Leaching requirement for soil salinity control: Steady-state versus transient models

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ABSTRACT

Water scarcity and increased frequency of drought conditions, resulting from erratic weather attributable to climatic change or alterations in historical weather patterns, have caused greater scrutiny of irrigated agriculture's demand on water resources. The traditional guidelines for the calculation of the crop-specific leaching requirement (LR) of irrigated soils have fallen under the microscope of scrutiny and criticism because the commonly used traditional method is believed to erroneously estimate LR due to its assumption of steady-state flow and disregard for processes such as salt precipitation and preferential flow. An over-estimation of the LR would result in the application of excessive amounts of irrigation water and increased salt loads in drainage systems, which can detrimentally impact the environment and reduce water supplies. The objectives of this study are (i) to evaluate the appropriateness of the traditional steady-state method for estimating LR in comparison to the transient method and (ii) to discuss the implications these findings could have on irrigation guidelines and recommendations, particularly with respect to California's Imperial Valley. Steady-state models for calculating LR including the traditional model, which is an extension of the original U.S. Salinity Laboratory LR model, WATSUIT model, and water-production-function model were compared to transient models including TETrans and UNSATCHEM. The calculated LR was lower when determined using a transient approach than when using a steady-state approach. Transient conditions and the influence of preferential flow did not have as significant an effect on lowering the LR as salt precipitation for a representative study of the Imperial Valley using Colorado River water (EC = 1.23 dS/m) for irrigation. A valley-wide LR of 0.08 for a crop rotation of alfalfa/alfalfa/alfalfa/alfalfa/wheat/lettuce, as calculated by both WATSUIT and UNSATCHEM, was concluded to be the most reasonable estimate for the entire Imperial Valley as compared to a LR of 0.13 by the commonly used traditional method. The reduced LR for the Imperial Valley would result in a diminished drainage volume of approximately $1.23 \times 10^8\,m^3$ (i.e., 100,000 ac-ft). The most significant conclusion derived from the comparison is that the use of the traditional steady-state model for estimating LR needs to be reevaluated.

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1. Introduction

The accumulation of excess soluble salts in the root zone of arid and semi-arid irrigated soils is a widespread problem that seriously affects crop productivity throughout the world. The predominant mechanism causing the accumulation of salt in irrigated agricultural soils is evapotranspiration, which concentrates salts in the remaining soil water. Effects of soil salinity are manifested in loss of stand, reduced plant growth, reduced yields, and in severe cases, crop failure. Salinity limits water uptake by plants by reducing the osmotic potential making it more difficult for the plant to extract water. Some constituents of salinity may also cause specific-ion toxicity or upset the nutritional balance of plants. In addition, the salt composition of the soil water influences the composition of cations on the exchange complex of soil particles, which influences soil permeability and tilth. Irrigated agriculture, which accounts for 35–40% of the world's total food and fiber, is adversely affected by soil salinity on roughly half of all irrigated soils (totaling about 250 million ha) with over 20 million ha severely affected by salinity worldwide (Rhoades and Loveday, 1990).

To prevent the accumulation of excessive soluble salts in irrigated soils, more water than required to meet the evapo-transpiration needs of the crops must pass through the root zone to leach excessive soluble salts. This additional irrigation water has typically been expressed as the leaching requirement (LR). Leaching requirement was originally defined as the fraction of infiltrated water that must pass through the root zone to keep soil salinity from exceeding a level that would significantly reduce crop yield under steady-state conditions with associated good management and uniformity of leaching (U.S. Salinity Laboratory Staff, 1954; Rhoades, 1974). Reclamation of inherently saline soils, or of soils allowed to salinize through under-irrigation and other similarly inappropriate forms of management (e.g., by fallowing soils for extended periods of time in the presence of a shallow water table), is not included in the determination of the LR. Root water extraction of shallow groundwater, runoff, and leaching from effective precipitation are also not considered.

The relationship between crop yield and seasonal amount of water required is essential to determine the optimum irrigation management (Letey et al., 1985). As pointed out by Letey et al. (1985), LR does not provide sufficient information concerning optimum irrigation since optimum irrigation is the amount of water that maximizes profit and maximum profit may not coincide at all times with maximum yield. For this reason, crop-water-production-functions have been advocated as a means of determining the economically optimum amount of water that is needed to prevent excessive accumulation of salts. Nevertheless, LR is still widely used by growers and irrigation management districts in the southwestern USA and many other semi-arid regions of the world.

