The same crop grown in arid and semi-arid regions needs more water to sustain it than it would in other areas because of high temperatures, which cause high evapotranspiration. Sustainable use of drainage water or brackish groundwater as a water source for irrigation

depends on a number of factors. Basically, the use of saline water requires three changes from standard irrigation practices: (1) selection of appropriately salt-tolerant crops; (2) improvement in water management; and (3) maintenance of soil-physical properties to assure soil tilth and adequate soil permeability to meet crop water leaching requirements.

To date most studies support the feasibility of irrigating crops with saline water, but uncertainty still exists about long-term effects of this practice on the physical characteristics of the soil. Irrigation, fresh or saline, may increase soil salinity, soil sodicity and may even reduce soil infiltration rate. The most limiting factor to the use of saline waters on soils may be the deterioration of soil physical conditions with consequent effects on crop production. Also, one should note that the deterioration of soil physical conditions generally does not result from using saline water per se but from subsequent rainfall or application of low salinity waters. Thus far, the emphasis on using saline waters for crop production has centred on yields and less attention has been given to the long-term consequences on soil physical conditions.

An array of models is available to simulate the effects of various saline water irrigation management strategies. Based on results computed from these models, which consider the osmotic and matric potential effects on plant growth, promising strategies can be developed for the effective use of saline water for crop production. The major deficiency of these models is that they do not directly account for the effects of water quality on soil physical conditions.

Numerous management strategies have been suggested for economical use of saline water for crop irrigation. One approach blends the saline water with good quality water to an acceptable salinity as characterised by the electrical conductivity of the water (EC_{iw}) and then uses this water to irrigate crops (Rolston et al., 1988). Choice of EC_{iw} would be based upon the salt tolerance of the specific crop and availability of the

water supplies. A second method uses a cyclic irrigation strategy whereby the crop is initially irrigated with high quality water when the crop is generally more sensitive to salinity and then uses a lower quality water for later irrigations when the crop is more tolerant to salinity (Rhoades 1984, 1987). A third strategy cycles waters of various salinities in a crop rotation scheme as a function of the crop's salt tolerance. This strategy allows osmotic stress to be applied to the crop which is most tolerant to this stress (Rhoades et. al, 1988).

Long-term field experiments are one way to develop suitable irrigation strategies, but are expensive, site specific, and time consuming. A supportive activity is the use of computer simulation models. Once calibrated using experimental information these models could aid as management and decision-making tools to obtain quantitative and qualitative guidance in developing and evaluating irrigation strategies. Such a computer model should allow the use of different combinations of existing field conditions (soil, crop, climate and water). Models can provide a quick and reasonably accurate estimate of crop growth, water needs and salt balance.

"Mathematical modeling is an accepted scientific approach for providing the mechanism comprehensively integrating basic processes and describing a system beyond what can be accomplished using subjective human judgements" (Hutson and Wagenet, 1989). In recent years, great strides have been made to better understand the complex soil-water-plant-atmosphere system. This, coupled with easy availability of microcomputers, sufficient computer languages, and lower computing costs are turning the attention of scientists and engineers to develop computer models to be used as research and management tools in agriculture.

"The boom in agriculture modeling during the past two decades is producing a dramatic impact on agricultural research, management, planning and policy making, thus fostering a much needed change from

qualitative to quantitative approaches in agriculture" (Stockle, 1989). According to Huston and Wagenet (1989), the next step in modeling water and solute movement under field conditions is to condense the comprehensive descriptions provided by research models into management tools useful in providing quantitative guidance under field conditions.

1.2 STUDY OBJECTIVES

The general objective of this study is to evaluate the LEACHM-C model, a process-based model of water and salt movement, for assessing the impact of irrigation management with saline water on soil salinity and leaching, at field scale. In particular the objective is to determine if the model is applicable to field scale analysis of the semi-arid basins. The specific objectives are:

1. Review one-dimensional computer transient models used for predicting salt and water movement in unsaturated soils.
2. Test the LEACHM-C computer model performance for simulating water and salt movements in the soil profile using data obtained from field work in India.
3. Demonstrate the predictive use of the model for semi-arid basins of Syria where the problem of fresh water availability exists and irrigation with poor quality groundwater is a recent development.

1.3 SCOPE OF THE THESIS

This study investigates the performance of the LEACHM-C model (Salinity submodel of LEACHM) in its unmodified form, version 3.0, in semi-arid conditions. Suitable field data for the model validation were collected in irrigation studies conducted by the Central Soil Salinity Research Institute,

Karnal, India and represents an irrigated semi-arid area where saline water (brackish ground water and drainage water) is used for crop production.

This study is considered a first step towards further research directed at developing suitable strategies for the safe use of saline aquifers for sustainable supplemental irrigation in the semi-arid regions of Syria.

2. LITERATURE REVIEW

This review has been divided into two sections. The first section presents selected references to saline water use for irrigation and its effect on soil physical properties. The second section reviews computer transient models developed over the last 10 years for water and salt movement, salt chemistry and interaction in the root zone. In the latter section, no attempt is made to give a comprehensive review of simulation models of flow and transport processes in the soil, as only the models relevant to the current study are presented.

2.1 USE OF SALINE WATER FOR IRRIGATION

Depending on local conditions and management options adopted for its use, saline water for irrigation has been practiced throughout the world with varying degrees of success. However, its indiscriminate use in some places has led to severe soil and environmental degradation. Several extensive reviews of the world literature have been conducted on this topic, including those of Bresler (1979), Gupta (1979), Gupta and Pahawa (1981) and Rhoades (1992). Some examples of the beneficial use of saline water for irrigation are given here to emphasize the point that saline water can be used successfully for field scale crop production.

Farmers have successfully used waters that are conventionally classified as having moderate to severe restrictions to irrigate a broad spectrum of crops (Ayers and Westcot, 1985; Rhoades, 1992) in Bahrain, Egypt, Ethiopia, India, Iraq, Israel, Pakistan, Somalia, Tunisia, United Arab Emirates and The United States. In addition, numerous experiments have reported successful use of saline irrigation waters ranging in salinity from 2 to 8 dS m⁻¹ (Pasternak et al., 1986; Hamdy, 1989; Maas and Poss, 1989; Minhas and Gupta, 1993a; van Hoorn, 1991).

In the Pecos Valley of West Texas, United States, groundwater averaging about 2500 mg l^{-1} , but ranging far higher (to at least 6000 mg l^{-1}), has been successfully used to irrigate chile pepper, cotton, small grains, sorghum and alfalfa on about 81000 hectares of land for three decades (Moore and Henfer, 1977; Miyamoto et al., 1984).

Other uses of saline water for successful irrigation under hot dry (arid) climates were demonstrated by Ayers and Westcot (1985) and Rhoades (1988). The experience of Israel of 16 years of research carried out in the field of Ranat Negev experiment station (Pasternak et al., 1986), evidently support the potentiality of using relatively high saline water for irrigation under arid conditions even under the harsh desert conditions of Israel. They cultivated different crops that could be grown commercially such as: wheat, sorghum, sweet corn, sugarbeets, cotton, tomato, asparagus, broccoli, beet, celery, melon and lettuce.

Use of saline water for irrigation is not new. Listed below are examples of areas where saline water is the only available water resource. Yet, it has been used extensively for a long time and the local population has learned, mostly by trial and error, the conditions and limits of its use.

The Middle East and North African countries are examples where fresh water resources for agricultural use are rather limited and extension of irrigated agriculture is heavily dependent on the exploitation of saline water resources. Due to inherent water resource scarcities prevailing in these arid countries, saline water resources of different types are increasingly used for crop production. In Egypt, the official policy is to use drainage water, up to 5 dS m^{-1} , for irrigation. Currently, the drainage water used for irrigation amounts to $5.0 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ and it is likely to increase to $7.7 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ by the year 2000 (Abu-Zeid, 1989). Saline surface water, of up to 3.0 dS m^{-1} , is used for irrigation in Tunisia (Medjerda River) (Van't Leven and Haddad, 1968; van Hoorn, 1971) and Iraq (Shatt El Arab River) (Hardan, 1976). Unconfined aquifers salinized by seawater intrusion in the coastal plains of

Yemen, Gaza, Bahrain and Libya (Tagora area) are widely used for cereals and fruit trees. Saline aquifers in Egypt (western deserts), Jordan (desert areas), Tunisia (Messoudia and Msherfa areas), Iraq (central and southern regions), Morocco and the United Arab Emirates, are currently used for crop production.

The sustainability of viable, permanent irrigated agriculture, especially with the use of saline irrigation waters requires the implementation of appropriate management practices to control soil and water salinity, not only with irrigated soils, but also within entire irrigation projects and even whole geohydrologic systems.

Three general management strategies seem practical: (a) control salinity within permissible levels, (b) change specific conditions of use to improve crop response, (c) change management practices to maintain yield at the field level when salinity causes damage at the plant level. All three can be used together, but the first one is the most commonly used.

Nevertheless, the sustainable use of saline water for irrigation requires that research programs should be modified from individual to integrated ones where crop rotation, water management and soil amendments are all combined. In this way, many very poor quality water sources can be sustained and successfully used.

2.1.1 Water quality assessment

Water quality has different meanings and usually denotes "suitability" for use, which depends obviously on the specific purpose (Chhabra, 1996). For irrigation water, suitability is related to its effect on soils and crops and on the management that may be necessary to obtain optimum crop yields.

The evaluation of sources of saline water is complex and has to be done individually for each region, depending on local conditions. Nevertheless, for simplification some general schemes of water classification have been proposed and used. Most schemes have three basic criteria: salinity or total concentration of soluble salts; sodicity or concentration of sodium relative to calcium and magnesium ion concentration; and concentrations of boron and other elements that may be toxic to plant growth (Shainberg and Oster, 1978). They have ranged from general schemes designed for average conditions (U.S. Salinity Laboratory Staff, 1954; Doneen, 1967; Rhoades 1972; Ayers and Westcot, 1985) to specific water quality ratings based on a given crop in a specific region (Gupta, 1979; Minhas and Gupta, 1992).

Salinity is the most important criterion for evaluating irrigation water quality. Total concentration is important because most crops respond to total concentration of ions in the growth medium rather than to any specific ion. Generally an increase in the salt content of irrigation water will result in an increase in the salinity of the soil water. The rate and extent of the increase will depend on a number of factors including: the leaching fraction; the ionic composition of the irrigation water; and physical properties of the soil such as infiltration, moisture characteristics, drainage and water application.

Sodicity or sodium hazard of irrigation and soil waters can negatively affect crop production. Unlike salinity hazards, excessive sodium does not impair the uptake of water by plants but does impair the infiltration of water into the soil and the movement of the water within the soil. Plant growth is thus affected by unavailability of soil water (Pratt and Suarzes, 1990; Rhoades, 1992).

Toxicity normally results when certain ions, which are taken up with the soil water, accumulate in the leaves during water transpiration to an extent that results in damage to the plant. The usual toxic ions in irrigation water are chloride, sodium and boron. Ayers and Westcot (1989) describe these toxicities and provide data on the tolerance of crops with regard to these and other elements.

Some trace elements that occur in water and soil are essential for plant growth, but can become toxic at an elevated concentration. Pratt and Suarez (1990) provide data on the recommended maximum concentration of 15 trace elements (arsenic, beryllium, cadmium, chromium, cobalt, copper, fluorine, lead, lithium, manganese, molybdenum, nickel, selenium, vanadium and zinc). Similar data are also available in Ayers and Westcot (1989).

Rhoades (1990) argues that numerous schemes for the classification of water for irrigation are essentially empirical and have some problems. For example, substantial experience in using brackish water for irrigation shows that waters which would be classified by Ayers and Westcot (1989) as having a severe restriction for use have been successfully used in numerous places throughout the world under widely varying conditions of soil climate, irrigation technique, cropping system, economics and cultural organizations. This fact shows that actual suitability of a given water for irrigation depends much on the specific conditions of use and on the relative economic benefits that can be derived from irrigating with that water compared to viable alternatives.

However, the ultimate method of assessing the suitability of water for irrigation awaits the attainment of our capabilities to: (1) effectively predict the composition and matric potential of the soil both in time and space, and (2) interpret such information in terms of how soil conditions are affected under any set of climatic conditions (Rhoades, 1992). As stated by Rhoades, the basic approach is to (1) predict the salinity, sodicity, and toxic-solute concentrations of the soil water within a simulated crop root zone

resulting from use of a particular irrigation water of given composition at a specified leaching fraction, and (2) evaluate the effect of this salinity level (or solute concentration) upon crop yield and of the sodicity level on soil permeability.

Prognoses of water suitability are made after the soil water composition is predicted. A soil salinity problem is deemed likely if the predicted root zone salinity exceeds the tolerance level of the crop to be grown. Use of the water will result in a yield reduction unless there is a change in crop and/or leaching fraction (LF). If yield reduction can be tolerated, then the appropriately higher salinity tolerance level can be used in place of the no yield loss threshold values.

2.1.2 Leaching management

Leaching is the key factor by which soil salinity can be maintained at acceptable levels that are not toxic to the crops. A certain amount of excess irrigation water is required to pass through the root zone. A minimum net amount is required to remove salts (originally in the irrigation water) that have accumulated from evapotranspiration. This amount, in fractional terms, is referred to as the "leaching requirement" (U.S. Salinity Laboratory Staff, 1954). However, soil salinity control becomes more difficult as water quality decreases. The higher the salinity of the irrigation water, the higher the leaching or drainage required to maintain the salinity in the soil at levels below that may cause undue damage to crops. Indeed, one implication of increased need for leaching as the salinity of the irrigation water increases is that soil physical properties must be maintained and in some instances improved. Therefore, there is a need to be aware of the sodicity hazards associated with water infiltration, hydraulic conductivity and soil tilth.

How are assessment of the best strategy for leaching usually made? As stated by Shalhevet (1994), leaching need not occur with every irrigation. Starting from non-saline soils, as may occur after a rainy season, it makes no sense to start a leaching scheme before salts have accumulated in the soil. He indicated that the rate of salinization depends on the amount of saline water applied, which should thus be kept to a desirable minimum. Only when soil salinity reaches hazardous levels, should leaching be applied (Shalhevet and Yaron, 1973). Such procedures will also result in a more efficient removal of salts and water use. Thus, seasonal leaching is preferred to leaching every irrigation.

An irrigation test conducted by Hamdy (1990a,b) which consisted of four periodical leaching treatments: T1=Leaching at each irrigation, T2= Leaching after one month of irrigation with saline water, T3= leaching after two months of irrigation with saline water, T4= Leaching after harvest in combination with four salinity levels of irrigation (0.9, 3, 6, 9 dS m⁻¹) used durum wheat as an indicator plant. He concluded that, periodical leaching is more efficient rather than leaching at each irrigation. In addition, supporting the idea of seasonal leaching, Hamdy (1996) recommended that leaching should be carried out in accordance with critical stages of the crop where stress should be prevented.

Rainfall is an unmanageable variable in the leaching equation. When rainfall is seasonal, as in the Mediterranean region and the Middle East where rainfall occurs during the winter, the accumulated salinity may be removed annually from the root zone, depending on the water holding capacity of the soil and the total effective rainfall. van Hoorn (1993) demonstrated from a salt balance study conducted in Tunisia that leaching during high demand can be postponed to when more water is available, during the winter. He stated that leaching during a period of high consumptive use means that not only are larger amounts of water applied but also that larger amounts of salt are brought into the soil. The author also

showed that, as permanent leaching (imposing a leaching fraction with each irrigation) means greater water applications, there is greater risk of water stagnation and suffocation of the crops.

In practice, more or less leaching occurs during water applications depending on irrigation regime and method, but there is no strict need for permanent leaching during the summer period of peak demand. Moreover, the combined effect of irrigation water and rainfall in winter at least in the Mediterranean area and the Middle East draws advantages such that leaching should be limited to the winter period (period of low consumptive use) as much as possible.

2.1.3 Management strategies

Use of saline water (brackish ground water or drainage water) in irrigation has appeared as one the more important options in arid and semi-arid regions, depending on the quality and availability of the water. A major issue related to the use of saline water is the mode of application. Saline waters can be applied to crops in three ways: application of saline water alone; application after blending fresh water and saline water; and cyclic use of fresh water and saline waters.

A blending strategy involves the mixing of saline water with good quality water in order to obtain water suitable for irrigation as characterized by electrical conductivity (EC) and then uses this water to irrigate crops (Rains et al. 1987; Rolston et al., 1988). Choice of EC would be based upon the salt tolerance of the specific crop and availability of the water supplies. Shalhevet (1984) discussed two blending processes: mixing waters together in the irrigation conveyance system, or using the soil as a medium for mixing waters of different qualities by intermittently irrigating with the two waters. Considerable research efforts on technical aspects of the dilution process (mixing different kinds of water into a single distribution system) within the

water distribution network have been pursued by Jury et al., 1980, Tyagi and Tanwar, 1986 and Tyagi, 1996.

Meiri et al. (1986) conducted a three-year study in Israel to compare crop performance under mixing irrigation waters or intermittently applying them to the soil. Their main finding was that no significant difference in yield occurred whether the waters were mixed prior to application, or were intermittently applied for different lengths of time. They concluded the crops responded to the weighted mean water salinity regardless of the blending method.

A cyclic irrigation strategy consists of initially irrigating a crop with high quality irrigation water when the crop is more sensitive to salinity and then the use of a lower quality water for later irrigations when the crop is more tolerant to salinity (Rhoades 1984; 1987). The cycle strategy also advances a crop rotation plan that makes use of salt-tolerant and moderately salt-sensitive crops. Indeed, it is possible to cycle waters of various salinities in a crop rotation scheme as a function of the crop's salt tolerance. This strategy allows osmotic stress to be applied to the crop which is most tolerant to this stress (Rhoades, et al. 1988).

Rhoades et al. (1988) conducted an extensive study on a 20-ha commercial field located in the Imperial Valley, California. The objective was to test a strategy of seasonal cyclic use, called "dual rotation", where non-saline water is used for salt sensitive crops and for initial growth stages of tolerant crops to leach out salts accumulated from previous irrigations. The first was a rotation of wheat, sugar beets, and melons. Colorado River water (900 mg l^{-1}) was used to irrigate the melons and for preplant and early irrigations of wheat and sugar beets. Alamo River drainage water (3500 mg l^{-1}) was used for all of the other irrigations. The two-year rotation was repeated a second time. Sugar beet and wheat yields were not reduced, even when drainage water supplied up to 75% of the irrigation water. Subsequent melon yields also were not reduced.

