Assessment of LEACHM-C Model for semi-arid saline irrigation*

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Abstract

Arid and semi-arid countries are facing the exhaustion of their fresh 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.

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.

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. The 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 (Hutson and Wagenet, 1992). The RMSE values, following adjustment of the water retention parameters, ranged from 13 to 24%, indicating the importance of obtaining accurate values of soil parameters for optimum model performance.

Résumé

Les pays arides et semi-arides sont maintenant confrontés au problème de raréfaction de leurs ressources en eau et sont contraints d'utiliser des eaux salées (eaux saumâtres et eaux de drainage) pour l'agriculture irriguée.

Très souvent, on aboutit à des résultats désastreux car une bonne part de régions productives sont atteintes de salinité. Cependant, il existe un large potentiel pour le développement de l'agriculture provenant de l'usage des eaux salées en irrigation.

L'étude présente une analyse de la performance du modèle LEACHM-C de simulation du transport de l'eau et des solutés en régime transitoire. Cette évaluation est effectuée dans

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* **Evaluation de performance du modèle LEACHM-C pour l'irrigation des régions semi-arides avec de l'eau salée**

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les régions où l'usage d'eau salée est retenu comme une option pour la production des cultures. Le modèle permet d'établir des bilans d'eau et de sels d'un profil du sol et de tester différentes stratégies pour l'irrigation et la rotation des cultures.

La capacité de prédiction du modèle a été testée en utilisant les données recueillies au cours d'une année d'expérimentation sur le terrain entreprise dans une région sèche de l'Inde. Les valeurs observées et celles prévues de la salinité du profil du sol, (0 à 120 cm) ont été comparées grâce à une représentation graphique et à l'utilisation des quatre indices statistiques : erreur quadratique moyenne (ERCM), coefficient de la masse résiduelle (CMR), coefficient de détermination (CD) et efficience de modélisation (EF). Sur la base des statistiques et de la représentation graphique, il a été constaté que les premières simulations réalisées sont de qualité marginale. Le modèle surestime les valeurs mesurées. Les résultats de l'ERCM varient de 28 à 70%. La concordance s'est améliorée quand les paramètres de retention d'eau "a" et "b" ont été ajustés en utilisant les équations de régression pour le calcul de retention (Hutson et Wagenet 1992). Les valeurs de l'ERCM obtenues suite à l'ajustement des paramètres varient de 13 à 24% ce qui souligne la nécessité d'obtenir des valeurs précises des paramètres du sol pour la performance optimale du modèle.

Introduction

Poor quality water (brackish groundwater or drainage water) is a common feature of arid and semi-arid regions and is often used for irrigation in absence or limited availability of better quality waters (Bresler, 1979; Gupta, 1979; Rhoades, 1992 and Hamdy, 1996). Sustainable use of saline water 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.

Most studies to date support the feasibility of irrigating crops with saline water, but uncertainty still exists about long term effect of this practice on the physical characteristics of the soil, including soil-water retention, infiltration and drainage rates, and unsaturated hydraulic conductivity. Irrigation, fresh or saline, may increase soil salinity, soil sodicity and may even reduce soil infiltration rates. The most limiting factor in the use of saline waters on soils may be structural deterioration which retards crop growth by limiting salt leaching and causing water stagnation and thereby, aeration problems. Indeed, 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 (Frenkel and Shainberg, 1975; Minhas and Sharma, 1989).

Long-term field experiments are one way to develop suitable irrigation strategies, but are expensive, site specific and time consuming. A field application of simulation models being developed to describe soil water and salt movement (Hutson et al., 1990; Majeed et al., 1994; Hagi-Bishow, 1998) guarantee realistic estimates of soil water, salt and sodium build up. 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. Further, simulations allow for predictions at other field sites and for different boundary conditions to assess long term salinity effects.

The LEACHM-C model was previously tested using data from a lysimeter study (Majeed et al., 1994). The model predictions compared well with the experimental results. To test the model under field conditions, field data were obtained from the Sampla experimental station of the Central Soil Salinity Research Institute, Karnal, India.

This paper presents the description of the model, describes the experimental set-up and procedures for evaluating model performance, and then assesses the applicability of the model to simulate field-measured soil salinity profiles.

Material and Methods

Description of model

LEACHM (Hutson and Wagenet, 1992), Leaching Estimation and CHemistry Model, 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. In this study LEACHM-C, the Chemistry, Salt Movement and Water Transport submodel of LEACHM will be the focus.