The traditional method used to determine LR was developed by Rhoades (1974) from the original steady-state LR model of the U.S. Salinity Laboratory Staff (1954). Steady-state conditions do not exist under most field situations. This raises the question of the appropriateness of the traditional method for more common transient conditions. The traditional method also ignores the chemical processes of salt precipitation which can, in some cases, significantly reduce levels of

soil salinity within the root zone and, thus, reduce LR. Furthermore, the traditional method does not account for preferential flow, which influences water flow and the efficiency of salt leaching. With these concerns in mind, the objectives of this study are (i) to evaluate the appropriateness of the traditional steady-state model for estimating LR in comparison to other steady-state models and transient models by establishing if differences exist, the extent of the differences, and the reasons for the differences, and (ii) to discuss the implications these findings could have on irrigation guidelines and recommendations, particularly with respect to California's Imperial Valley. If differences occur between the traditional LR model and more rigorous and robust transient models, then the assumption of steady-state is brought into question and a new paradigm may be needed, particularly for research applications. The comparison of transient approaches for estimating LR, which account for processes such as bypass flow or precipitation–dissolution reactions, with the traditional steady-state approach is intended to ascertain if the current means of estimating LR from a functional, steady-state model needs reevaluation and if a reevaluation is indeed needed, then (i) what is the weakness in the traditional approach for estimating LR and (ii) what is the recommended course of action. Other questions that may affect LR, such as rainfall, irrigation uniformity resulting from the type of irrigation (e.g., flood, sprinkler, or drip irrigation), the manner in which spatio-temporal variation in salinity within the root zone affects crop response and water uptake, and scale issues are not addressed in the model comparison. Furthermore, no discussion is given to additional factors that influence the estimation of LR including (i) horizontal leaching and subsequent redistribution of salts for cracking soils when flood irrigation is used, (ii) basing the LR on the most salt-sensitive crop in a crop rotation, and (iii) uncertainties in salt-tolerance data developed from experimental plots when applied to field situations, but these are discussed in Rhoades (1999).

2. Review of leaching requirement methods

The level and distribution of salinity in cropped soils are the result of time-dependent interactions of rainfall, irrigation, evapotranspiration, leaching, and drainage. These interactions and relationships involving crop yield, root water extraction, soil salinity, irrigation, salt-loading, leaching, and drainage are complicated and are not fully understood or quantified. Some models have been developed to describe these interactions and relationships, but few have been tested and shown to be applicable for the estimation of LR under a wide variety of field conditions. Moreover, the estimated LR results of these models have been compared for a given set of cropping conditions in only one instance. Five different steady-state LR models were compared against field and plot experiments by Hoffman (1985) with the model by Hoffman and van Genuchten (1983) fitting the results best. However, this comparison involved conditions of high frequency irrigation, which may not necessarily apply to general irrigation management in the field. One of the most comprehensive modeling studies of transient conditions

was carried out by Goncalves et al. (2006) who analyzed transient water flow and solute transport in three soil lysimeters irrigated with waters of different quality over a period of 3 years using the HYDRUS-1D (Šimůnek et al., 2005) model with implemented major ion chemistry sub-routines from UNSATCHEM. In this study, HYDRUS-1D successfully described field measurements of water content, overall salinity, concentration of individual soluble cations, as well as the sodium adsorption ratio and exchangeable sodium percentage. No comparison has been made in the past of steady-state and transient models for estimating LR.

Five models have been selected to compare and contrast their estimation of LR to meet our study's objectives: (i) the traditional LR model originally developed by the USDA-ARS, U.S. Salinity Laboratory (U.S. Salinity Laboratory Staff, 1954) and modified by Rhoades (1974), (ii) WATSUIT (Rhoades and Merrill, 1976), (iii) water-production-function (WPF) model (Letey et al., 1985), (iv) TETrans (Corwin et al., 1990), and (v) UNSATCHEM (Šimůnek and Suarez, 1994). These models were specifically selected because they reflect a spectrum of categories of models ranging from steady-state to transient models and from functional to mechanistic, they provide potential insight into the influence of physical and chemical processes (e.g., precipitation and dissolution, preferential flow, and plant water uptake) on the estimation of LR, and they are well-known and understood by the authors. The traditional LR, WATSUIT, and WPF models are steady-state models while TETrans and UNSATCHEM are transient models. The WATSUIT and UNSATCHEM models account for precipitation and dissolution reactions while the traditional LR, WPF, and TETrans models do not. The WPF model is unique in its handling of ET and plant yield as influenced by matric and osmotic stress. Finally, TETrans is the only model within the group that accounts for preferential flow. There are a number of other models that could have been used also, such as the steady-state model by Hoffman and van Genuchten model (1983) and the transient models MACRO by Jarvis (1994) and ENVIRO-GRO by Pang and Letey (1998), just to name a few. These models were not used in the comparison because the authors were not as knowledgeable about and familiar with these models as the five selected models.