The dual cropping consisted of cotton/wheat, followed by two years of alfalfa. Saline water was used only on cotton after seedlings were established. Colorado River water was used for all other irrigations. In this crop pattern, they found that no significant yield losses occurred for any crop grown with the cyclic strategy.

Minhas and Gupta (1993a,b) and Naresh et al. (1993) performed a comprehensive study to compare varying mixing and cyclic use modes of saline ground water (12 dS m^{-1}) and canal waters (0.2 dS m^{-1}) in terms of crop responses and salinity build-up in soils. The authors stated if facilities for blending exist and different quality waters are available on demand for each irrigation, cyclic use is preferable than blending. The cyclic use of water of low and high salinity prevents the soil from becoming too saline while permitting the substitution of brackish water by non-saline water to irrigate salt-sensitive crops and for the initial stages of tolerant crops. During the initial stages of growth the root interaction zone is limited to a few centimeters below the surface, where most of the salts are concentrated after evaporation. Hence, germination and seedling stages have been identified as the most sensitive stages for most crops for saline irrigation. Therefore, they concluded that, higher efficiency obtained with the cyclic irrigation strategy when canal water is applied in the initial stages (pre-irrigation and first post-sowing irrigation) and saline water is used at later growth stages when the crop can tolerate the salts better.

As pointed out by Minhas (1996), the cyclic type of management is useful for arid climates of India even with very low rainfall, but such an option is of natural occurrences for the continental monsoonal type of climate (rainfall is used to leach out salts accumulated from irrigation with saline water to previously grown tolerant crops) where rains concentrate during a short span (June-September) and satisfy most of the water requirements of summer crops. In addition, salts accumulated during irrigations to the first crop did not show residual effects on the yield of the

following crop seeded after the onset of monsoons. This is followed by an irrigation season (October-April) of winter crops.

An intensive research programme was conducted by Hamdy et al. (1993) for more than five years to evaluate practically the forementioned two strategies. They affirmed that, the data and results obtained favoured more the cyclic water application than the blending one. The advantage of the cyclic strategy is that steady-state salinity conditions in the soil profile are never reached. This behaviour occurs because the quality of irrigation water changes over time. The intermittent leaching that takes place under this strategy can be more effective at leaching salts than continuous leaching strategies, i.e., imposing a leaching fraction with each irrigation (Shalhevet, 1984). Furthermore, blending may deprive plants of the opportunity to use good quality water fully (Rhoades, 1988; Hamdy et al., 1993). According to Hamdy (1996) this water could be used at the time it would be most needed, for instance at the germination and seedling stages, as well as to satisfy the leaching requirement which requires water of relatively good quality. However, uncertainty still exists about the long-term effects of these practices on the physical characteristics of the soil.

2.1.4 Effects on soil-physical properties

Shainberg and Letey (1984) and Shainberg and Singer (1990) reviewed the literature on the effects of salinity and sodicity on soil physical properties. Soil infiltration rate and soil hydraulic conductivity are affected by the sodium adsorption ratio (SAR) and total electrolyte concentration of the irrigation water.

In general, increasing SAR and decreasing EC of the irrigation water tends to decrease soil hydraulic conductivity and infiltration. These results suggest that saline waters can be applied to soils without destroying their

soil physical properties because of the high electrolyte concentration, which offsets the effect of a high SAR value of the water. This has been observed in the field, i.e., application of high saline water does not reduce infiltration rate or hydraulic conductivity of the soil.

Irrigation with saline waters, however, can potentially lead to poor soil physical conditions. As water of a given chemical composition becomes concentrated through evaporation and evapotranspiration, the SAR of the water increases. This effect is further enhanced if the solution becomes sufficiently concentrated so that the divalent cations precipitate. Thus, waters with high salinity also tend to be high in SAR. As the water is applied to the soil, the exchangeable sodium percentage (ESP) on the soil exchange sites equilibrates with the SAR of the irrigating water. Thus, waters with high SAR lead to soils with high ESP. The high ESP is not detrimental to hydraulic conductivity as long as the percolating solution is also high in total electrolyte concentration. However, almost all irrigated regions of the world are subject to small amounts of rainfall during the course of the year. Since rain is essentially distilled water, the electrolyte concentration in the soil solution is reduced and the effects of the high ESP become manifest in clay swelling and dispersion and formation of a dense, hard crust on the soil surface.

Generally, it is recognized that two main mechanisms alter the physical properties of soils: clay swelling and clay particle dispersion. However, difference of opinion exists in the literature regarding which of these two processes is more important. McNeal (1968) and Kamphorst (1988) related swelling of clays to a decrease in permeability. Rhoades and Ingvalson (1969) and Felhendler et al. (1974) concluded that dispersion and consequent blocking of soil pores was mainly responsible for decreasing the hydraulic conductivity.

As stated by Bonnell (1993), clay swelling will always reduce the water transmitting ability of a soil whereas clay dispersion can decrease or

increase the hydraulic conductivity of a soil. The latter mechanism, is directly influenced by ions adsorbed on particle surfaces, particularly clay minerals. The presence of high sodium especially at low salt concentrations in the soil water causes clay dispersion and consequent movement of fine particles within the pores. The particles may then clog smaller pores, blocking water and air. On the other hand, if these migrating clay particles are completely removed from a soil profile, say via a subsurface drain pipe, the whole soil profile may become more permeable (Frenkel and Rhoades, 1977).

As mentioned by Von Hoyningen Huene (1993) two conditions seem to favour clay dispersion: (1) a sharp reduction in the concentration of the soil solution, below the threshold concentration at which the clay particles flocculate and (2) a high concentration gradient between the dilute solution of the macropores and the more concentrated solutions of the micropores inside the aggregates. Emerson and Bakker (1973) found that the optimum condition for clay dispersion in loamy and sandy loam soils of low exchangeable sodium percentage (ESP) is when the soil is leached with a dilute solution. In this process, water will move into the interplatelet region of clay particles from the bulk soil solution if an osmotic gradient exists; that is to say, an osmotic gradient between the dilute soil solution and the higher concentration of the interplatelet solution. This process will continue until the osmotic potential between the clay platelet and the bulk solution is the same.

They concluded that a high concentration gradient will force the water to move into the interplatelet region, thereby causing swelling and consequent destruction of the particle. The swelling process will in fact reduce the size of the soil pores, which, in turn, will reduce the hydraulic conductivity. These findings are corroborated by Shainberg et al. (1971) and Frenkel et al. (1978). Sharp reduction of the bulk soil solution concentration, by leaching the soil with distilled water tended to disperse the clay. In other words, swelling pressure becomes greater than the forces holding the clay

platelets together. This may lead one to conclude that there exists a soil solution concentration level at which a soil particle will disperse or flocculate.

As stated by Frenkel and Shainberg (1975) the loss of soil permeability in the arid and semi-arid Mediterranean regions is often due to the irrigation period being followed by winter rainfall, which is essential for leaching out the excess salts from the soil profile. The electrolyte concentration of the irrigation water often exceed values of $EC=0.5 \text{ dS m}^{-1}$, while the electrolytic concentration in rainwater is less than $EC=0.1 \text{ dS m}^{-1}$. Thus, in the first stages of leaching, the permeability of such soils will drop sharply and possibly, irreversibly. As a result, leaching of salts during the rainy season is not complete and the fresh water leaching practiced to remove salt from the soil profile is not practicable. In addition, loss of permeability in such soils is conducive to increased runoff and erosion.

In summary, soil solutions composed of high solute concentrations (salinity), or dominated by calcium and magnesium salts, are conducive to good soil physical properties. Conversely, low salt concentrations and relatively high portions of sodium salts can adversely affect soil permeability and tilth.

2.2 WATER AND SALT FLOW SIMULATION MODELS

A number of both management and research models have been developed over the years to simulate crop growth and salt and water movement in the soil. Research models generally provide quantitative estimates of water and solute movement, but require comprehensive data regarding the system to be simulated. Management models are less quantitative in their ability to predict water and solute fate under transient field conditions but generally require less data. Huston and Wagenet (1989) point out that few of either model types have been tested against field data. Little attention has been paid to the use of so-called management models for

the actual purpose of managing applications of salty irrigation water, fertilizers, amendments, pesticides or other solutes. They concluded that the next step in modeling water and solute movement under field conditions is to condense the comprehensive descriptions provided by research models (both deterministic and stochastic) into management models useful in providing qualitative guidance under field conditions.

Several mathematical models describing unsaturated water flow have been cited in the literature. These include both analytical (Bresler, 1973) and numerical (Bresler and Hanks, 1969; Ross, 1990; Ross and Bristow, 1990) approaches. Numerical models simultaneously simulating water flow and solute transport in the vadose zone include those by Childs and Hanks (1975), Robbins et al. (1980b), Belmans et al. (1983) and Van Genuchten (1987). In particular, there are models that integrate soil water, solute and crop processes for salinity: LEACHM-C model (Huston and Wagenet, 1989; 1992b), SOWATSAL (Hanks and Cui, 1991), and the V-H model (Cardon and Letey, 1992a,b). These models are based on a one-dimensional finite difference solution to Richard's equation and include a root extraction term.

Numerical simulations of water flow and solute transport in the root zone requires knowledge of soil hydraulic properties and water uptake by plants. Campbell (1974), Van Genuchten and Nielsen (1985) and Hutson and Cass (1987) describe soil hydraulic properties by analytical functions. Functions describing water uptake by plant roots have been reported by Nimah and Hanks (1973a,b), Feddes et al. (1978), Molz (1981), Bresler et al. (1982) Van Genuchten (1987) and Cardon and Letey (1992a).

Robbins et al. (1980b) developed a first generation model SALTFLO, which describes transient soil and solute fluxes in the presence of plant extraction of water and soil chemical reactions. The model includes description of the precipitation and dissolution of both lime and gypsum and considers cation exchange. Water flow is simulated using Darcy's law

based on a finite difference solution of the Richard's equation. Solute transport is assumed to result from the combined process of diffusion-dispersion and mass flow. The model was tested and found to be a satisfactory predictor of salt transport in the presence of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and lime (CaCO_3).

SWATRE (Soil Water and Actual Transpiration Rate, Extended) is a physically based model, which simulates transient water and salt transport in a heterogeneous soil profile (Belmans et al., 1983). Equations representing water movement and salt transport in the unsaturated zone were embedded in the model, namely Richard's equation and the convection-dispersion equation, respectively. The model contains different types of boundary conditions, including the possibility of drainage and irrigation. An improved version of the model, SWAP93, has the following advantages: better numerical solution scheme for Richard's equation; solute transport with adsorption and decomposition; and implementation of hysteresis of the water function (van den Broek et al., 1994)

Van Genuchten (1987) presented a model named WORM that simulates water flow and solute transport in a one-dimensional non-homogeneous cropped soil profile using the Richard's and convection-dispersion equations with numerical integration by the finite element method. Root uptake is calculated with a simple S-shaped curve using the assumption that water and salinity stress have similar but not necessarily additive effects on transpiration. This model is primarily designed to study water and salt movement in the root and vadose zone of an irrigated salt affected agricultural soil. The model can also be used for pesticide transport simulation because linear equilibrium adsorption and first order decay process are included in the model. The model does not, however, include mechanisms for crop simulation or salt chemistry interaction.

Hanks and Cui (1991) developed SOWATSAL a general purpose water flow model that provides for the flow of a noninteracting salt with soil

water, root uptake of pure water leaving salt behind, and flow to and from the water table. Chemical exchange, precipitation, or dissolution is not considered in the model. The model uses a finite difference formulation of the nonlinear, unsteady, unsaturated water flow equation (Richard's equation) with root extraction and the finite difference form of the diffusion-convection transport equation.

SOWATSAL computes water uptake by plants based on water potential gradients. Plants will extract water from the cells with the highest water potential. Potential evaporation and transpiration are converted from values given on a daily basis to those on an hourly basis that vary sinusoidally with time during the day. The model uses short time steps and requires detailed soil water characteristics.

Cardon and Letey (1992a) formulated a model by combining and modifying existing models for irrigation and salinity management. The model was formulated by combining routines adapted from Van Genuchten (1987) and Hanks and colleagues (Nimah and Hanks, 1973 a,b; Childs and Hanks, 1975; Torres and Hanks, 1989) and was referred to as the modified Van Genuchten-Hanks model (V-H model). Water and salt distributions resulting from irrigation and or rainfall were computed using routines adapted from Hanks and co-workers. Once the irrigation or rainfall was completed, the modified Van Genuchten water uptake/redistribution routines were used. The two components of the model exchange a file containing water and solute distribution data to be used as initial conditions for each respective section.

The V-H model accounts for transient water and salt movement, salt tolerance of the crop, seasonally variable potential ET, seasonally variable irrigation or precipitation, salinity of irrigation water, rooting depth increase with time, the presence or absence of the water table, and is conducive to multi seasonal simulations with crop rotation possibilities. The model can be used to compute crop yield, actual ET, deep percolation, salt and water

profiles at any time and water table fluctuations. The model is particularly useful for simulating the effects of any proposed management scheme.

A comprehensive model known as Leaching Estimation and Chemistry Model (LEACHM) was developed at Cornell University by Hutson and Wagenet (1989). LEACHM refers to five versions of simulation models, which describe the water regime and the chemistry and transport of solutes in unsaturated or partially saturated soils to a depth of about 2 m meters. These versions utilize similar numerical solution schemes to simulate water and chemical movement. They differ in their descriptions of chemical equilibrium, transformation and degradation pathways. LEACHM-C describes transient movement of inorganic ions (Ca, Mg, Na, K, SO_4 , Cl, CO_3 , HCO_3), LEACHM-N describes nitrogen transport and transformation, LEACHM-P simulates pesticide displacement and degradation, LEACHM-B describes microbial population dynamics in the presence of a single growth-supporting substrate and LEACHM-W describes the water regime only. These models are intended to be applied to laboratory and field situations.

The LEACHM model uses a numerical solution to Richard's equation dependent on knowledge of soil hydrological characteristics (K- θ -h relationships), boundary conditions, and source and sink terms to predict water flow. Chemical transport is estimated using a numerical solution to the diffusion-convection equation, taking into account concurrent sources and sinks of solute (such as chemical equilibrium calculations that consider precipitation/dissolution reactions) and multiple ion exchange or sorption on the soil phase.

Some of the procedures in LEACHM were developed or evolved from several earlier models (Bresler, 1973; Nimah and Hanks, 1973a,b; Robbins et al., 1980a,b; Tillotson et al., 1980). However, the general theory, its improvements and its application to issues of solute migration has been presented in several publications (Wagenet, 1983; Biggar et al., 1990; Wagenet and Rao, 1990; Hutson and Wagenet, 1992; Majeed et al., 1994).

3. LEACHM MODEL DESCRIPTION

LEACHM is a one-dimensional model of water and solute movement, chemical reactions and transformations and plant uptake in the unsaturated zone. The model written in FORTRAN, utilizes numerical solution techniques in which water flow is based on solution of Richard's equation and solute movement is based on solution of a convection-dispersion equation (CDE) including source and sink terms. LEACHM denotes all versions, and LEACHM-C, LEACHM-N, LEACHM-P, LEACHM-B and LEACHM-W specify the salinity, nitrogen, pesticides, microbial growth and water regime submodels, respectively.

3.1 MODEL STRUCTURE AND REQUIREMENTS

LEACHM submodels are organised in a modular fashion. In each of the five submodels, a main program initializes variables, calls subroutines, and performs the necessary mass balancing. Some of the subroutines are common to all submodels, while others are intended for specific submodels of LEACHM. Subroutines deal with data input and output, time step calculation, evapotranspiration, water flow, solute movement, sources, sinks, transformations and chemical interactions, leaf and root growth, temperature, and solute absorption by plants.

The way in which nodes and segments are defined in LEACHM is illustrated in Figure 3.1. The soil profile is divided into equal horizontal depth segments (Δz , mm) throughout the profile; usually between 25 and 100 mm thick. The model uses nodes situated at the centre of each segment. Two nodes, "k", below the bottom soil layer and "1" above the top soil segment, are used to maintain boundary conditions. Mass balancing is performed using nodes 2 to k-1 which are located inside the soil profile.