LEACHM-C submodel

LEACHM-C is the salinity model of the Leaching Estimation and Chemistry Model, LEACHM. 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, and calculation of potential evapotranspiration based on pan evaporation data and its partitioning into potential evaporation and estimating water uptake based on the Nimah and Hank model (Nimah and Hanks, 1973). More complete details of the model are given in the model user's manual (Hutson and Wagenet, 1992).

Water flow simulation

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 :

$$\frac{\partial \theta}{\partial t} = C_w \frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta) \frac{\partial H}{\partial z} \right] - U(z,t) \tag{1}$$

Where θ represents the volumetric water content (m^3 - m^{-3}), t is time (d), C_w is the differential water capacity ($\partial\theta/\partial h$, 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 (d^{-1}).

Retentivity is described by Campbell's (1974) equation

$$h = a\left(1 - \frac{\theta}{\theta_s}\right)^{-b} \tag{2}$$

Where θ_s is the volumetric fraction of water at saturation, and a and b are constants.

Hydraulic conductivity (K, mm-d^{-1}) is described using Campbell's (1974) conductivity relationship :

$$K(\theta) = K_s\left(\frac{\theta}{\theta_s}\right)^{2b+2+p} \tag{3}$$

Where K_s is hydraulic conductivity at saturation and p is a pore interaction parameter [usually used empirically to adjust the shape of the K(θ) curve].

The values of a, b, θ_s and K_s can be entered directly into the input data file; if known (Table 1), or can be predicted by the model using one of five possible regression equations (Hutson and Cass, 1987) relating water retention to particle distribution, organic matter and bulk density. 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.

Table 1. Hydrological parameters used as representative field soil properties over the 1200mm profile depth.

Name	Symbol	Value
Parameters in Campbell's eq.	a	- 1.98 kPa
	b	3.88
Soil bulk density	ρb	1.52 Mg-m^{-3}
Saturated hydraulic conductivity	K_{sat}	5.0-10.8 mm/h
Water content at field capacity (volumetric)	θ_{fc}	27-34%
Water content at saturation (volumetric)	θ_s	36-43%

Source : Minhas and Gupta (1993); Sharma et al. (1991).

Upper boundary flux of water

The upper boundary flux of water can vary between zero flux, upward evaporative flux, constant flux infiltration or ponded (zero matric potential) infiltration.

Lower boundary conditions

The model provides a choice of five lower boundary conditions: (1) fixed-depth water table, (2) free-draining profile having a unit hydraulic gradient flux at the lowest node, (3) zero flux (unsaturated condition), (4) lysimeter tank from which water drains when the bottom node reaches saturation, but has zero flux when unsaturated, or (5) a fluctuating water table, specified in the input data. More detailed description of the lower boundary conditions used in the model can be seen in the user's manual for LEACHM (Hutson and Wagenet, 1992). In this paper, condition two was used as the lower boundary condition.

Solute transport

The generalized convection-dispersion equation (CDE) with some modification has been used in the model to simulate solute transport. 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 and assumed equal; sorption equals volatilization, the CDE equation reduces to equation 4 given below :

$$\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z}\left[\theta D(\theta, q)\frac{\partial c}{\partial z} - qc\right] \tag{4}$$

where c is concentration (mg-l^{-1}), t is time (d), z is depth (mm), D is an effective dispersion coefficient (mm^{2}-d^{-1}), θ represents the volumetric water content (m^{3}-m^{-3}) and q is water flux density (mm-d^{-1}).

Upper and lower boundary flux of solute

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 or 5) 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.

Modeling chemical interactions

In LEACHM-C equilibrium chemistry is not included in the convection-dispersion equation because of its complexity; instead, the chemical processes including cation exchange, atmospheric exchange and precipitation-dissolution are simulated in a separate chemical equilibrium subroutine, CHEM (Robbins et al, 1980). The chemical species treated are Ca, Mg, Na, K, Cl, SO_4, CO_3, HCO_3, 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.