2.1. Steady-state leaching requirement models

Steady-state LR models consist of the original model developed by the U.S. Salinity Laboratory Staff (1954) and subsequent models based on steady-state or long-time average conditions. These models were based on simple salt-balance concepts, though some refinements were made to account for salt precipitation and dissolution reactions.

2.1.1. Traditional leaching requirement model
As originally published in Handbook 60 (U.S. Salinity Laboratory Staff, 1954) the original LR model is based on the concept of leaching fraction (LF) for steady-state conditions with no precipitation or dissolution and good drainage:

$$LF = \frac{V_{dw}}{V_{inf}} = \frac{EC_{iw}}{EC_{dw}} \tag{1}$$

where V_{dw} (mm) and V_{inf} (mm) are the volumes of drainage water and infiltrating irrigation water, respectively, and EC_{iw} (dS/m) and EC_{dw} (dS/m) are the electrical conductivities of the irrigation and drainage water, respectively.

The LR was originally defined by U.S. Salinity Laboratory Staff (1954) as the lowest value of LF that could be allowed without EC_{dw} (and thus, inferentially, soil salinity) becoming excessive for optimum plant growth. Thus, the minimum value of LF (i.e., LR) would be given when the maximum permissible salinity level of EC_{dw} (i.e., EC_{dw}^*) was inserted into Eq. (1) resulting in Eq. (2), which is considered the original LR model:

$$LR = \frac{EC_{iw}}{EC_{dw}^*} \tag{2}$$

The LR is an estimate of what the LF must be to keep soil water salinity within tolerable limits for crop production. Eq. (2) must still include a relationship between plant response and EC of the bottom of the root zone.

The determination of LR, as originally formulated in Eq. (2), required the selection of the appropriate value of EC_{dw}^* for the crop in question. Such crop-related values were not known and would be expected to vary with irrigation water salinity and irrigation/drainage management. However, data obtained from controlled studies carried out in test plots utilizing relatively uniform soil conditions and optimal irrigation and crop management were available (Bernstein, 1974; Maas and Hoffman, 1977). These controlled studies related the response of many crops to average root zone soil salinity in terms of the EC of the saturation extract, EC_e (dS/m), which is approximately half that of the soil water salinity at field-capacity (U.S. Salinity Laboratory Staff, 1954). The nearly uniform root zone EC_e values that resulted in 50% yield decreases in forage, field, and vegetable crops and 10% yield decreases in fruit crops were originally substituted for EC_{dw}^* in Eq. (2) to estimate LR. No direct evidence or clear reasoning was given to support the appropriateness of this substitution or the corresponding LR values. Another inherent assumption in the original approach used to determine LR is that plants respond primarily to average root zone soil salinity. This assumption is not always true. Some evidence for this conclusion is given in Rhoades and Merrill (1976).

Rhoades (1974) introduced a procedure for determining appropriate values of EC_{dw}^* for use in Eq. (2) using Eq. (3):

$$EC_{dw}^* = 5EC_e^* - EC_{iw} \tag{3}$$

where EC_e^* (dS/m) is the average EC of the saturation extract for a given crop appropriate to the tolerable degree of yield depression usually 10% or less and equivalent to the threshold EC values as defined by Maas (1990). Substitution of Eq. (3) into Eq. (2) yields Eq. (4), which has become referred to as the traditional LR model:

$$LR = \frac{EC_{iw}}{5EC_e^* - EC_{iw}} \tag{4}$$

Eq. (4) ties LR to irrigation water salinity and crop tolerance. The LR values obtained by Eq. (4) (i.e., the traditional LR model) are lower, especially for salt-tolerant crops, than those

obtained by Eq. (2) (i.e., the original LR model). The traditional LR model assumes uniform water applications and does not adjust for salt precipitation or dissolution, nor does it account for irrigation frequency effects, upward water flow, water chemical composition, and salt removal in surface runoff.