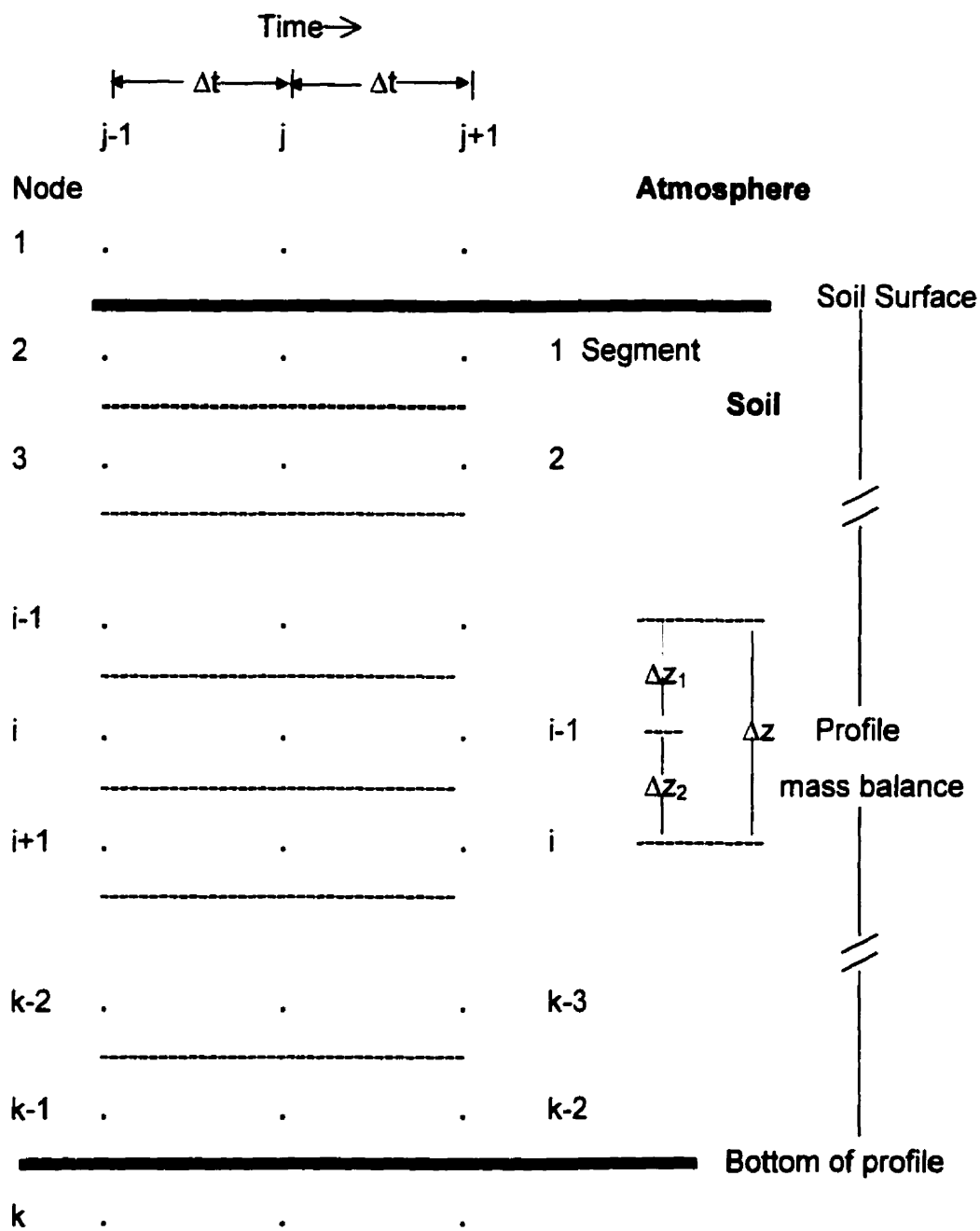


Figure 3.1 Definition of nodes and segments in LEACHM model (Hutson & Wagenet, 1992).

LEACHM calculates time steps based on a discrete time interval Δt . At the beginning of each time interval loop, the value of Δt is calculated in a subroutine TSTEP. Several factors constrain the length of the time interval:

1. The maximum value of user specified time interval in the data input file (usually 0.05 or 0.1 day time step).
2. Time remaining to the end of present 0.1 day period. Events such as data output, irrigation, etc. can only be achieved at times which are multiples of the 0.1 time step.
3. Time to complete an infiltration or irrigation event calculated using the surface flux density.
4. Time required for a specified maximum water flux anywhere in the profile.

In this study, LEACHM-C, the Chemistry, Salt Movement and Water Transport version of LEACHM, was selected to check the performance of the model for predicting salinity build-up in the soil profile (in terms of soil solution EC and SAR). The rest of the discussion in this study will focus on the LEACHM-C submodel.

3.2 LEACHM-C SUBMODEL

3.2.1 LEACHM-C submodel description

LEACHM-C is the salinity submodel of the Leaching Estimation and Chemistry Model, LEACHM (Huston and Wagenet, 1992). The main program initializes all the variables, calls subroutines that describe the following process categories: water flow, salt transport, chemical reactions, plant growth, estimating soil retentivity and conductivity parameters from soil textural data, calculation of potential evapotranspiration based on pan evaporation data and its partitioning into potential evaporation and estimating water uptake based on the Nimah and Hanks model (Nimah and

Hanks, 1973a). More complete details of the model are given in the model user's manual (Huston and Wagenet, 1992).

3.2.2 Water flow simulation

The soil-water flow is simulated using the Richard's equation. This equation is derived from combining the continuity equation with Darcy's law. For vertical one-dimensional flow under transient conditions this equation is:

$$\frac{\partial \theta}{\partial t} = C_w \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} \left[K(\theta) \frac{\partial H}{\partial z} \right] - U(z, t) \quad (3.1)$$

where θ represents the volumetric water content ($\text{m}^3 \text{ m}^{-3}$), t is time (days), C_w is the differential water capacity [$C(\theta) = \partial \theta / \partial h$, mm^{-1}], K is hydraulic conductivity (mm d^{-1}), H is hydraulic head [the sum of the pressure (h) and gravitational components of the soil water potential, kPa or mm], z is depth (mm), positive downwards and U is absorption of water by plants (day^{-1}). The model uses an implicit central-difference method (Crank-Nicolson, 1947) to solve Equation 3.1 for all the nodes.

Equations relating water content, water potential and hydraulic conductivity are required in the water flow model. The model can be accommodated to use any retentivity or conductivity functions, e.g., Van Genuchten (1980) but Campbell's (1974) equation described by an exponential relationship has been used in the model.

$$h = a \left(\frac{\theta}{\theta_s} \right)^{-b} \quad (3.2)$$

Where h is the soil water pressure head, a (air entry potential) in units of kPa, b (related to soil texture) is an empirical constant, θ is volumetric water content, and θ_s is the volumetric fraction of water at saturation.

Equation 3.2, has a sharp discontinuity at a potential equal to the air entry value ($h=a$) and at a water content equal to saturated water content ($\theta/\theta_s=1$). To overcome this sharp discontinuity, Hutson and Cass (1987) modified Equation 3.2 replacing it with a parabolic function at high potentials which gives a better representation of retentivity in real soils. They developed a sigmoidal and continuous function with a differential water capacity equal to zero at saturation as shown in Equation 3.3.

$$h = \frac{a \left(1 - \frac{\theta}{\theta_s} \right)^{1/2} \left(\frac{\theta_c}{\theta_s} \right)^{-b}}{\left(1 - \frac{\theta_c}{\theta_s} \right)^{1/2}} \quad (3.3)$$

Variables h_c and θ_c (respectively the potential and water content at point of intersection of the exponential and parabolic curves, point of coincidence of Equations 2.3 and 3.3) are given by,

$$h_c = a \left[\frac{2b}{1+2b} \right]^{-b} \quad (3.4)$$

$$\theta_c = \frac{2b\theta_s}{1+2b} \quad (3.5)$$

The point of inflection where the two curves coincide is depicted in Figure 3.2.

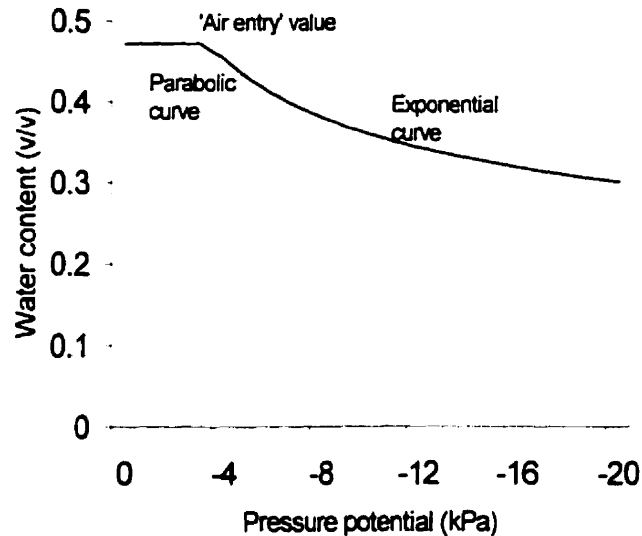


Figure 3.2 An example of the two-part retentivity function using $\theta_s = 0.472$, $b = 3.92$ and $a = -350$ mm water or -3.42 kPa (Hutson and Cass, 1987).

Hydraulic conductivity is described using Campbell's equation derived by applying a capillary model to Equation 3.1 to obtain

$$K(\theta) = K_s \left(\frac{\theta}{\theta_s} \right)^{2b+2+p} \quad (3.6)$$

Where $K(\theta)$ is the unsaturated hydraulic conductivity (mm d^{-1}) at water content θ , K_s is hydraulic conductivity at saturation and p is a pore interaction parameter [usually used empirically to adjust the shape of the $K(\theta)$ curve].

The values of a , b , θ_s and K_s can be entered directly into the input data file, if known, or can be predicted by the model using one of five possible regression equations (Hutson and Cass, 1987) relating water

retention to particle-size distribution, organic matter and bulk density (Appendix D). A separate utility Fortran program, which is supplied with the model can also be used to fit the two-part retention equation to measured retention data.

Boundary conditions

The model provides a choice of five lower boundary conditions: (i) a fixed pressure potential or fixed-depth water table, (ii) free draining profile having unit hydraulic gradient flux at lowest node, (iii) zero flux (unsaturated condition), (iv) a combination of (i) and (iii) to represent a lysimeter tank from which water drains when the bottom node reaches saturation, but has zero flux when unsaturated, or (v) a specific fluctuating water table, specified in the input data. The upper boundary can vary between zero flux, upward evaporative flux, constant flux infiltration or ponded (zero matric potential) infiltration. If soil conditions limit infiltration, the model will change a constant infiltration flux density boundary condition to ponded infiltration, which may lead to incomplete infiltration of water.

3.2.3 Solute transport

The generalized convection dispersion equation (CDE) with some modification has been used in the model to simulate solute transport. The CDE is formulated on the premise that net solute flux is the sum of convection and diffusion fluxes, therefore the rate of change of concentration with time will depend on both water flux density and solute concentration gradient. The CDE equation is:

$$\frac{\partial c}{\partial t} = (\theta + \rho_s K_d + \varepsilon K_n) = \frac{\partial}{\partial z} \left[\theta D(\theta, q) \frac{\partial c}{\partial z} - qc \right] \pm \phi \quad (3.7)$$

where c is solution concentration (mg l^{-1}), t is time (days), ρ_b is soil bulk density (kg dm^{-3}), K_d is the distribution coefficient, ε is fractional air-filled porosity, K_H Henry's law constant, z is depth (mm), positive downwards, $D(\theta, q)$ is the apparent diffusion coefficient ($\text{mm}^2 \text{d}^{-1}$) including both molecular diffusion and hydrodynamic dispersion, q is water flux density (mm d^{-1}), ϕ represents source and/or sink terms ($\text{mg dm}^{-3} \text{d}^{-1}$).

The source/sink term is assumed negligible because of the small uptake of salts by plants. Also because the multi-cation exchange processes are competitive; sorption ($\rho_b K_d$) and volatilization (εK_H) in Equation 3.7 are not used. In the absence of these terms Equation 3.7 reduces to Equation 3.8 given below which has been used in the model.

$$\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z} \left[\theta D(\theta, q) \frac{\partial c}{\partial z} - qc \right] \quad (3.8)$$

Boundary conditions

Upper boundary conditions for solute transport in the liquid phase may be zero flux or solute concentration of the infiltrating water. The lower boundary is either a specified concentration (used when lower boundary conditions are 1, fixed-dept water table or 5, free-draining profile having unit hydraulic gradient at lowest node) or that calculated from the current concentration in a mixing cell below the simulated profile. For unit gradient drainage, no solutes move up into the profile.

3.2.4 Modeling chemical interactions

In LEACHM-C, equilibrium chemistry is not included in the convection-dispersion equation because of its complexity; instead, the chemical processes (precipitation, dissolution and sorption or exchange) are

simulated in a separate chemical equilibrium routine (CHEM). The chemical species treated are Ca, Mg, Na, K, Cl, SO₄, CO₃, HCO₃⁻, H, OH, and their major ion pairs. The subroutine CHEM contains a system of mass balance equations for all the cations and anions mentioned above based on the definitions of stability constants

LEACHM-C model local equilibrium is assumed. This implies that reactions are complete at a specified point in space and time. This assumption is weakest when water fluxes are high and when geometry of the soil pores is such that ion diffusion towards sorption sites is important.

The chemical equilibrium routine adjusts solution and sorbed composition so that the following thermodynamic constants are satisfied:

1. First- and second-dissociation constant of H₂CO₃,

$$K_{a1} = \frac{(H^+)(HCO_3^-)}{(H_2CO_3)} \quad (3.9)$$

$$K_{a2} = \frac{(H^+)(CO_3^{2-})}{(HCO_3^-)} \quad (3.10)$$

2. The solubility products of gypsum (K_{sp1}) and calcite (K_{sp2}),

$$K_{sp1} = (Ca^{2+})(SO_4^{2-}) \quad (3.11)$$

$$K_{sp2} = (Ca^{2+})(CO_3^{2-}) \quad (3.12)$$

3. Ion pair stability constants for 11 ion pairs,

$$K_f = \frac{(Cat^{m+})(An^{n-})}{(CatAn^{m-n})} \quad (3.13)$$

Where Cat^{m+} represents a cation of positive charge m , An^{n-} represents an anion of negative charge n and $(CatAn^{m-n})$ represents the ion pair activity.

4. The equilibrium between a given cation's activity in solution and its concentration in the exchange phase is defined using the concept of a modified Gapon selectivity coefficient (Robbins et al., 1980a) defined as:

$$K_G = \frac{(M^{m+})^{1/m} (XN_{1/m})}{(N^{n+})^{1/n} XM_{1/m}} \quad (3.14)$$

where K_G is selectivity coefficient, X refers an exchange cation, M and N are metal cations with charges of $m+$ and $n+$, respectively.

The system of mass equations, 3.9 through 3.14, is solved by successive approximations (Robbins et al., 1980a). Moreover, chemical equilibrium is re-established at a user-specified frequency, usually every four to ten time steps. A detailed description of the inorganic chemical equilibrium in LEACHM-C can be found in the user's manual for LEACHM-C (Hutson and Wagenet, 1992).

3.2.5 Input requirements

Simulations begin at 00h00 on the first day for which a set of initial conditions are required. The soil need not be homogeneous in the vertical direction. For each soil segment, the following inputs and initial conditions are required:

- **Soil properties:** water content or water potential, hydrologic constants for calculating retentivity and hydraulic conductivity or particle size distribution, soil bulk density for each layer, chemical contents and soil chemical properties.
- **Soil surface boundary conditions:** irrigation and rainfall amounts and rates of application, pan evaporation, water table depth.
- **Crop details** (to be used if crops are present): time of planting, root and crop maturity and harvest, root and cover growth parameters, soil and plant water potential limits for water extraction by plants. If it is assumed that no crops are present, a control variable allows bypass of the plant-related subroutines.
- **Other constants:** to calculate lower boundary conditions, time step, dispersion and diffusion coefficients and chemical reactions.

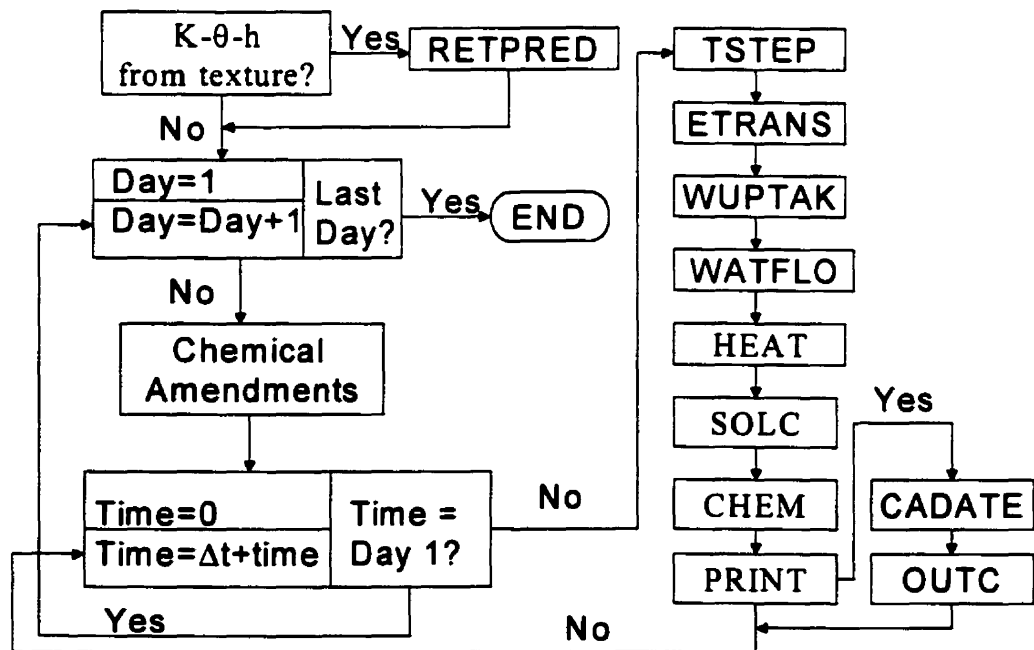


Figure 3.3 Flow chart for LEACHM-C submodel of LEACHM.

These parameters are common to all LEACHM submodels and are read from separate input files constructed appropriately for each version. The functions and subroutines associated with LEACHM-C are summarized below:

CADATE	Calculates calendar dates.
CHEM	Adjust input water and soil composition to match pCO ₂ and equilibrium constants.
ETRANS	Potential transpiration and evaporation for the time step assuming sinusoidal change during the day.
GROWTH	Estimates canopy and root growth and distribution using empirical or regression equations.
HEAT	Finite difference simulation of heat flow.
LEACH-C	Initializes all variables.
OUTC	Prints mass balance components and profile data.
POTET	Calculates daily potential evaporation and transpiration from pan evaporation and crop cover.
READC	Reads the data.
RETPRED	Performs retentivity and conductivity parameter calculations from sand, silt, clay and bulk density data.
WATDAT	Calculates water retentivity and hydraulic conductivity data for the soil hydrological constants used and prints in tabular form.
WATFLO	Finite difference solution of soil water flow equation using appropriate upper boundary and specified lower boundary conditions.
WUPTAK	Calculates water uptake by plants according to root distribution, soil water potential and hydraulic conductivity.
SOLC	Finite difference solution of solute transport equation.
TSTEP	Calculates the length of the time step (Δt) according to expected water flux density or specified limits.

3.2.6 Limitations

LEACHM-C is not intended to be applied in unequal soil depth increments, does not predict runoff water quantity and quality, does not simulate the transport of immiscible liquids and is not intended to simulate the response of plants to soil or environmental changes, or predict crop yields. Other limitations include inability to handle two- or three- dimensional flux patterns.