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

1. First- and second-dissociation constant of H_2CO_3,

$$K_{a1} = \frac{(H^+)(CO_3^-)}{(H_2CO_3^-)} \tag{5}$$

$$K_{a2} = \frac{(H^+)(CO_3^{--})}{(HCO_3^-)} \tag{6}$$

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

$$K_{sp1} = (Ca^{2+})(SO_4^{2-}) \tag{7}$$

$$K_{sp2} = (Ca^{2+})(CO_3^{2-}) \tag{8}$$

3. Ion pair stability constants for 11 ion pairs,

$$K_f = \frac{(Cat^{m+})(An^{n-})}{(CatAn^{m-n})} \tag{9}$$

   Where Cat^{m+} represents a cation of positive valence 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 :

$$K_G = \frac{(M^{m+})^{1/m}(XN_{1/m})}{(N^{n+})^{1/n} XM_{1/m}} \tag{10}$$

   Where KG is the selectivity coefficient, X refers to an exchange cation, and M and N are metal cations with charges of m+ and n+, respectively.

Input requirements

In LEACHM-C, three groups of input data are needed for model operations. The first group consists of soil physical and chemical parameters. These data include: (i) initial soil water content and soil characterisation of the relationship among water content, matric potential and hydraulic conductivity; (ii) initial profile of soil chemical data (Ca^{2+}, Mg^{2+}, Na^+, Cl^-, SO_4^{2-}, HCO_3^-); and (iii) 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.

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.

Site description and measurements

For six years (1986-1992) personnel at the Sampla experimental station of the Central Soil Salinity Research Institute (CSSRI), Karnal, India conducted an experiment on sandy loam soils (Sharma et al., 1994). The study area has a subtropical, semi-arid climate and receives an average annual rainfall of 645 mm. Total rainfall in 1990, 1991 and 1992 was 522, 545 and 615 mm, respectively. 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 monthly 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).

Soil data

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, on a volume basis, the soil has a field capacity of 27-34%, a total porosity of 36 to 43 % and a bulk density of 1.48 to 1.55 Mg m^{-3} (Table 1).

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 raw data described below was supplied by personnel at the CSSRI, Karnal, India.

Crop data

The experiment was conducted under a wheat and pearl-millet/sorghum rotation. A pre-sowing irrigation of about 70 mm was given uniformly in November with non-saline canal water (EC_{iw} = 0.4 dS m^{-1}) and (*Triticum aestivium* var. HD 2329) wheat was seeded in the second week of November and harvested in the second week of April. 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; the crops were dependent on the monsoon rainfall.

Irrigation data

Irrigation treatments of the wheat consisted of seven combinations of non-saline canal water (EC_{iw} = 0.4 dS m^{-1}) and drainage water (EC_{Dw} = 12.5-15.5 dS m^{-1}). Each treatment was replicated four times in a randomised block design. Initially, soils were desalinised by leaching with rainwater 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 (Table 2). Irrigations were applied at crown root initiation, late tillering, flowering and dough growth stages of wheat.

Table 2. Average composition of canal water and ground water

Water	EC dS-m^{-1}	SAR $(mmole/l)^{0.5}$	Solute concentration (meq-l^{-1})				
			Ca+Mg	Na	K	HCO_3	Cl
Canal water	0.4	0.7	2.1	0.7	0.1	1.4	1.1
Drainage water	12.5-15.5	14.5	126	115	0.3	1.6	212

Source : Sharma et al. (1994).

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 irrigations 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.

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 the Central Soil Salinity Research Institute, Karnal.

Procedures for Model Evaluation

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 visually quantified. 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), and 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 0.0, 0.0, 1.0 and 1.0, respectively.

(a) Root mean square error (RMSE) :

$$RMSE = \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n} \right]^{0.5} * \frac{100}{\bar{O}} \tag{11}$$

(b) Coefficient of determination (CD) :

$$CD = \frac{\sum_{i=1}^{n} \left(O_i - \bar{O} \right)^2}{\sum_{i=1}^{n} \left(P_i - \bar{O} \right)^2} \tag{12}$$

(c) Modeling efficiency (EF) :

$$EF = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O} \right)^2} \tag{13}$$

(d) Coefficient of residual mass (CRM) :

$$CRM = \frac{\sum_{i=1}^{n} (O_i - P_i)}{n \bar{O}} \tag{14}$$

Where :