2.1.2. WATSUIT model

In contrast to the traditional steady-state model previously described, WATSUIT considers the composition of the irrigation water and includes the processes of salt precipitation and mineral weathering. Salt precipitation and mineral weathering can significantly affect the levels of soil salinity, depending upon irrigation water composition and LF (Rhoades et al., 1974). The assumption is made that plant water uptake occurs from successively deeper quarter-fractions of its root zone in the ratios of 40/30/20/10. The concentrations of the major cations and anions in the soil water within an irrigated root zone are predicted at equilibrium by WATSUIT as a function of the irrigation water composition, LF, presence or absence of soil $CaCO_3$, and several alternative amendment treatments such as gypsum. The WATSUIT model accounts for the precipitation and dissolution of the two most relevant soil minerals, calcite and gypsum (Rhoades and Merrill, 1976). With WATSUIT, the LR is determined by accounting for the chemistry of the irrigation water and soil mineralogy to estimate the LF for which the level of average root zone salinity equals the threshold value for the crop in question (i.e., the maximum salinity that can be tolerated without excessive loss in yield). The WATSUIT model also considers irrigation management in the determination of LR, distinguishing between conventional irrigation and high-frequency forms of irrigation.

In WATSUIT, the effect of salinity on evapotranspiration (ET; mm) is not taken into account. Rather, it is assumed that there will be no loss in yield due to salinity and concomitantly no loss in ET, provided the average root zone salinity does not exceed the threshold value of salinity (EC_e^*; dS/m). The same assumption is also made in the TETrans model, which is discussed later. The WATSUIT model also assumes uniform water application and does not account for the effects of irrigation frequency and upward water flow from a shallow water table.

2.1.3. Water-production-function model

In order to calculate drainage volumes and soil salinity under less than optimum yield conditions, some approach is needed to reduce ET, thereby increasing LF and drainage, when excess salinity buildup causes reduced ET by plants. A simplified, practical model was developed for this purpose by Letey et al. (1985). This model includes the effects of total water application on crop yield as well as LF.

The premise of the WPF model is that a unique relationship exists between yield and ET for a given crop and climate that is independent of whether the water stress leading to a reduction in ET is caused by deficit water, excess salinity, or some combination of the two. Excess salinity will decrease crop yield due to osmotic stress. This reduced yield ought to be associated with a decrease in plant size, and thus, a decrease in ET. For a given amount of irrigation, leaching will increase as ET decreases, which will reduce the level of soil salinity.

Thus, some point will exist at which values for yield, ET, leaching, and soil salinity are consistent with one another. The yield at this point is the yield that can be achieved with a given irrigation water quantity and salinity; the LF will be dependent on the salt-tolerance of the crop and irrigation water salinity.

Letey et al. (1985) combined three relationships: (i) yield and ET, (ii) yield and average root zone salinity (conventional crop salt-tolerance relations), and (iii) average root zone salinity and LF to develop an equation that relates yield to the amount of seasonal applied water of a given salinity for steady-state conditions. A linear relationship between yield and ET was assumed in the model. The exponential water uptake relation of Raats (1974) was used to relate average root zone salinity and LF assuming steady-state. The resulting equation (given in Letey et al., 1985) provides a model for predicting salinity, yield, drainage volume, and the salinity of the water percolating below the root zone for given quantities of seasonal applied water of a given salinity for steady-state conditions. The model assumes uniform water applications and does not adjust for salt precipitation or dissolution, nor does it account for effects of irrigation frequency, upward water flow from a shallow water table, and water composition. The model was modified (Rhoades et al., 1992) to give results in terms of relative yield and relative water (in terms of ET_{max}, i.e., the non-stressed ET given the crop and climate).

The advantage of this model is that simple calculations and measurements are used to predict crop yield, drainage volume, and drain water salinity. Although it has never been used to estimate LR, it can be used to do so. For this purpose, the lowest value of LF that can be used without any (or excessive loss) loss in yield would be equivalent to the LR.

2.2. Transient leaching requirement models

Leaching requirement is an agricultural concept that was originally based on an assumption of steady-state conditions. Over long time periods when steady-state conditions can be more closely approximated, the traditional concept of LR applies quite well. However, perturbations to the system (e.g., change in crop, alteration of irrigation management, introduction of varying irrigation water quality, etc.) result in transient conditions, which reduce the general applicability of the traditional LR model approach, rendering a temporal tracking of the system with transient approaches more appropriate.