3.3 INPUT DATA FILE

A LEACHM-C data input file is easily prepared by editing the existing data in a sample input data file, which is supplied with the model. The data file name can be chosen by the user as desired. However, the name should be a maximum of eight characters in length and have no extension. The file name should also be written in the top left hand corner (the first eight positions of the first record) of the data file. This is used when running batch executions under DOS. Output files are created by the model and have the same name as the input file with the extension .OUT, .SUM and .BTC. An explanation of the variables used in the input data file is given in Appendix A.

3.4 OUTPUT DATA FILES

There are three kinds of output files generated by the model. The first type (with the extension .OUT) gives the salt and water balance in detail and is printed at specified time intervals or at specified times. It consists of several tables.

- 1) A table of profile water retentivity and hydraulic conductivity data.
- 2) A cumulative mass balance summary for the whole profile.
- 3) Profile chemical contents and water content potentials and fluxes.
- 4) Plant growth, chemical uptake and transpiration details.

Either Tables 1 and 2, Table 1, 2 and 3 or Tables 1, 2, 3 and 4 will print depending upon the option (1, 2 or 3) specified under 'table printed' in the input data file.

The second type of output file (with the extension .SUM) gives cumulative time, cumulative (rain + irrigation), actual transpiration and evaporation, depth to water table, chemical fluxes at three depths in the profile and at the bottom of the root zone, water fluxes at these depths and at the surface, and water and chemical contents (EC, SAR, cations and anions) in each profile section and in the root zone. This file, in which each record contains one record per print time, is convenient for preparing time series plots (see Appendix C).

The third type of output file (with the extension .BTC) lists cumulative time, pore volumes and leachate concentration at a selected depth increment of the drainage water. The pore volume data are intended for evaluation of steady-state or interrupted steady-state breakthrough curves, and are calculated from column water content, not porosity.

4. PREDICTIVE CAPABILITY WITH DATA FROM INDIA

4.1 MATERIALS AND METHODS

The utility of a simulation model for irrigation and salinity management is based largely on the agreement between measured and predicted water and solute movement in the soil profile. The LEACHM-C model was previously tested for wheat and sorghum crops using data from a lysimeter study (Majeed et al., 1994). The model predictions compared well with the experimental results. However, in the previous tests no validation was done on the model regarding the prediction of salinity build-up in the soil profile under field conditions

To test the model under field conditions, data of soil moisture and salinity, that are required for comparison of LEACHM-C model predictions and field measurements were obtained from the literature (Sharma et al., 1991; 1994 and Agnihotri et al., 1992). The data include: water quality data, soil data, climatic data, crop data and management options.

4.1.1 Site description

For six years (1986-1992) personnel at the Sampla experimental station of the Central Soil Salinity Research Institute, Karnal, India conducted an experiment on sandy loam soils. The project area was part of a field in which a subsurface drainage system (Figure 4.1) was installed in the summer of 1984 at a depth of 1.75 m. This land remained barren before the installation of the drainage system and the water-table used to reach the surface during the rainy season. The salinity of the ground water at the water-table level varied from 10 to 40 dS m⁻¹. The electrical conductivity of the saturated soil extracts (EC_e) ranged from 25 to 80 dS m⁻¹ in the top layer (0-15 cm) and reduced to about 20 dS m⁻¹ at 100 cm depth.

Installation of the subsurface drainage system resulted in an appreciable reduction in soil salinity due to monsoon leaching and continuous cropping. The water-table regime in the experimental site ranged from 1.2 to 1.4 m throughout the crop growing period and the salinity of the groundwater at the water table level ranged from 8 to 10 dS m⁻¹.

The study area has a subtropical, semi-arid climate and receives an average annual rainfall of 645 mm. Total rainfall in 1989, 1990, 1991 and 1992 was 290, 522, 545 and 615 mm, respectively. The 15-year average annual rainfall and pan-evaporation (1978-1992) for the area is given in Figure 4.2. About 70-80% of the annual rainfall is confined to the monsoon season during June to September and satisfies most of the water requirements of the winter crops. The annual pan evaporation values are generally higher than the annual rainfall with the exception of the month of August. Maximum pan-evaporation occurs in May to June when the fields generally remain fallow. There is a large variation in temperature between the seasons. The climate is such that the year is divided into two crop growing seasons, Kharif (summer) and Rabi (winter).

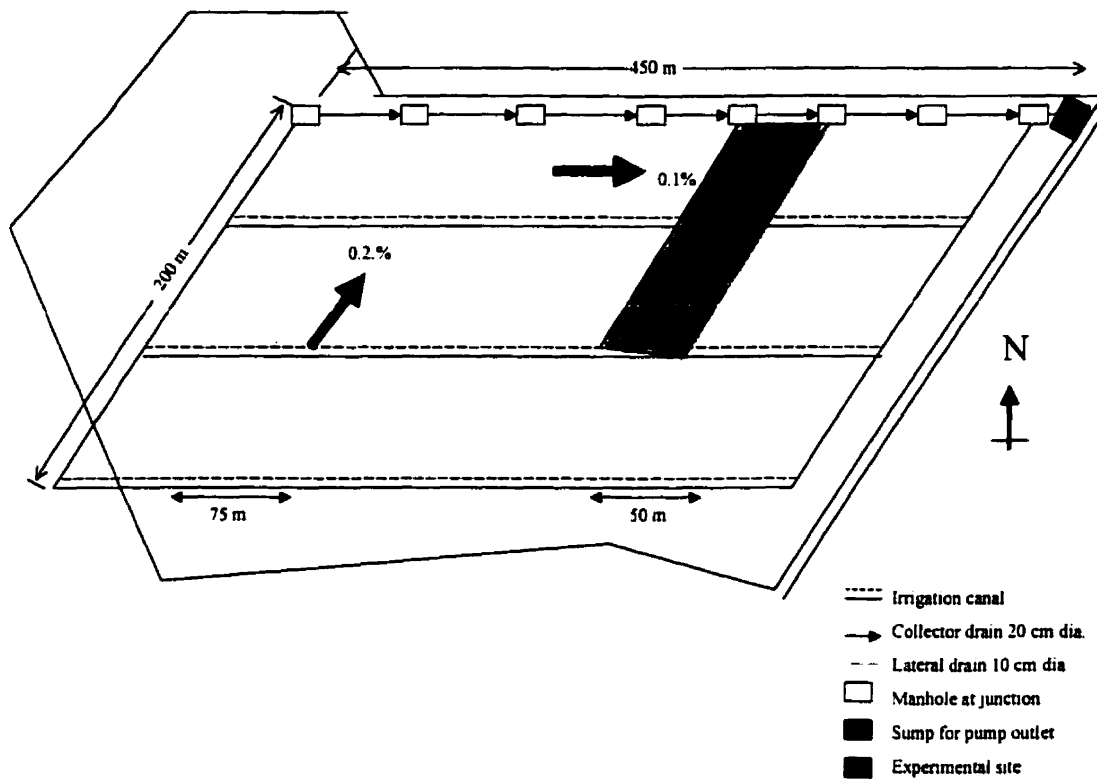


Figure 4.1 Experimental site in subsurface drainage command area at Sampla.

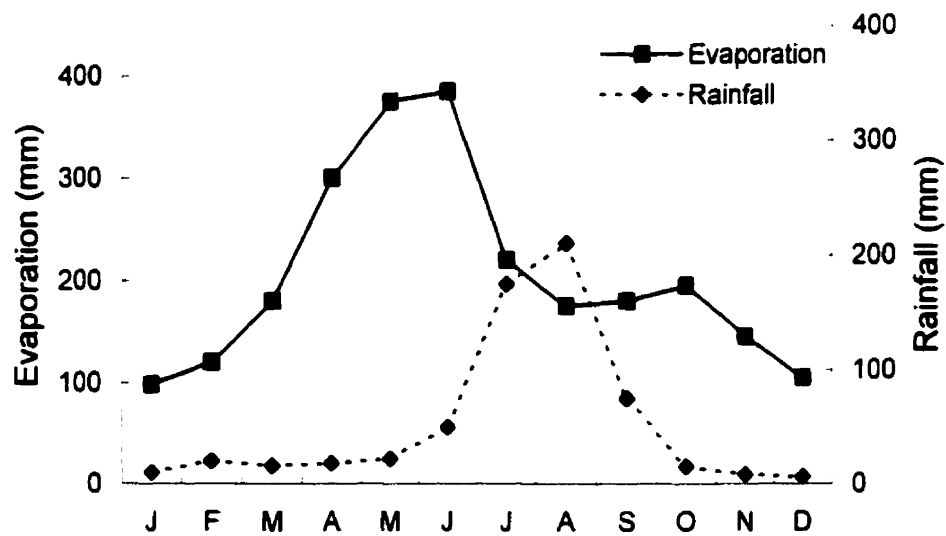


Figure 4.2 Average annual rainfall and pan evaporation of the area based on data from January 1978 to December 1992.

4.1.2 Model inputs

Soil data

Soil physical data are very important for soil-based numerical models. Details of the physical and chemical characteristics of the soil of the study area are given in Table 4.1. The soil is a coarse loam (hyperthermic Camborthid) with an average horizontal hydraulic conductivity of 1 m d^{-1} . In the 0-120 cm depth, the soil has a field capacity of 18-22% (w/w), a total porosity of 36 to 43 % and a bulk density of 1.48 to 1.55 Mg m^{-3} . The soil texture throughout the profile is classified: 0-30 cm, sandy loam; 30-60 cm, loam; 60-90 cm, sandy clay loam and 90-120 cm as a loam.

Soil samples were collected at each sowing and harvest time from all replicates with a 5-cm diameter auger at 15-cm depth intervals down to 90 cm and at 30-cm intervals down to 120 cm soil (for details see Sharma et al., 1991). Soil moisture was determined gravimetrically at sowing, before and after each irrigation and at harvest. Chemical properties and electrical conductivity of the saturation extract, EC_e , was measured using the methods of U.S. Salinity Laboratory Staff (1954).

The LEACHM-C model uses the Hutson and Cass (1987) soil hydraulic property functions to calculate the hydraulic conductivity-water content-matric pressure relationships ($K-\theta-h$). Values for these functions were obtained from a similar study on the same type of soil (Table 4.2)

Table 4.1 Initial soil physical and chemical properties of the site selected for the model testing.

Physical properties of soil						
Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH _s	ρ _b (Mg m ⁻³)	
0-15	68.10	16.50	15.40	7.80	1.48	
15-30	62.60	20.20	17.20	7.76	1.51	
30-45	64.00	15.80	20.00	7.86	1.52	
45-60	62.70	15.80	21.50	7.86	1.54	
60-75	64.50	12.10	23.40	8.00	1.55	
75-90	61.80	12.10	26.10	8.00	1.50	
90-120	66.90	10.50	22.60	8.15	1.50	
Chemical properties of soil						
Soil depth (cm)	EC _e (dS m ⁻¹)	SAR _e (mmol/l) ^{0.5}	Ca ²⁺ +Mg ²⁺ (mmol l ⁻¹)	Na ⁺ (mmol l ⁻¹)	Cl ⁻ (mmol l ⁻¹)	HCO ₃ ⁻ (mmol l ⁻¹)
0-15	1.30	2.20	11.45	6.60	16.50	4.01
15-30	1.40	2.40	11.75	6.10	13.66	3.25
30-45	1.60	2.80	13.94	9.15	19.28	2.40
45-60	1.90	3.40	13.94	9.15	19.30	2.41
60-75	2.10	4.50	13.21	15.90	24.68	2.00
75-90	2.20	5.80	13.21	15.90	24.70	2.00
90-120	2.50	6.20	13.50	22.26	32.30	2.10

Source: Agnihotri et al. (1992); Sharma et al. (1994).

pH_s, ρ_b denote pH of saturated paste and soil bulk density, respectively.

Table 4.2 Hydrologic parameters used to simulate field soil properties.

Name	Symbol*	Value
Campbell parameters	a	-1.98 kPa
	b	3.88
Hutson and Cass	θ_c	0.372
	h_c	-3.17 kPa
	K_s	22.5 mm/h
	θ_s	0.42

Source: Minhas and Gupta (1993b).

(*) Parameters defined in section 3.2.2.

Crop data

The experiment was conducted under wheat and pearl-millet/sorghum rotation for three years. A pre-sowing irrigation of about 70 mm was given uniformly in November with non-saline canal water ($EC_{iw}=0.4 \text{ dS m}^{-1}$) and (*Triticum aestivum* var. HD 2329) wheat was seeded in the second week of November, 1989 and harvested in the second week of April (Table 4.3). After the wheat crop, pearl-millet or sorghum was sown for the Rabi (winter) season with a pre-plant canal irrigation of 70 mm. No irrigations were applied during the growing period of the pearl-millet/sorghum and the crops were dependent on the monsoon rainfall. Recommended cultural practices were followed including the application of 120 kg N and 30 kg P per ha (Table 4.3). One third of nitrogen and the full dose of P were applied at sowing and the remaining nitrogen was applied in two equal splits at first and second irrigations (25 and 55 days after sowing). The investigation was carried out in field plots of (3.5m x 2m), separated by 1 m buffers.

Table 4.3 Salient features of the experiment during the year 1989-1990.

Operation	Wheat	Pearl-millet
Date of sowing	November 10	July 8
Variety	HD-2329	BK-560
Fertilizer dose (kg/ha):		
N	120	100
P	13	17.5
No. of post plant irrigations (50 mm each)	4	-
Rainfall during growing period (mm)	50	470
Date of harvest	April 10	October 9

Source: Sharma et al. (1994).

Irrigation data

Irrigation treatments consisted of seven combinations of non-saline canal water ($EC_{iw} = 0.4 \text{ dS m}^{-1}$) and drainage water ($EC_{Dw} = 12 \text{ dS m}^{-1}$). Each treatment was replicated four times in a randomised block design. Initially, soils were desalinised by leaching with rain water conserved in field. Irrigation schedules were based on the recommendations for non-saline

irrigated soils of the area and for each irrigation, 50 mm water was applied. Irrigations were applied at crown root initiation, late tillering, flowering and dough growth stages of wheat. The various modes of application of non-saline and saline waters were:

1. 4CW: canal water throughout the growing season.
2. CW/DW: alternate irrigations with canal and saline drainage water starting with canal water.
3. 2CW+2DW: first two irrigations with canal water followed by two irrigation with drainage water.
4. DW/CW: alternate irrigations with drainage water and canal water starting with drainage water.
5. 2DW+2CW: two irrigations with drainage water and followed by two irrigations with canal water.
6. 1CW+3DW: one irrigation with canal water followed by three irrigations with drainage water.
7. 4DW: drainage water throughout the growing season.

Table 4.4 Average composition of canal water and drainage water.

Water	EC (dS m ⁻¹)	SAR (mmol/l) ^{0.5}	Ca+Mg	Na	K	HCO ₃	Cl
Canal water	0.4	0.7	1.0	0.7	0.1	1.4	1.1
Drainage							
1989-90	12.5-15.5	14.5	63	115	0.3	1.6	212
1990-91	12.5-14.0	14.5	60	112	0.2	1.5	192
1991-92	10.5-12.5	12.3	51.5	88	0.3	1.8	162

Source: Sharma et al. (1994).

Weather data

Daily values of precipitation, class A pan evaporation and maximum and minimum daily temperatures are needed as input for LEACHM. These data were collected at Central Soil Salinity Research Institute, Karnal. Summary of weather data is given in Appendix G.

4.1.3 Assumptions in model runs

In LEACHM-C, three types of input data are needed for model operations. The first group consists of soil physical and chemical parameters. These data include: initial soil water content and soil characterisation of the relationship among water content, matric potential and hydraulic conductivity; initial profile of soil chemical data (Ca^{2+} , Mg^{2+} , Na^+ , Cl^- , SO_4^{2-} , HCO_3^-); and Gapon type selectivity coefficients describing the relationship between soil solution and exchangeable cations. The second group is comprised of frequency and duration of irrigation and rainfall. The parameters in the third group include the ionic composition of the irrigation water. Inclusion of an optional plant growth simulation module requires additional inputs describing dates from planting to maturity, and root and cover growth factors.

Parameters in the second and third group were taken directly from the above-described experiment. The parameters of the first group had to be taken from similar soil types in the same region of Haryana. However, due to a lack of a complete data set, the following input soil parameters were assumed:

1. The soil was assumed to be at field capacity at start of simulation. Day 1 of the simulation corresponded to the planting date. Note that there was a pre-irrigation of 70 mm.
2. To run the model, the following data on initial exchangeable cations (in mmol kg^{-1}) were taken to be the same as a similar nearby soil:
Ca=10.2, Mg=14.6, Na=1.3, K=0.3, CEC=11.2

4.1.4 Model performance

The model was evaluated by both graphical and statistical methods. In the graphical approach, the measured and simulated values of soil salinity (EC) were plotted against soil depth. The response of the model can, therefore, be quantified visually. The statistical approach, involved the use of the goodness of fit test proposed by Loague and Green (1991) to compare observed data with results predicted by the model. The mathematical expressions which describe these measures of analysis are: the root mean square error (RMSE), coefficient of determination (CD), modeling efficiency (EF), coefficient of residual mass (CRM). The RMSE values show how much the simulations under- or over-estimate the measurements. The CD statistics demonstrate the ratio between the scatter of simulated values to the average value of measurements. The EF value compares the simulated values to the average value of the measurements. A negative EF value indicates that the average value of the measurements gives a better estimate than the simulated values. The CRM is a measure of the tendency of the model to overestimate or underestimate the measurements. Positive values for CRM indicate that the model underestimates the measurements and negative values for CRM indicate a tendency to overestimate. For a perfect fit between observed and simulated data, values of RMSE, CRM, CD, and EF should equal to 0.0, 0.0, 1.0 and 1.0, respectively.