P_i = predicted values

O_i = observed values

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

n = number of samples

Results and Discussions

To check the performance of the model for predicting salinity build up in terms of electrical conductivity of the soil extract (EC_e, dS-m^{-1}), simulations were run using the following five irrigation treatments: 4CW (4 irrigations with canal water), CW/DW (4 alternated irrigations of canal and drainage water, 2CW+2DW (2 irrigations with canal water followed by 2 drainage water, 1CW+3DW (1 irrigation of canal water followed by 3 drainage water) and 4DW (4 irrigations with drainage water). The simulations started at sowing (November, 1989) with initial soil salinity ranging from 1.3 to 2.5 dS-m^{-1}. Depth-wise salinity profiles, measured after wheat harvest (April, 1990) were compared with the model simulations. Results of observed and predicted values of soil solution EC_e for the five irrigation treatments are depicted in Figures 1 to 5. The results of the statistical analyses are summarized in Table 3 using the above mathematical expressions (Eqs. 11 to 14). The final values of constants a & b used (all else held constant) were determined by minimizing the RMSE.

Table 3. Model performance statistics comparing predicted vs. observed data

Treatments	RMSE (%)	CRM	CD	EF
Optimum	0.0	0.0	1.0	1.0
4 CW	13	- 0.05	0.83	0.88
CW : DW	20	- 0.15	0.72	0.89
2 CW + 2 DW	14	- 0.11	0.80	0.95
1 CW + 3 DW	22	- 0.21	0.77	0.83
4 DW	24	- 0.13	0.72	0.79

RMSE : Root Mean Square Error

EF : Modelling efficiency

CW : Canal Water

CD : Coefficient of determination

CRM : Coefficient of Residual Mass

DW : Drainage Water

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 1. Observed soil solution EC_e and predicted values do not show any appreciable increase from the initial conditions (November, 1989). 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 this could be that the initial data on the cation exchange capacity were assumed.

The graphs of predicted soil solution EC_e versus observed data for saline irrigation treatments are given in Figures 2 to 5. The general pattern of salt distribution and relative values agree very well. The soil solution increased from an average initial value of 1.8 dS m^{-1} at start of simulation to as much as 10.5 dS-m^{-1}. This is due to a combination of

Figure 1. Observed vs. predicted soil salinity after harvest for treatment 4CW: 4 irrigations with canal water. Initial conditions indicated by the dashed line.

Figure 2. Observed vs. predicted soil salinity after harvest for treatment CW/DW: 4 alternated irrigations of canal and drainage water. Initial conditions as in Figure 1.

Figure 3. Observed vs. predicted soil salinity after harvest for treatment 2CW+2DW: 2 irrigations with canal water followed by 2 drainage water. Initial conditions as in Figure 1

the salinity load applied and evapotranspiration from the soil. Both phenomena are more pronounced in the upper soil layers. The predicted absolute EC_e values of the upper 60-cm layer were found to be always more than those observed. The LEACHM-C model does not account for water flow in macropores. By ignoring the fact that more of the salt load under flood irrigation can bypass the upper soil layers via macro-pore bypass, the model will tend to overestimate EC_e in this upper zone. Differences between observed and predicted are much less at depths over 80 cm. Also, nonuniform downward and upward movement of soil solution in pores of different sizes occurs. Both redistribution and evaporation processes might have contributed to the trend and magnitude of disagreement between observed and predicted EC values.

Figure 4. Observed vs. predicted soil salinity after harvest for treatment 1CW+3DW: 1 irrigation of canal water followed by 3 drainage water. Initial conditions as in Figure 1

Figure 5. Observed vs. predicted soil salinity after harvest for treatment 4DW: 4 irrigations with drainage water. Initial conditions as in Figure 1

Conclusion

This study demonstrates the utility of the LEACHM-C submodel for predicting soil salinization and management of saline water irrigated soils. The performance of the LEACHM-C submodel 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_e values with one-year data (1989-1990) obtained from a field study in India. 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 (EF) and the coefficient of determination (CD). Reasonable agreement was found between absolute values of the model predictions and the experimentally measured data for the conditions tested. Also, the patterns of relative salt distribution throughout the profile agreed very well. The RMSE results from the different treatments ranged 13 to 24%. In addition, the performance of the model is fairly good as seen by the EF values that ranged from 0.79 to 0.95. Based on the CRM values, however, the model over-estimated with respect to the measured data. This was probably a result of the model not accounting for macro-pore bypass flow.

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 submodel has tremendous capability for interpreting soil solute dynamics and provides useful insights into root zone hydrology. This should 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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