2.2.1. TETrans

The TETrans model is a functional, "tipping-bucket", layer-equilibrium model that predicts incremental changes over time in amounts of solute and water content occurring within the crop root zone (Corwin et al., 1990; Corwin and Waggoner, 1990a,b). In TETrans, transport through the root zone is modeled as a series of events or processes within a finite collection of discrete depth intervals. These sequential events or processes include infiltration of water, drainage to field-capacity, plant water uptake resulting from transpiration, and/or evaporative losses from the soil surface. Each process is assumed to occur in sequence within a given depth interval as opposed to reality where transport is a collection of simultaneous processes. Other assumptions include: (i) the soil is

composed of a finite series of discrete depth intervals with each depth interval having homogeneous properties, (ii) drainage occurs through the profile to a depth-variable field-capacity water content, (iii) the depletion of stored water by evapotranspiration within each depth increment does not go below a minimum water content that will stress the plant, (iv) dispersion is either negligible or part of the phenomenon of bypass, and (v) upward or lateral water flow does not occur.

Included within TETrans is a simple mechanism to account for preferential flow or bypass. The phenomenon in which all or part of the infiltrating water passes through a portion or all of the soil profile via large pores or cracks without contacting or displacing water present within finer pores or soil aggregates is referred to as bypass. This process is typical of cracking clay soils (such as those in the Imperial Valley). The net effect of bypass is that some resident salt is not miscibly displaced by incoming water; this reduces the leaching efficiency and increases the amount of salt retained within successive soil-depth intervals. The TETrans model offers a means to quantify the importance of bypass in estimating LR for such soils.

In TETrans, bypass is approximated using a simple mass-balance approach; it is simulated by ascribing a spatial variation in the fractional quantity (or % water bypass) of the resident pore-water present in the soil at the time an infiltration event occurs that is not involved in piston-type displacement following the event. The means of estimating bypass is by assuming that any deviation from piston flow for the transport of a conservative solute is due to bypass (Corwin et al., 1990).

The total amount of ET occurring between irrigation events and the plant root distribution are needed as inputs in TETrans. Plant water uptake is simulated by reducing the amount of water in the soil over time in accordance with the assumed rate of ET and in proportion to the changing rooting distribution that occurs within the soil profile as the crop matures and the roots grow. Root growth is assumed to occur linearly from the date of planting to the date of maturity. Between crops, water loss from the root zone is simulated as evaporation from the soil surface. The distribution of water removal by the plant root system is simulated by a choice of extraction models: linear and exponential. Concomitant with the removal of water by the roots is the concentration of the salts. Salt precipitation and mineral weathering are not considered in TETrans, nor does the model predict crop-yield reductions caused by salinity stress.

2.2.2. UNSATCHEM

The UNSATCHEM model is a sophisticated transient, numerical model that simulates the flow of water in unsaturated soils, along with transport and chemical reactions of solutes, and crop response to salinity (Šimůnek and Suarez, 1994; Šimůnek et al., 1996). The model has submodels accounting for major ion chemistry, crop response to salinity, CO_2 production and transport, time-varying concentration in irrigated root zones, and the presence of shallow groundwater. While variably-saturated water flow is assumed to be described using the Richards equation, the transport of solutes and CO_2 is described using the convection–dispersion equation. Root growth is described using the logistic growth function and root

distribution can be made user-specific. Precipitation, evapotranspiration, and irrigation fluxes can be specified at any user-defined time interval.

While UNSATCHEM has not been used to determine LR, it is suited to do so by determining the minimum LF that can be used under a specified set of soil, crop, and management conditions while preventing undue losses in crop yields. The UNSATCHEM model does not account for the phenomenon of bypass. The complex transient chemical processes included are precipitation and/or dissolution of solid phases, cation exchange, and complexation reactions as influenced by the CO_2 composition of the soil air, which largely controls the soil pH, as well as sulfate ion association, which affects the solubility of gypsum. Since the original version of UNSATCHEM could simulate only a single growth season, UNSATCHEM was modified for this study to include a restart option that allows simulation of a subsequent growth season using final conditions of the previous season.

3. Modeling conditions

In order to estimate LR using the previously described steady-state and transient models, a data base is needed for the following: climate, crops grown, crop rotations, solute transport-related soil properties, irrigation management practices, drainage conditions, and irrigation water composition. For the purposes of this comparative study, a set of realistic conditions and properties was sought so that the estimated LRs from the models could be compared. A data set was developed from available data sources representative of California's Imperial Valley (for details see Rhoades, 1999).