(a) Root mean square error (RMSE):

$$RMSE = \left[\frac{\sum_{i=1}^n (P_i - O_i)^2}{n} \right]^{0.5} * \frac{100}{\bar{O}} \quad (4.1)$$

(b) Coefficient of determination (CD):

$$CD = \frac{\sum_{i=1}^n (O_i - \bar{O})^2}{\sum_{i=1}^n (P_i - \bar{O})^2} \quad (4.2)$$

(c) Modeling efficiency (EF):

$$EF = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (4.3)$$

(d) Coefficient of residual mass (CRM):

$$CRM = \frac{\sum_{i=1}^n (O_i - P_i)}{n \bar{O}} \quad (4.4)$$

Where:

P_i = predicted values

O_i = observed values

$\bar{O}$ = mean of the observed data

n = number of samples

4.2 SIMULATION RESULTS AND DISCUSSION

To check the performance of the model for predicting salinity build up in terms of electrical conductivity (EC_e , $dS\ m^{-1}$), simulations were run using the following five irrigation treatments: 4CW, CW/DW, 2CW+2DW, 1CW+3DW and 4DW, described in the "materials and method". The simulations started at sowing (November, 1990) with soil salinity ranging from 1.2 to 2.5 $dS\ m^{-1}$. Soil salinity increased with the increasing the number of saline water irrigations. The EC_e values under saline irrigation treatments were higher in the upper layers of the soil profile. This may be ascribed to the combination of salt load of the irrigation water and the to upward movement of soluble salts due to capillary rise under high evaporation during later period (February-April) of growth of wheat crop. As a result, salts accumulated at a shallow depth during periods of water evaporation from the soil surface. In fact, soil salinity increased at all depths simulated to a depth of 80 cm, but the increase was generally greater in the 0-60 cm depth. This confirms the findings of Sharma et al. (1991).

Depth-wise salinity profiles, measured after wheat harvest (April, 1990) were compared by the model simulations. Results of observed and predicted values of soil solution EC_e for the five irrigation treatments are depicted in Figures 4.3 to 4.7. The results of the statistical analysis are summarized in Table 4.5 using the mathematical expressions (Equations 4.1 to 4.4) given in section 4.1.4.

The graph of predicted soil solution EC_e and the corresponding observed data for the treatment 4CW (4 irrigation with good quality water), is given in Figure 4.3. Observed soil solution EC_e and predicted values do not show any appreciable increase from the initial conditions (November, 1990).

This is due to the fact that the irrigation water used in this treatment was of good quality ($EC=0.4\ dS\ m^{-1}$). The discrepancies between observed and predicted values that occur at some points on the curves are slight. The

reason for these could be that the initial data on the cation exchange capacity were assumed.

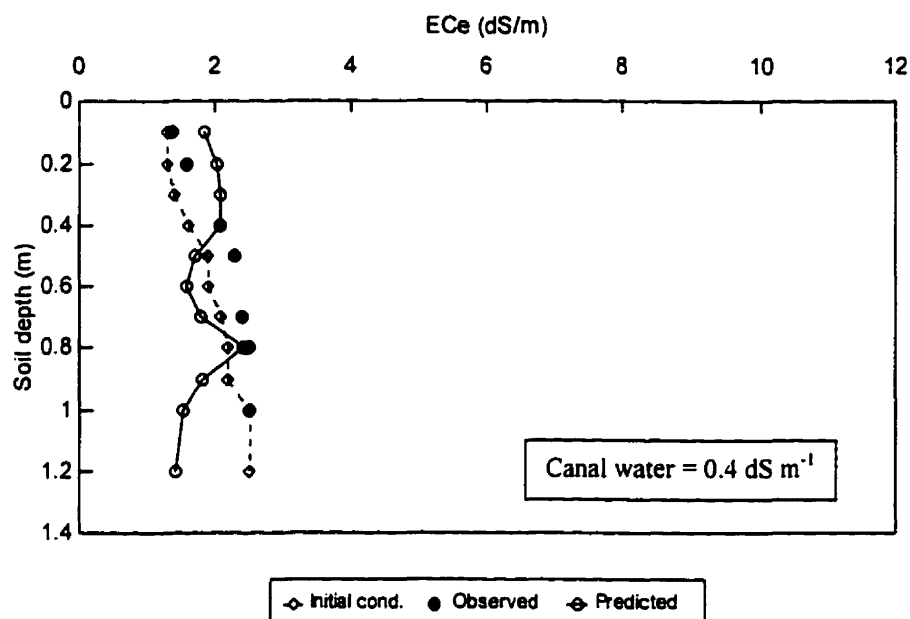


Figure 4.3 Observed vs. predicted soil salinity for treatment 4CW.
4CW: 4 irrigations with canal water.

The graphs of predicted soil solution EC_e versus observed data for saline irrigation treatments are given in Figures 4.4 to 4.7. The predicted EC_e values of the upper 60 cm layer were found to be always more than those observed. The soil solution increased from an average of 1.8 dS m^{-1} at start of simulation to over 8.2 dS m^{-1} . This is due to high salinity water application and the evaporation from the soil that is more pronounced in the upper layers. Equally important, the LEACHM-C model does not account for water flow in macropores. Consequently, nonuniform downward and upward movement of soil solution in pores of different sizes, both redistribution and evaporation processes, might also have contributed to the trend and magnitude of disagreement between observed and predicted EC values.

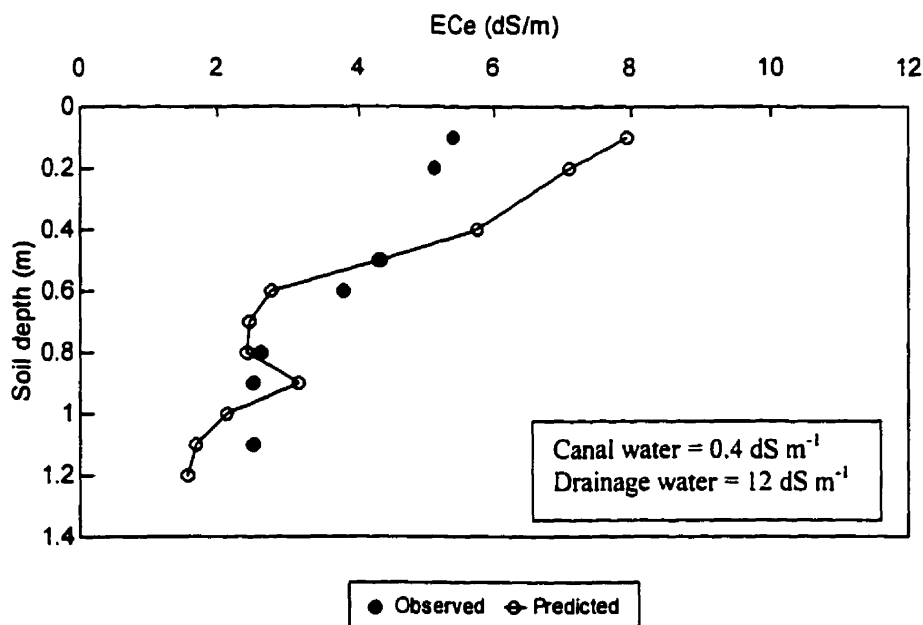


Figure 4.4 Observed vs. predicted soil salinity for treatment CW/DW.
CW/DW: 4 alternated irrigations of canal and drainage water.

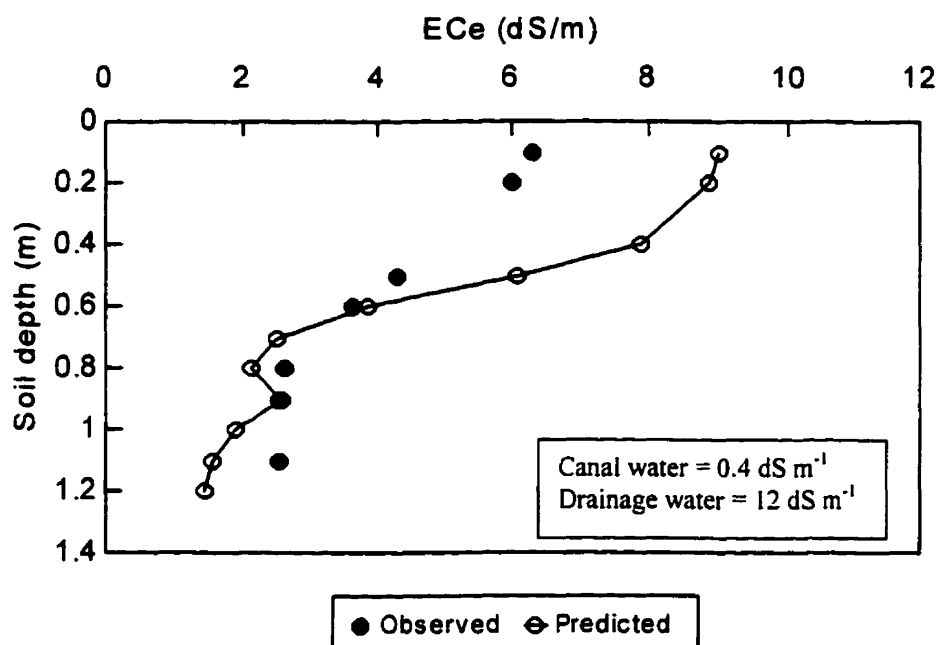


Figure 4.5 Observed vs. predicted soil salinity for treatment 2CW+2DW.
2CW+2DW: 2 irrigations with canal water followed by 2 drainage water.

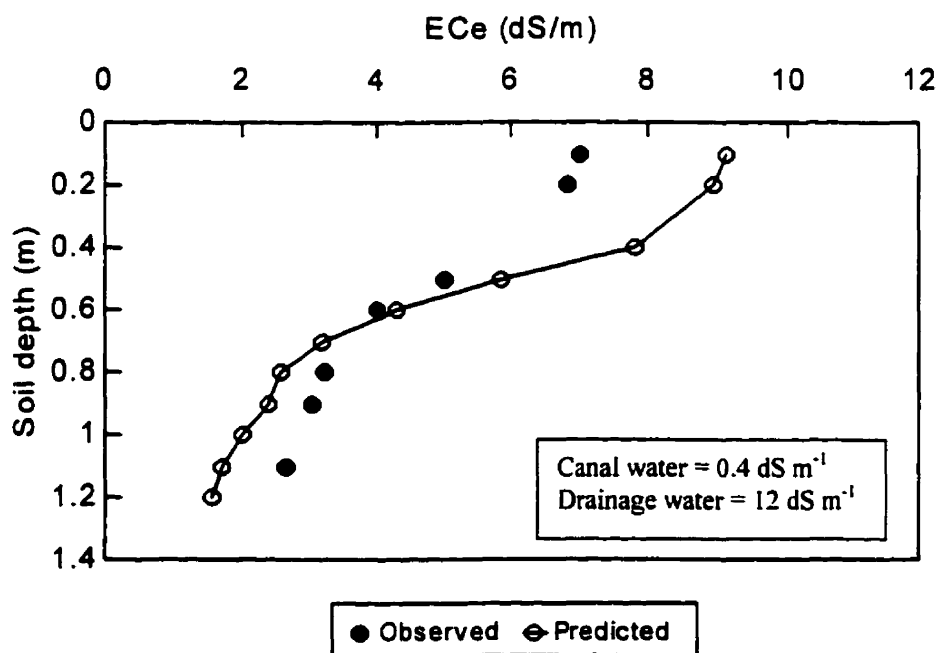


Figure 4.6 Observed vs. predicted soil salinity for treatment 1CW+3DW.
1CW+3DW: 1 irrigation of canal water followed by 3 drainage water.

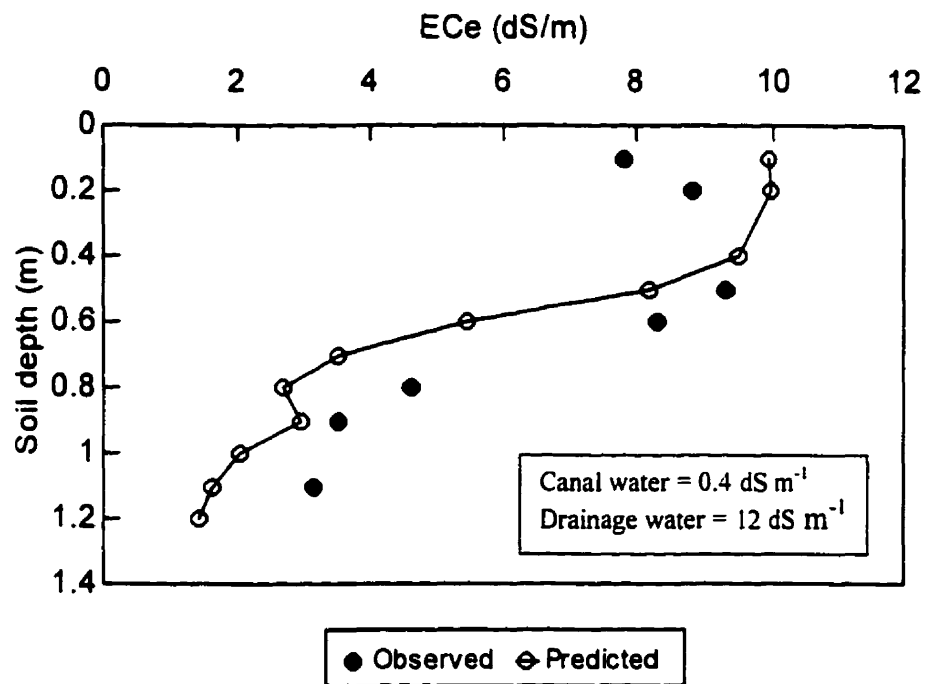


Figure 4.7 Observed vs. predicted soil salinity for treatment 4DW.
4DW: 4 irrigations with drainage water.

- (1) Consistent with the graphic interpretation, the RMSE indicates the average deviations of the predicted data from that observed. The RMSE results from the different treatments ranged 26 to 36%.
- (2) By reviewing the CRM value it can be observed that the model under-predicts for the fresh irrigation treatment (4CW) and over-predicts the saline irrigation treatments (CW/DW, 2CW+2DW, 1CW+3DW and 4DW).
- (3) Examination of the CD parameter indicates that the treatments 4CW and 4DW gives less variability between observed and predicted values.
- (4) The performance of the model is marginal as seen by the negative EF values. Figure 4.3 illustrates how the model fails to predict the shape of the observed soil salinity in the lower soil profile.

Table 4.5 Model performance statistics^{*} comparing predicted vs. observed data.

TREATMENTS	RMSE (%)	CRM	CD	EF
Optimum ^{**}	0.0	0.0	1.0	1.0
4 CW	26	0.09	0.61	-0.67
CW : DW	36	-0.12	0.25	-0.37
2 CW + 2 DW	36	-0.20	0.53	-0.11
1 CW + 3 DW	28	-0.09	0.33	-0.41
4 DW	27	-0.06	0.87	-0.68

(*) For explanation of symbols see section 4.1.4 (comparison methods).

(**) If all predicted and observed values were the same, then the statistics would yield: RMSE = 0.0; CRM=0.0; CD=1.0; EF=1.0.

Another important source of error between observed and predicted data will be a result of sampling positions not being concurrent with model node positions. Model node positions were 50 mm above and below the sampling depth depths.

In this study simulated and experimental results did not agree. The reason could be that some physical and chemical soil parameters at the site were not available and had to be assumed. For instance, uniform initial water content at field capacity was assumed at the beginning of the simulations. The hydrologic retentivity constants a and b were taken from a similar soil type in the region and do not represent the actual physical properties of the soil.

Having run the above scenarios, a sensitivity analysis is another method of evaluating model performance. The remainder of this section demonstrates model sensitivity to several soil parameters.

Sensitivity analysis

A sensitivity analysis was performed to evaluate the effect of change in initial moisture content and soil retentivity parameters on the simulation results obtained. Soil moisture content was increased or decreased by 10 and 20 % throughout the 120 cm depth of the soil profile simulated (Figure 4.8). Changes of the initial moisture content, assumed for the simulations to be 0.22, do not influence the salt movement in the soil profile. Hence, the greater difference observed in the top layer can be attributed to hydrologic retentivity constants a and b , and salt load of the irrigation water.

Results of sensitivity analysis using regression equations, reported in Appendix D, revealed that the best predictions were achieved when Equations 1 and 2 were combined. Retentivity at the top of the 30 cm soil layer was simulated by Equation 2 and in the rest of the soil profile by Equation 1. Comparison of the results of the combined Equations (1 and 2) with the initial simulations obtained from soil retentivity constants a and b

reported in Table 4.2 are shown in Figure 4.9. The simulation was done for the treatment CW/DW (four alternate irrigations with canal water and drainage water).

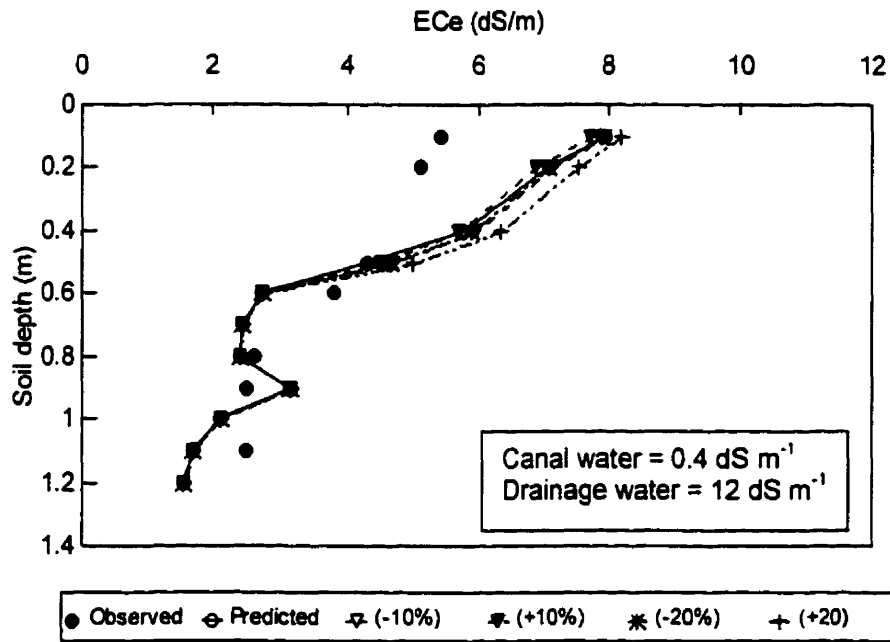


Figure 4.8 Sensitivity tests of the initial soil moisture content with $\pm 10\%$ & 20% . Observed data are from treatment CW/DW.

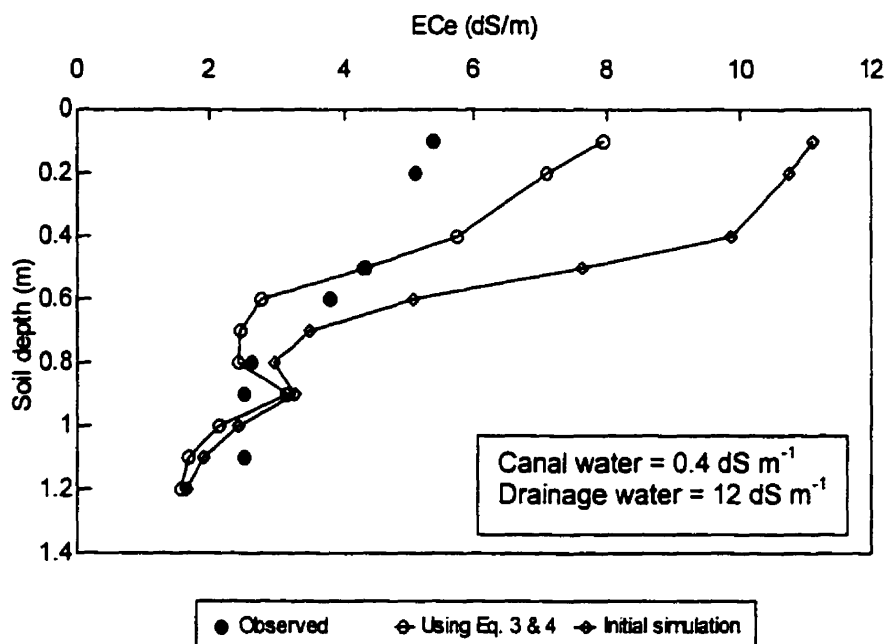


Figure 4.9 Sensitivity tests of the water retention parameters.

Observed data are from treatment CW/DW.

Regression Equation 2 was developed for South African sandy loam soils. The better predictions by regression Equation 2 for sandy loam soils used in this study are the results of the combination of a linear regression and an exponential model to describe the two part retentivity curve explained in section 3.2.2.

Despite some differences between observed and predicted EC_e values, the results shown in Figures 4.3 to 4.7 and Table 4.5 indicate that the LEACHM-C model could predict distribution of total salt in a soil profile with irrigations of poor-quality waters.

5. LEACHM-C AND MANAGEMENT SCENARIOS FOR SYRIA

5.1 BACKGROUND

Agriculture is a major component of the Syrian economy. Syria is situated in arid and semi-arid zones and its surface water resources are limited. To date, Syria like other arid and semi-arid lands in the Middle East, uses ~85 to 90% of its total water resources for agriculture (Wakil, 1993a). In order to augment the irrigated land base and to increase crop yields, many growers in Syria currently use waters of lesser quality from groundwater sources. Thus, during the last ten years, brackish groundwaters (with an electrical conductivity (EC) greater than 0.75 dS m^{-1}) are increasingly used for irrigation of winter crops.

Brackish aquifers in Syria are located predominately in two basins: the Khabur basin in the north east (heavy textured soils) and the Aleppo basin in the north central (medium to light texture soils). In addition, some minor isolated saline aquifers occur in other regions of Syria such as the Euphrates and Salamieh regions.

The Khabur aquifer is the largest aquifer in Syria and its productivity is estimated to be 2000 million $\text{m}^3 \text{ yr}^{-1}$ of which approximately one-third is considered saline (greater than 0.75 dS m^{-1}) (Wakil, 1993b). The annual productivity of the Aleppo basin aquifer is estimated to be 650 million $\text{m}^3 \text{ yr}^{-1}$ of which 20% is considered saline (EC of 0.75 to 13 dS m^{-1}). The typical crop rotation in the Khabur basin is: wheat (50% cropping intensity) in the winter and cotton (35%), corn (15%) and legumes (5%) in the summer. While, the typical crop rotation in the Aleppo basin is: wheat (50%) in the winter and vegetables (35%) and cotton (15%) in the summer. In both basins a traditional surface furrow-basin irrigation method is widely applied.

A field study was conducted in these semi-arid regions of Syria to define wheat (*Triticum aestivum* L.) salt tolerance with respect to irrigation water salinity and development of soil salt accumulation in the root zone

(Wakil and Bonnell, 1996; Haffar, 1997). The two regions experience similar climatic conditions (semi-arid Mediterranean climate) but have different soil textures, varying from sandy loam to clay. According to these authors, the threshold water salinity values obtained in their study were different from the "universal" irrigation water threshold value for wheat of $EC_{iw} = 4 \text{ dS m}^{-1}$, as reported in the literature (Maas and Hoffman, 1977; Ayers and Wescot, 1985). For the fine textured soils in the Khabur low plains the irrigation water threshold salinity value was found to be $EC_{iw} = 1.2 \text{ dS m}^{-1}$. On the other hand, in the case of the coarse textured soils of the Aleppo south plains the threshold value was found to be 3.5 dS m^{-1} . These researchers concluded in their studies that the "universal" threshold value of $EC_{iw} = 4 \text{ dS m}^{-1}$ (or $EC_e = 6 \text{ dS m}^{-1}$, soil salinity of saturated extract) was too high. The differences were attributed to the artificial conditions used during the experiments in establishing the universal values. These conditions included: artificially salinized field plots seeded under non-saline conditions and frequent irrigations (to minimize the matric potential build-up between irrigations). Thus, the universal standards do not represent the levels of soil salinity in the root zone and crop response under prevailing field conditions including climate, soil condition and irrigation water management techniques. Indeed, their findings demonstrate the requisite of establishing specific criteria for saline water use under in situ field conditions.

Regional rainfall amounts to about 250 mm yr^{-1} which is much lower than the potential evapotranspiration (2500 mm yr^{-1}). Consequently, very little natural leaching of the soil can be expected. This can result in a progressive build-up of salts in the root zone. Moreover, the irrigated areas using groundwater are not provided with surface or subsurface drainage systems. This in turn can lead to soil degradation and crop yield reduction, and to the destruction of the local agri-ecosystem. Signs of soil deterioration have been noted in several locations in the two basins. In some areas, land has been already abandoned.

In this chapter an effort is made to demonstrate as an example, how the model LEACHM-C can be used as a management tool by providing an estimate of how much water and length of time may be required in order to maintain, or if need be, reclaim the soil profile to desired levels of salinity and sodicity.

5.2 DEVELOPMENT OF SCENARIOS

A hypothetical salt-affected case was constructed with climatic and other field data representative of the semi-arid regions of Syria. LEACHM-C model was applied to assess the consequences of three water management scenarios to the reclamation of an artificially constructed soil profile. Farmers are currently using fallow as a means of attempting to reclaim slightly salinized fields. Before the initiation of water application for reclamation, this soil is assumed to have the characteristics presented in Table 5.1 after a number of irrigations with saline water. In these calculations, it was also assumed that the mean soil salinity values (EC_e) should not exceed 4 dS m^{-1} at the end of the simulations. This assumption was made on the basis of experience at the study site. Wakil (1994) found that for wheat the threshold level was about 4 dS m^{-1} . The simulations started on November 1 at the beginning of the winter season and lasted until February 15, which corresponds to the rainy season. The following scenarios were simulated for three fallow years:

Scenario 1: (low salinity/high quantity)

Water application: Seven 60-mm flood irrigation applications.

Frequency of application: Once every two weeks for 14 weeks

Water quality (mmol l^{-1}): $\text{Ca}=0.30$, $\text{Mg}=1.00$, $\text{Na}=0.50$, $\text{K}=0.20$, $\text{Cl}=0.30$,
 $\text{SO}_4=4.40$, $\text{HCO}_3=2.60$; $\text{EC}=0.4 \text{ dS m}^{-1}$.

Scenario 2: (low salinity/low quantity)

Water application: Seven 30-mm flood irrigation applications.

Frequency of application: Once every two weeks for 14 weeks

Water quality (mmol l^{-1}): $\text{Ca}=0.30$, $\text{Mg}=1.00$, $\text{Na}=0.50$, $\text{K}=0.20$, $\text{Cl}=0.30$,
 $\text{SO}_4=4.40$, $\text{HCO}_3=2.60$; $\text{EC}=0.4 \text{ dS m}^{-1}$.

Scenario 3: (high salinity/low quantity)

Water application: Seven 30-mm flood irrigation applications.

Frequency of application: Once every two weeks for 14 weeks

Water quality (mmol l^{-1}): $\text{Ca}=17.5$, $\text{Mg}=9.00$, $\text{Na}=4.20$, $\text{K}=0.30$, $\text{Cl}=8.00$,
 $\text{SO}_4=23.0$, $\text{HCO}_3=3.64$; $\text{EC}=4 \text{ dS m}^{-1}$.

Note:

It is assumed that the mass load remains constant for the remaining months of each fallow year simulated (no water table, no rain and no irrigation), therefore, no new salts.

Table 5.1 Initial soil physical and chemical properties of the area selected for the model demonstration.

Physical properties*							
Soil depth (cm)	Clay (%)	Silt (%)	Sand (%)	pH _s	θ _i (m ³ /m ³)	ρ _b (Mg/m ³)	
0-20	30.00	44.20	25.80	8.00	0.11	1.30	
20-40	39.80	40.50	19.70	8.00	0.10	1.30	
40-60	45.30	41.20	13.50	8.00	0.14	1.30	
60-80	45.10	39.40	15.50	8.00	0.20	1.30	
80-100	41.40	40.60	18.00	8.00	0.18	1.30	
100-120	41.40	40.60	18.00	8.00	0.18	1.30	
Solution ion concentration (mmol l ⁻¹)**							
Soil depth (cm)	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃
0-20	19.20	12.50	10.00	5.50	28.00	19.90	0.48
20-40	18.45	7.50	10.00	5.50	15.00	17.00	0.49
40-60	17.50	7.00	5.00	1.00	12.50	17.20	0.57
60-80	16.90	6.50	4.50	1.00	12.50	17.20	0.57
80-100	17.50	7.00	4.500	1.00	10.50	17.1	0.67
100-120	16.90	6.50	4.00	1.00	10.50	17.1	0.67

(*)Source: Haffar (1997); (**) assumed values.

pH_s, θ_i , ρ_b denote pH of saturated paste, initial water content and soil bulk density, respectively.

Area selected for the model demonstration

Aleppo basin was selected for the purpose of demonstrating the use of the model for developing reclamation strategies. Soils in the Aleppo irrigated plains are predominantly clay loam and soil structure is generally subangular blocky in the surface horizon and prismatic below. The soils contain about 25% calcium carbonate, 40% clay, 41% silt and 19% sand and have a pH_e of 8 throughout the profile. Bulk density of the soil ranges between 0.9 to 1.3 $Mg\ m^{-3}$. The volumetric water content at saturation (θ_s) and water holding capacity (h_c) was found to be 0.45 m^3/m^3 and 0.24 cm/cm, respectively. The water retention characteristic of the soil of the area is depicted in Figure 5.1.

Weather data

Weather data from a meteorological station located at Tel Hadya Research Station were available for this simulation. Precipitation, maximum and minimum temperatures and pan evaporation data were measured on a daily basis. Summary of the weather data for the site is reported in Appendix H.

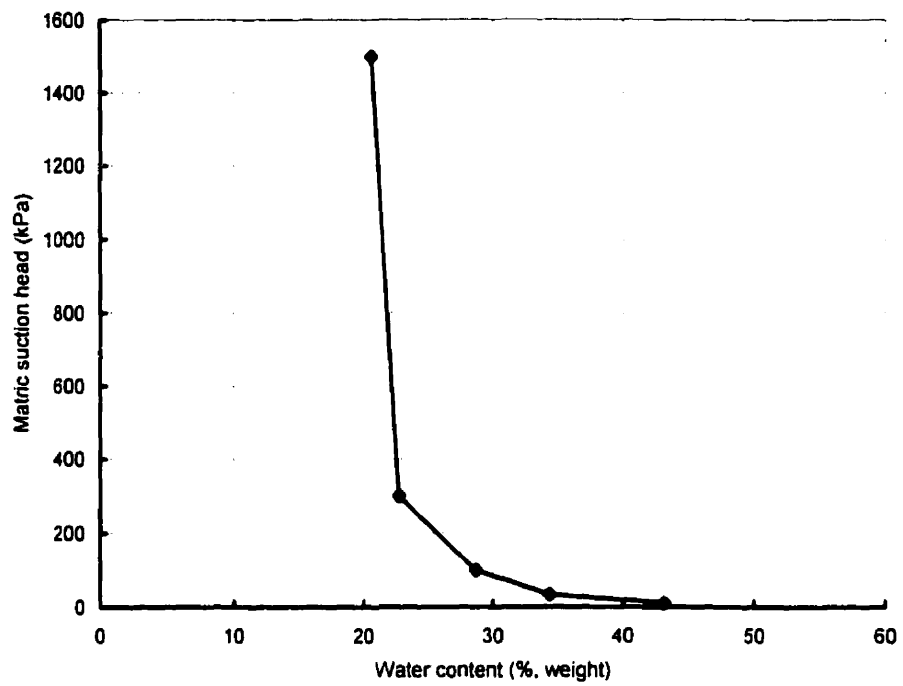


Figure 5.1 Soil water characteristic of the Aleppo basin (Haffar, 1997).

5.3 SIMULATION RESULTS AND DISCUSSION

The model was run with initial conditions as reported in Table 5.1 and input data as in Appendix F. Two qualities of water were used, high quality water (scenario 1 and 2, see section 5.2) and the low quality water (scenario 3). Two water management options were also used, high quantity (scenario 1) and low quantity (scenario 2 and 3).

Figures 5.2 to 5.4 show the salinity profile for the three scenarios during 100 days of simulations for each year. Three depths 300, 600 and 900 mm in the soil profile were selected to depict the salt movement during the course of the reclamation process. Table 5.2 shows the complete descriptions of the soil profile characteristics at selected times during the three year period considered for the reclamation process to be carried out.

It is apparent that the best reclamation efficiency was attained using high quality and quantity water (scenarios 1) scheme. The 420 mm of water applied, in combination with the rainfall was sufficiently large to achieve net percolation. This results in leaching of salts (Figure 5.2). It is recognized that with time, this leaching fraction may in areas lead to waterlogging. The depicted EC values show that soil salinity increased with respect to depth. Conversely, this pattern was reversed in scenario 3 which uses less water and water of higher salinity.

In scenario 2, the total amount of applied water for leaching was reduced from 420 to 210 mm. By the end of the third fallow year, a substantial quantity of salt had been removed from the soil profile (Figure 5.3), however, since the quantity of water applied was less, scenario 2 never achieved the level of reclamation as did scenario 1.

In scenario 3, the net effect was a substantial increase in EC of the soil profile, primarily because of the high chloride content of the irrigation water and relatively small quantity of water applied (thus no deep leaching occurred). Since the irrigation water itself contained salts, the upper 30 cm of the soil profile gave higher EC values (Figure 5.4). This was due not only

to water quality, but also to evaporation at the soil surface. The evaporation acted to concentrate salts remaining there at the end of each year, producing a higher calculated EC_e . Evaporation and the concentration of salts were therefore the primary process operating in the soil. In scenario 3, in order to decrease the rate of salinization and to attain a favourable salt balance, either the irrigation amounts should be increased or saline water should be excluded from the leaching process. However, any attempt to utilize saline water for irrigation, calls for leaching of accumulated salts either by conserving rainfall (water harvesting) or by applying good quality water imported from an alternative water source.

It is thought that, the LEACHM-C model, which is based on transient soil-water conditions and non-steady state soil chemistry, has proven to be a very useful tool in classifying the waters, assessing their suitability and evaluating management strategies for reclaiming salt affected soils. Hence, this model could be a useful tool to predict leaching requirements as well as crop root zone salinity in the semi-arid areas of Syria.

Scenario 1: 60 cm of Fresh Water Application

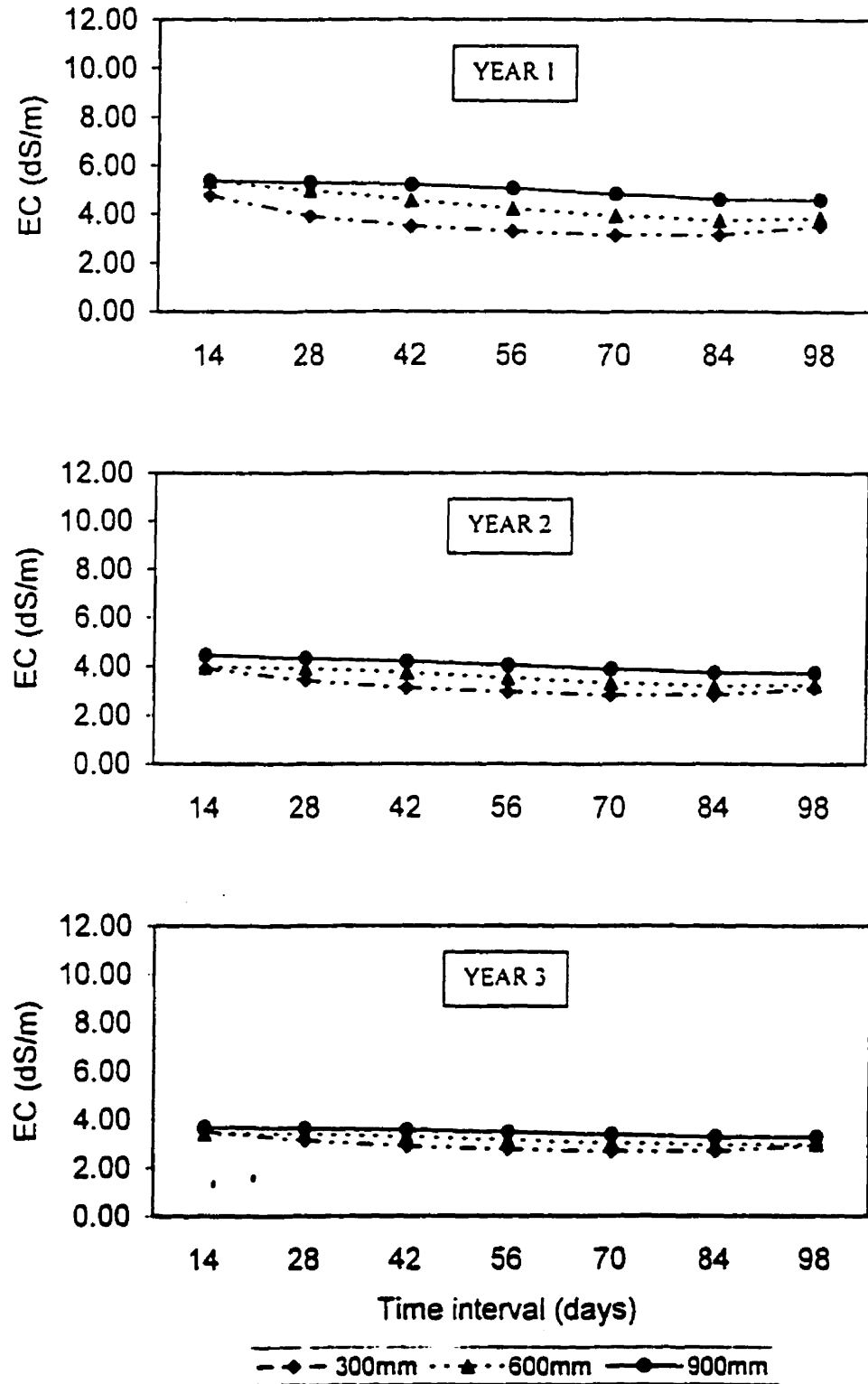


Figure 5.2 Predicted soil salinity at three depths in the soil profile.

Scenario 2: 30 cm of Fresh Water Application

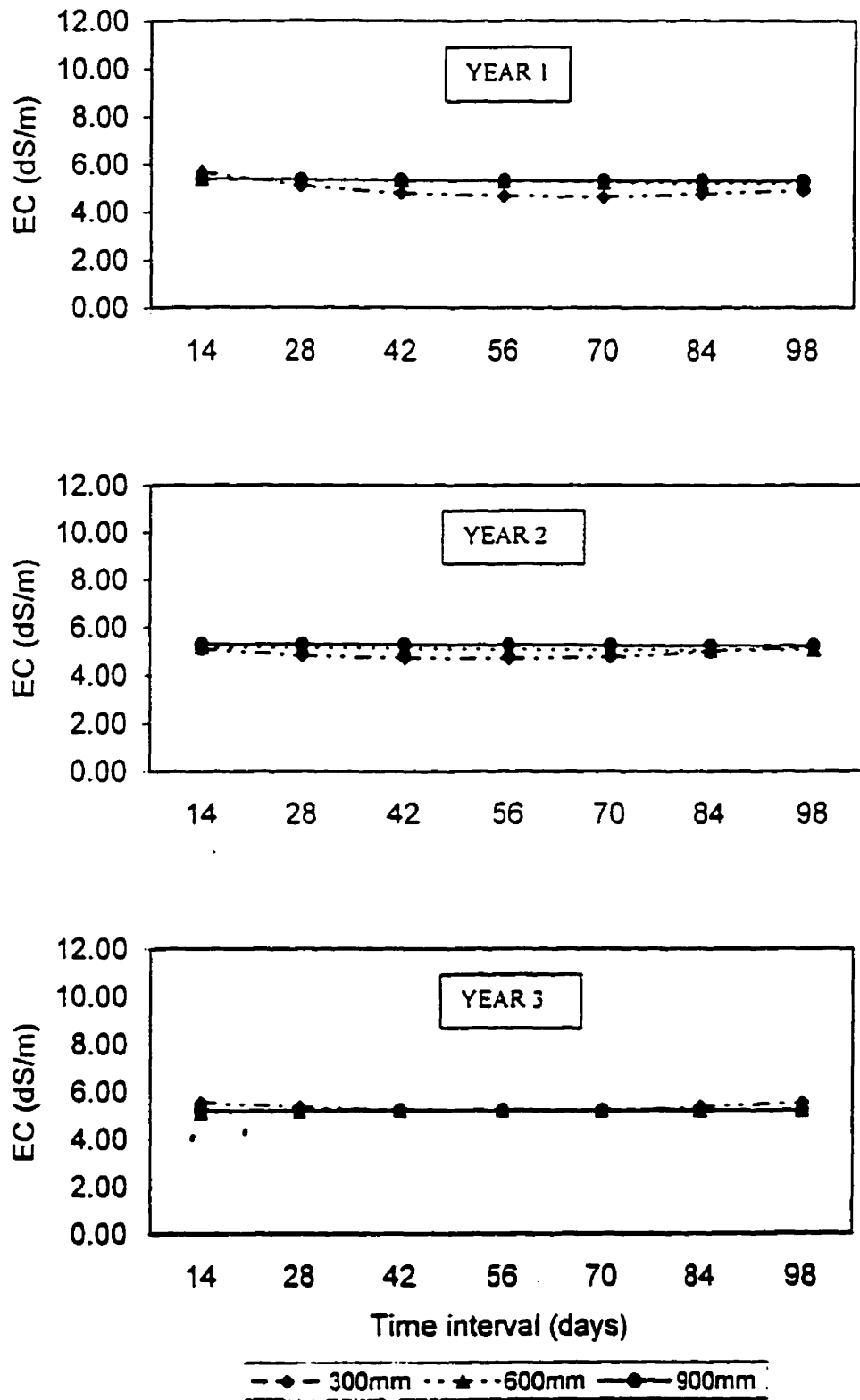


Figure 5.3 Predicted soil salinity at three depths in the soil.

Scenario 3: 30 cm of Saline Water Application

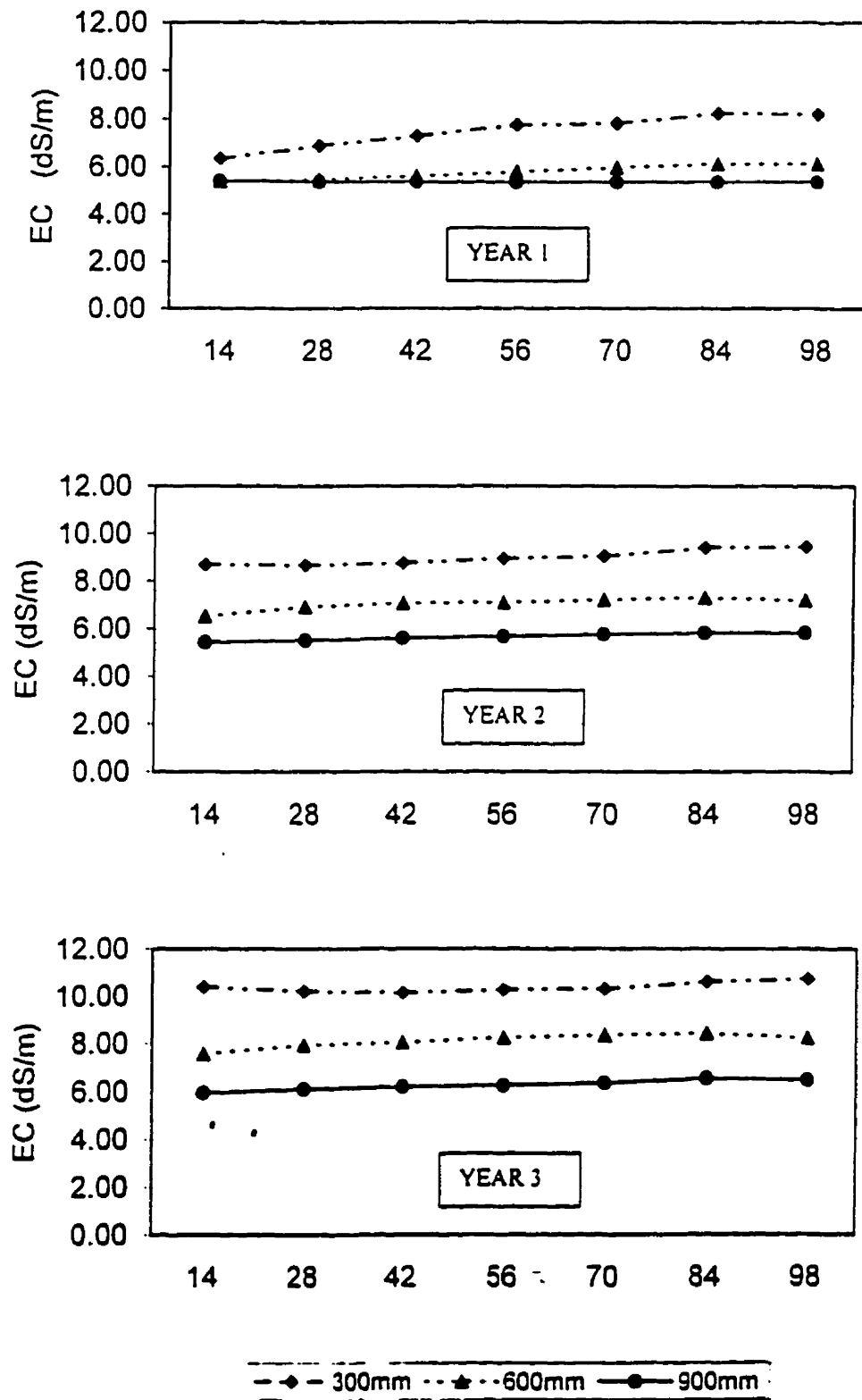


Figure 5.4 Predicted soil salinity at three depths in the soil.

Table 5.2 Predicted EC and SAR during the reclamation process.

Depth (cm)	Time = 0.00					
	EC (dS m ⁻¹)			SAR (mmol/l) ^{0.5}		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
0-20	7.52	6.72	7.52	1.59	1.80	1.90
20-40	5.85	5.02	5.85	1.40	1.70	2.40
40-60	5.42	5.14	5.42	1.05	1.35	1.05
60-80	5.30	5.29	5.30	1.05	1.05	1.05
80-100	5.34	5.30	5.32	1.00	1.00	1.00
100-120	5.20	5.23	5.20	0.90	1.09	0.90
Time = 12 months (1 st fallow year)						
0-20	6.00	6.01	11.88	1.45	1.65	2.30
20-40	3.75	5.05	7.76	1.30	1.70	1.75
40-60	3.85	5.14	6.38	1.30	1.35	1.40
60-80	4.27	5.29	5.61	1.25	1.05	1.05
80-100	4.71	5.30	5.34	1.10	1.00	1.00
100-120	5.00	5.23	5.23	1.00	0.90	0.90

(*) Beginning of simulation (01/11/87).

Table 5.2 (continued)

Depth (cm)	Time = 24 months (2 nd fallow year)					
	EC (dS m ⁻¹)			SAR (mmol/l) ^{0.5}		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
0-20	5.57	7.44	10.30	1.35	1.85	2.10
20-40	3.84	5.18	7.85	1.30	1.45	1.75
40-60	3.85	5.05	6.38	1.30	1.35	1.40
60-80	4.28	5.16	5.61	1.25	1.15	1.05
80-100	4.71	5.24	5.34	1.10	1.00	1.00
100-120	5.00	5.24	5.23	1.00	0.90	0.90
Time = 36 months (3 rd fallow year)						
0-20	3.00	6.79	15.00	1.10	1.70	2.65
20-40	3.28	5.24	8.96	1.00	1.45	1.74
40-60	3.28	5.05	7.42	1.15	1.35	1.50
60-80	3.55	5.16	6.40	1.20	1.15	1.25
80-100	3.85	5.24	5.70	1.20	1.00	1.05
100-120	4.00	5.25	5.35	1.10	0.90	0.90

6. SUMMARY AND CONCLUSIONS

This study demonstrates the utility of the LEACHM-C model for predicting soil salinization-desalinization and management of saline water irrigated soils. In part one of this study, the performance of the LEACHM-C model was investigated for predicting salinity build up in the soil profile (in terms of soil solution EC_e) as affected by irrigation water quality. The LEACHM-C model was used to compare the simulated EC values with one-year data (1989-1990) obtained from a field study in India. In the experiment, canal water ($EC=0.4 \text{ dS m}^{-1}$) and drainage water ($EC=12 \text{ dS m}^{-1}$) was used to irrigate wheat (*Triticum aestivum* L.). First, evaluation of predicted versus measured results was graphically determined. Second, agreement between predicted and observed salinity values were quantified with four objective functions; root mean square error (RMSE), coefficient of residual mass (CRM), modeling efficiency and the coefficient of determination (CD). Reasonable agreement was not found between model predictions and experimentally measured data for the condition tested. The results show that the initial soil condition assumed was critical for the model performance. Agreement between observed and predicted results were improved when water retention constants a and b were adjusted using regression equations for estimating retentivity proposed by Hutson and Cass (1987).

In the second part of this study, simulations were performed to study the capability of the LEACHM-C model for developing management scenarios for a semi-arid region in Syria. Three management scenarios and three years of fallow period were considered to attain acceptable soil salinity in the soil profile ($EC_e=4 \text{ dS m}^{-1}$). In scenario 1, 60 mm of water with high quality water ($EC=1.2 \text{ dS m}^{-1}$) was applied on the soil by flood irrigation for 14 day intervals over a total period of 100 days. In scenario 2, 30 mm of water was applied using the same quality of scenario1. In scenario 3, 30

mm of water was applied using low quality water (4 dS m^{-1}). Scenario 1, was found to be the optimum strategy for reclaiming from the initial soil salinity conditions.

The movement of salts through the root zone is a highly dynamic process, which favours the use of transient soil-water-chemistry models. On the basis of this study, it is thought that the LEACHM-C model could be a useful tool to predict crop root zone salinity on land irrigated with saline water as well as for planning reclamation activities. Definitely, the LEACHM-C model has tremendous capability for interpreting soil solute dynamics and provides useful insights into root zone hydrology. Moreover, information provided by the model on the quality and quantity of drainage water leaving the root zone can prove useful in designing drainage systems necessary for controlling root zone salinity and minimizing disposal of salts to other environments. These would, evidently, help reduce the number of experiments required to ascertain the hazardous effects of poor-quality water on soil properties in semi-arid areas.

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APPENDIX A

EXPLANATION OF VARIABLES USED IN THE INPUT FILE

MAIN INPUT DATA VALUES

Date format	User option for date format: 1 for US (mm/dd/yy) and 2 for UK (dd/mm/yy).
Starting date	Starting date of simulation in the format specified by data format.
Ending date	Date when the simulation is supposed to end.
Time interval	User specified minimum number of time intervals per day. The maximum value is 0.1 day.
Water flux/ time step	Maximum permissible water flux during a time step (usually about $0.01 \Delta z$, mm d ⁻¹).
No. of years	Number of repetitions of rainfall, crop and chemical application data. For most purpose set this to one.
Profile depth	Depth of the profile in (mm) to be performed the simulation, preferably a multiple of the segment thickness.
Segment thickness	Depth of the profile should be divided of equal thickness (Δz mm) throughout the profile.
Lower boundary	1: fixed-depth water table; 2: free-drainage profile; 3: zero flux; 4: lysimeter tank; 5: fluctuating water table.

**Water table
depth**

If lower boundary condition is 1 or 5; it is required
initial water table depth (mm).

**No. output
files**

User selected options of output files: 1: OUT only;
2: OUT + SUM; 3: OUT + SUM + BTC.

CROP INPUT DATA VALUES

Plants present	1 yes, 0 no: A value of "0" results in all plant related routines to be ignored; all other data pertaining to plants, including growth and transpiration, is overridden.
Roots	1 Constant, 2 growing: Specifying "1" selects a constant root distribution, defined in the root fraction column in a subsequent table. Indicating "2" the GROWTH subroutine simulates root growth using empirical or regression equation.
Minimum root water potential	Minimum value of the crown potential which limits transpiration.
Wilting point	Matric potential which no water is taken up by plants.
Root flow resistance	Accounts for resistance to water flow through the xylem vessels.
Planting data	Respective date of planting of crop. Must provide by the user and must be in the format (U.S. or U.K.) as selected in the main.
Emergence Date	Respective date of emergence of plant.
Maturity date	Respective date of crop maturity.

Harvesting Date	Respective date of harvesting of plant.
Relative root depth	Coefficient usually taken to be 1.0. To compress or expand the root distribution.
Crop cover fraction	Fraction of the ground surface covered by leaves which increases from zero on the day of seedling emergence and reaches a maximum at plant maturity.
Pan factor	Dimensionless pan coefficient. Will be read only when potential evapotranspiration is to be made estimated using pan evapotranspiration data for the location.

IRRIGATION INPUT DATA VALUES

Starting time	Time of start of irrigation event in terms of date and time.
Date or day no.	Date of irrigation event. Must be in the same format (U.S. or U.K.) as specified in the main.
Time of day	Time of start of water application to be given to the nearest of the multiple of tenth of a day. Zero day starts at midnight.
Amount	Amount of water application.
Rate of application	Rate of water application in mm/day. For ponded case the rate must be specified as 999.9.

APPENDIX B

EXPLANATION OF WEATHER INPUT FILE

WEATHER INPUT FILE

Weather input file contains daily weather data. This input file consists of daily minimum temperature, daily maximum temperature, daily precipitation, daily potential evapotranspiration (usually pan evaporation), and snow depth. The assumption is that the first record in the data file will correspond to day 1 of LEACHM simulation, so it may be necessary to select the records required by a specific simulation. For instance, if you are performing a LEACHM simulation starting on 1st February, then this will be day 1, and the first 31 records will have to be deleted from weather data file. The data file can contain more records that required by the simulation.

A Weather Utility Program will reads this daily weather data and converts it to the units and format required by LEACHM. This includes estimating potential ET, summing daily ET values to weekly values, calculating weekly mean temperatures and amplitudes and writing all of these data in the format required by LEACHM. The program will prompt for the names of two output files one for evapotranspiration and one for precipitation. These two output files can be copied directly into the LEACHM-C input data file.

Acceptable input units in the weather input file are the following:

Temperature	Degrees Centigrade (°C) or Fahrenheit (°F).
Precipitation	mm, cm, inches, hundredths of an inch.
Snow depth	mm, cm, inches.
Potential Evaporation	mm, cm, inches, hundredths of an inch.

APPENDIX C
EXPLANATION OF ".SUM" OUTPUT FILE

“.SUM” OUTPUT FILE VARIABLES

The summary file contains one record per print time. For the purposes of the summary, the soil profile is divided into three, sections, bounded by user specified depths or by default, nodes closet to the thirds of the profile. The variables in the summary file are the following:

TIME	Time elapsed in days.
CRAIN	Cumulative rain (mm).
TRANAC	Cumulative actual transpiration (mm).
CEVAP	Cumulative actual evaporation (mm).
EC_n	Electrical conductivity ($\mu\text{S m}^{-1}$) at depth n.
TH_n	Water content (mm) in section n.
H_n	Water potential (kPa) at depth n.
SAR_n	Sodium adsorption ratio at depth n.
CFW_n	Cumulative water flux across depth n (mm).
CA_n	Calcium in solution at depth n (mmol l^{-1}).
MG_n	Magnesium in solution at depth n (mmol l^{-1}).

NA_n	Sodium in solution at depth n (mmol l ⁻¹).
K_n	Potassium in solution at depth n (mmol l ⁻¹).
Cl_n	Chloride in solution at depth n (mmol l ⁻¹).
SO_{4n}	Sulfate in solution at depth n (mmol l ⁻¹).
HCO_{3n}	Bicarbonate in solution at depth n (mmol l ⁻¹).
CO_{3n}	Carbonate in solution at depth n (mmol l ⁻¹).

APPENDIX D

ESTIMATION OF WATER RETENTION PARAMETERS

REGRESSION EQUATIONS FOR RETENTIVITY

LEACHM uses one of five sets of regression equations (Huston and Cas, 1978) relating water retention to easily measured soil properties such as particle-size distribution bulk density and organic matter content. The regression equations is of the form:

$$\theta = B_0 + B_1 \text{ Clay} + B_2 \text{ Silt} + B_3 \rho_b$$

Where B_0 , B_1 , B_2 , B_3 are dimensionless regression coefficients, Clay is % clay content, Silt is % silt content and ρ_b is bulk density (g/cm^3). The five equations used in LEACHM for estimating water retention properties of soils are following:

1. Huston's Regression for South African Soils (clay as variable)

$$\theta_1 = 0.394 + 0.00211 (\text{Clay} + \text{Silt}) - 0.096\rho_b$$

$$\theta_2 = (-3.23 + 0.437\text{Clay}^{0.5} - 2.44 \times 10^{-3}\text{Clay}^{1.5})$$

2. Huston's Regression for South African Soils (silt 2-20 μm)

$$\theta_1 = 394 + 0.00211 (\text{Clay} + \text{Silt}) - 0.096\rho_b$$

$$\theta_2 = \text{Exp}[-3.43 + 0.419(\text{Clay} + \text{Silt})^{0.5} - 1.83 \times 10^{-3}(\text{Clay} + \text{Silt})^{1.5}]$$

3. British Soil Survey Regression (topsoil, silt size 2-60 μm)

$$\theta = 0.4981 + 0.0027\text{Clay} + 0.0011\text{Silt} + 0.003\text{C} - 0.1778\rho_b$$

4. British Soil Survey Regression (subsoil, silt size 2-60 μm)

$$\theta = 0.4216 + 0.0034\text{Clay} + 0.0018\text{Silt} + 0.0022\text{C} - 0.1697\rho_b$$

5. Rawls and Brakensiek (USA)

$$\theta = 0.4180 - 0.0021\text{Sand} + 0.0035\text{Clay} + 0.0232\text{C}/0.67 - 0.0859\rho_b$$

Where Sand is % sand content, C is % carbon content. θ_2 values are calculated for the exponential curve of the two-part retentivity function.

APPENDIX E
INPUT DATA FILE FOR MODEL TESTING
(SAMPLA - INDIA)

SAMPLA DATA SIMULATION

Data must be present for each item, even if it not used

LEACHM-C does not accept blanks

Data type US:1 UK:2	2
Starting date	011189
Ending date (date or day no.)	100990
Largest time interval (day)	0.10
Max. theta change/time step	0.010
Read theta (1) or pot'l (2)	1
Calc. Sel. Coeff.	2
K-T-h from PSD?	0
No. of chemical applications	1
Years or cycles	1
No. of crops	2
No. of time steps/chemeq	40
PROFILE DETAILS	
Profile depth (mm)	1200.0
Bottom boundary condition	2
Segment thickness (mm)	100.0
Depth of water table (mm)	1400.0
SOIL DATA	
Soil bulk density (Mg/m3)	1.52
Air-entry-value (kPa)	-1.98
Exponent in Campbell's eq.	3.88
Sat'd K value (mm/day)	146
CROP DATA	

Wilting point (soil) kPa	-1500.000	
Max. actual tran/pot'l tran)	1.000	
Min. root water pot'l (kPa)	-3000.000	
Max. root water pot'l (kPa)	0.000	
Root flow resistance const. (0) var.(1)	1	
DIFFUSION/DISPERSION COEFFECIENTS		
Molecular diffusion (Do)	150.000	
Dispersivity (mm)	120.000	
Coefficient (mm ² /d)	0.010	
(Bresler's eq.)	10.000	
OUTPUT		
Segemnent print frequency	1	
Print option: 1, 2 or 3	2	
Summary print frequency (d)	1	
1: time intervals/print	1	
Number of output files	2	
2: days/print	1	
3: No. of prints (even)	2	
DAY OF PRINT OUT (if print options = 3)		
Date (or day No.)	Time of day (to nearest tenth)	
010490	0.5	
101090	0.5	
THREE DEPTHS WHICH DAILY SUMMARY IS TO BE RECORDED (mm)		
300	600	900

APPENDIX F

**INPUT DATA FILE FOR MODEL DEMONSTRATION
(TEL HADYA - SYRIA)**

TEL HADYA DATA SIMULATION

Data must be present for each item, even if it not used

LEACHM-C does not accept blanks

Data type US:1 UK:2	2
Starting date	011187
Ending date (date or day no.)	150290
Largest time interval (day)	0.10
Max. theta change/time step	0.01
Read theta (1) or pot'l (2)	1
Calc. Sel. Coeff.	2
K-T-h from PSD?	0
No. of chemical applications	1
Years or cycles	3
No. of crops	2
No. of time steps/chemeq	40
PROFILE DETAILS	
Profile depth (mm)	1200.0
Bottom boundary condition	2
Segment thickness (mm)	100.0
Depth of water table (mm)	0.000
SOIL DATA	
Soil bulk density (Mg/m3)	1.30
Air-entry-value (kPa)	-12.5
Exponent in Campbell's eq.	5.8
Sat'd K value (mm/day)	85.0
CROP DATA	

Wilting point (soil) kPa	-1500.000	
Max. actual tran/pot'l tran)	1.000	
Min. root water pot'l (kPa)	-3000.000	
Max. root water pot'l (kPa)	0.000	
Root flow resistance const. (0) var.(1)	0	
DIFFUSION/DISPERSION COEFFECIENTS		
Molecular diffusion (Do)	150.000	
Dispersivity (mm)	100.000	
Coefficient (mm ² /d)	0.010	
(Bresler's eq.)	10.000	
OUTPUT		
Segemnent print frequency	1	
Print option: 1, 2 or 3	3	
Summary print frequency (d)	1	
1: time intervals/print	1	
Number of output files	2	
2: days/print	14	
3: No. of prints (even)	3	
DAY OF PRINT OUT (if print options = 3)		
Date (or day No.)	Time of day (to nearest tenth)	
150288	0.6	
150289	0.6	
150290	0.6	
THREE DEPTHS WHICH DAILY SUMMARY IS TO BE RECORDED (mm)		
300	600	900

APPENDIX G

MONTHLY CLIMATIC DATA FOR SAMPLA (INDIA)

SAMPLA SITE WEATHER RECORD, 1989-90**(INDIA)**

Month	Pan Evaporation (Ave. mm/d)	Rainfall (mm/d)
January	1.8	1.2
February	2.6	23.3
March	4.3	8.1
April	7.6	1.6
May	11.4	15.6
June	10.3	38.9
July	8.0	133.2
August	6.0	127.4
September	5.8	60.2
October	5.1	5.5
November	3.4	-
December	1.8	8.5

APPENDIX H

MONTHLY CLIMATIC DATA FOR TEL HADYA (SYRIA)

TEL HADYA SITE WEATHER RECORD, 1987-88
(SYRIA)

Month	Pan Evaporation (Ave. mm/d)	Rainfall (mm/d)
January	1.3	81.8
February	2.0	95.1
March	3.1	90.7
April	4.6	22.7
May	9.4	2.5
June	12.5	4.0
July	15.2	0.0
August	14.1	0.6
September	10.5	1.0
October	6.4	69.2
November	2.5	44.4
December	1.4	70.3

APPENDIX I

OUTPUT FILLE SAMPLE

sample10.OUT

SOIL HYDROLOGICAL CHARACTERISTICS

PREDICTED RETENTIVITY AND CONDUCTIVITY DATA

Depth (mm)	Water content, theta (Conductivity mm/day)					Satrn -3 kPa -10 kPa -30 kPa -100 kPa -1500 kPa a (kPa) b p				
50.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00	
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05				
150.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00	
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05				
250.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00	
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05				
350.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00	
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05				
450.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00	
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05				
550.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00	
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05				
650.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00	
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05				
750.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00	
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05				

850.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05			
950.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05			
1050.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05			
1150.	.426	.383	.281	.212	.155	.077	-1.980	3.880	1.00
	.540E+03	.169E+03	.605E+01	.287E+00	.102E-01	.558E-05			

LEACHC used the Richards equation and CDE option

DATE 1/11/89

[illegible]

Node	Theta	Potnl	Flux	ET	Cl	SO4	HCO3	CO3	Balion	Total	Calcite	Gypsum	SAR	ESP	EC	pH
mm	kPa	mm	mm				mmol/l			mass fraction			mS/m			
50.	.0500 -8099.	.00	.00	1.9	.8	8.2	.0	.0	11.6	.000	.000	2.2	5.4	118.1	6.74	
150.	.0500 -8099.	.00	.00	1.9	.8	8.3	.0	.0	11.7	.000	.000	2.2	5.4	119.2	6.74	
250.	.0700 -2195.	.00	.00	3.6	1.4	10.0	.0	.0	16.4	.000	.000	1.7	4.5	167.3	6.68	
350.	.0700 -2195.	.00	.00	4.2	1.4	9.3	.0	.0	16.3	.000	.000	1.7	4.5	168.0	6.65	
450.	.0800 -1307.	.00	.00	4.2	1.6	12.2	.0	.0	19.6	.000	.000	1.5	4.1	195.0	6.72	
550.	.0800 -1307.	.00	.00	3.7	1.6	12.7	.0	.0	19.6	.000	.000	1.5	4.1	193.4	6.60	
650.	.1000 -550.	.00	.00	3.7	1.7	13.7	.0	.0	20.8	.000	.000	1.4	3.9	203.1	6.74	
750.	.1000 -550.	.00	.00	3.1	1.7	14.3	.0	.0	20.8	.000	.000	1.4	3.9	201.1	6.76	
850.	.1500 -114.	.00	.00	3.1	1.2	9.6	.0	.0	15.1	.000	.000	2.2	5.4	152.1	6.60	
950.	.1500 -114.	.00	.00	3.1	1.2	9.6	.0	.0	15.1	.000	.000	2.2	5.4	152.1	6.60	
1050.	.1500 -114.	.00	.00	3.1	1.2	9.6	.0	.0	15.1	.000	.000	2.2	5.4	152.1	6.60	
1150.	.1500 -114.	.00	.00	3.1	1.2	9.6	.0	.0	15.1	.000	.000	2.2	5.4	152.1	6.60	

Drainage flux : .00

(Water fluxes are cumulative since the previous printout and, except for the drainage flux, refer to the upper boundary of each depth segment.

CROP AND ROOT DATA, EXCHANGEABLE AND DISSOLVED CATIONS

Time: .000 Days Crop cover: .000 Root Potential:-.8099E+04kPa

Node	Roots	Ca	Mg	Na	K	Dissolved	
Depth	Exch	Soln	Exch	Soln	Exch	Soln	Exch
mm	fraction	me/kg	mmol/l	me/kg	mmol/l	me/kg	mmol/l
50.	.238	14.63	2.2	20.04	1.2	2.00	4.0
150.	.286	14.63	2.2	20.03	1.2	2.00	4.0
250.	.286	15.87	4.2	19.16	1.8	1.66	4.1
350.	.095	15.88	4.2	19.16	1.8	1.66	4.1
450.	.048	15.86	5.4	19.33	2.4	1.50	4.1
550.	.000	15.86	5.4	19.33	2.4	1.51	4.1
650.	.000	15.07	5.4	20.19	2.9	1.43	4.1
750.	.000	15.07	5.4	20.19	2.9	1.44	4.1
850.	.048	11.34	2.2	23.38	2.8	1.98	5.0
950.	.000	11.34	2.2	23.38	2.8	1.98	5.0
1050.	.000	11.34	2.2	23.38	2.8	1.98	5.0
1150.	.000	11.34	2.2	23.38	2.8	1.98	5.0

Node	Theta	Potnl	Flux	ET	Cl	SO4	HCO3	CO3	Balion	Total	Calcite	Gypsum	SAR	ESP	EC	pH
mm		kPa	mm	mm	-----mmol/l-----					mass fraction			mS/m			
50.	.0798	-1323.	220.71	42.77	8.8	17.3	1.0	.0	.0	44.2	.000	.000	1.4	4.5	511.7	5.75
150.	.0816	-1211.	174.54	51.18	8.8	16.6	1.5	.0	.0	43.6	.000	.000	1.6	4.9	502.8	5.94
250.	.0773	-1497.	119.97	53.10	10.2	18.1	5.2	.0	.0	51.6	.000	.000	1.7	5.5	592.6	6.37
350.	.0846	-1052.	65.91	28.93	8.9	14.5	5.0	.0	.0	42.9	.000	.000	1.6	5.2	496.8	6.35
450.	.0908	-801.	35.26	27.08	8.0	11.0	4.9	.0	.1	35.0	.000	.000	1.6	4.9	404.6	6.30
550.	.1044	-465.	7.04	.00	4.9	5.3	3.9	.0	1.5	21.0	.000	.000	1.5	4.2	243.1	6.08
650.	.1074	-417.	4.60	.00	3.8	2.7	5.0	.0	4.6	18.8	.000	.000	1.5	3.9	211.9	6.29
750.	.1043	-468.	3.85	.00	4.4	2.2	11.0	.0	2.9	22.8	.000	.000	1.6	4.3	234.6	6.64
850.	.0937	-707.	3.43	19.89	6.3	2.8	18.7	.1	1.7	32.5	.000	.000	2.2	5.8	313.5	6.85
950.	.1075	-415.	-10.84	.00	4.2	1.8	13.3	.0	.4	21.6	.000	.000	2.2	5.4	211.7	6.73
1050.	.1140	-330.	-6.59	.00	3.4	1.4	10.7	.0	.1	16.9	.000	.000	2.2	5.4	168.3	6.64
1150.	.1167	-302.	-2.99	.00	3.2	1.2	9.9	.0	.0	15.5	.000	.000	2.2	5.4	155.7	6.61

Drainage flux : .33

(Water fluxes are cumulative since the previous printout and, except for the drainage flux, refer to the upper boundary of each depth segment.

CROP AND ROOT DATA, EXCHANGEABLE AND DISSOLVED CATIONS

Time: 151.500 Days Crop cover: .800 Root Potential:-.3000E+04kPa

Node	Roots	Ca	Mg	Na	K	Dissolved				
Depth	Exch	Soln	Exch	Soln	Exch	Soln	Exch	Soln	cations	
mm	fraction	me/kg	mmol/l	me/kg	mmol/l	me/kg	mmol/l	me/kg	mmol/l	me/l
50.	.238	15.74	8.1	19.28	3.4	1.66	4.8	.02	.7	28.5
150.	.286	15.27	8.0	19.60	3.7	1.81	5.4	.02	.7	29.4
250.	.286	15.58	9.8	19.07	4.1	2.03	6.4	.03	.9	35.2
350.	.095	15.68	9.0	19.11	3.8	1.89	5.9	.02	.7	32.2
450.	.048	15.64	8.7	19.24	3.8	1.80	5.8	.02	.6	31.3
550.	.000	15.79	5.7	19.37	2.5	1.53	4.2	.01	.3	20.9
650.	.000	15.10	4.8	20.15	2.5	1.45	4.0	.01	.2	18.8
750.	.000	14.65	5.6	20.46	3.3	1.58	4.8	.00	.1	22.8
850.	.048	11.61	5.7	22.97	6.5	2.12	7.7	.01	.2	32.5
950.	.000	11.36	3.4	23.35	4.3	1.99	6.0	.00	.1	21.6
1050.	.000	11.34	2.6	23.38	3.2	1.98	5.3	.00	.1	16.9
1150.	.000	11.34	2.3	23.38	2.9	1.98	5.1	.00	.1	15.5

DATE 10/ 9/90

Initially in profile	:	120.0	13193.4	19372.6	3756.6	36.1	390.2	157.9	1274.0	1.9
Currently in profile	:	108.1	13529.5	19371.5	3943.7	63.0	686.0	819.0	865.0	1.4
Could not infiltrate	:	.0								128.2
Change	:	-11.9	336.1	-1.1	187.1	27.0	295.8	661.1	-409.0	-.4
Added:										
i) Infiltration	:	270.0	337.0	.0	189.0	27.0	297.0	661.5	393.4	11.6
ii) As amendment	:		.0	.0	.0	.0	.0	.0	.0	
iii) From calcite/gyp	:		.0				.0	.0		
iv) From CO ₂	:							.0		
Lost:										
i) In drainage	:	.4	.8	1.1	1.9	.0	1.2	.5	3.7	.0
ii) Tran/plant uptake	:	230.6	.0	.0	.0	.0	.0	.0	.0	
iii) To calcite/gypsum	:		.0				.0	.0		
iv) Evaporation/to CO ₂	:	49.8						-810.7		
Mass error	:	1.2	.0	.0	.0	.0	.0	.0		