To estimate the LR for the entire Imperial Valley, one must consider the crop sequence grown and associated rooting depth on each and every individual field. Even if known, the combinations would be too many to consider individually. Thus, a single rotation was sought that would be representative of the valley-wide cropping pattern. From available records, it was found that the dominant crops grown in the Imperial Valley during the period 1989–1996 were field crops (177,130 ha/year), followed by garden crops (48,626 ha/year) and permanent crops (9244 ha/year); totaling 235,000 ha/year. Among the field crops, alfalfa was dominant (77,320 ha/year) followed by wheat (30,840 ha/year). Among the garden crops, lettuce and cantaloupes dominated with 11,480 and 9615 ha/year, respectively. Consequently, a representative crop rotation would be alfalfa (grown for several consecutive years), followed by wheat and lettuce (or cantaloupes) in sequence. This rotation was selected as a basis for evaluating the various models for estimating LR for the Imperial Valley.

In order to determine the LR of a crop rotation, an appropriate schedule of irrigation and farming events must be established, along with the intervening amounts of ET, for the corresponding time periods. A schedule of events (i.e., planting and harvesting dates, dates and amounts of irrigation and rainfall, root development periods, mature root penetration depths, root water extraction patterns, stages of plant growth, and ET amounts for the period of the crop rotation) was developed for the 6-year crop rotation of alfalfa/alfalfa/alfalfa/alfalfa/wheat/lettuce. Imperial Water District reports

and data in Circulars 104-F and 104-V of the University of California Cooperative Extension for the Imperial Valley were used to develop the schedule (UCCE, 1996a,b), together with personal communications with Kalid M. Bali (Imperial Valley Farm Advisor, Irrigation/Water Science) and Marvin Jensen (Agricultural Consultant to the Bureau of Reclamation). These data were incorporated into a spreadsheet and used as the input data for the transient model simulations.

The resultant irrigation schedule was representative of irrigation practices in the Imperial Valley. Briefly, two irrigations occurred between cuttings of alfalfa; cuttings were made 6 days after the last previous irrigation; irrigations were resumed 12 days after each cutting. Thus, irrigations were scheduled about every 18 days during alfalfa production. For wheat, a pre-irrigation was followed by the first irrigation 45 days later and then about every 3 weeks thereafter until the ripening period began. Irrigation amounts were assumed to be 11.25 cm of water each time, except for pre-plant irrigations of 15 cm. For lettuce, 20 cm of irrigation water were applied 21 days before planting, 30 cm (spread over 3 days) were applied at planting time and, thereafter, about every 2 weeks until harvest in irrigation amounts of 11.25 cm of water each time. Some changes in the timings and amounts of irrigations were made after it was observed (during computer simulations) that the above described irrigations were either too infrequent (as occurred during alfalfa production) or too excessive (as occurred during wheat and lettuce production).

For purposes of estimating the crop evapotranspiration, ET_c (= $ET_0 K_{cb}$), crop coefficients (K_{cb}) were developed for each of the four growth stages based on values provided in the Imperial Water District reports. These coefficient values were modified on the advice of Marvin Jensen (personal communication) using Eq. (6.64) of ASCE Manual 70 to provide for the higher amounts of evaporation that occur from wet soil surfaces immediately after rain and irrigation events (Jensen et al., 1990). The values used for potential reference evapotranspiration (ET_0) are those obtained by multiplying the average daily values measured at the CIMIS-68 Station by the factor 1.05 (based on personal communications with Marvin Jensen).

Leaching will be more difficult to achieve while alfalfa is growing because of its high rate of ET, especially in the summer, and limited opportunities for irrigation caused by the numerous cutting, drying, and harvesting operations that occur. Thus, salinity would be more likely to accumulate to excessive levels during this period in the rotation. Since wheat is more tolerant of salinity than alfalfa, the required leaching will be less during its period of growth, assuming no extra leaching is needed to mitigate any excess build-up of salinity that occurs during alfalfa production, which is a question to be answered from the simulations. This, in turn, offers another opportunity for additional soil salinization to occur before lettuce production occurs. Lettuce is one of the more salt-sensitive crops grown in the Imperial Valley. Thus, the chosen rotation should provide an appropriate test of whether, or not, special reclamation leaching (i.e., leaching in addition to that considered in the LR) is typically needed in the Imperial Valley, or whether, or not, the leaching provided to all crops in the rotation should be that required by the most salt-sensitive crop grown in the rotation (i.e., lettuce in this case).

The conventional salt-tolerance data of Maas (1990), relating crop response to average root zone soil salinity, were used as the basis for estimating LR. The conventional salt-tolerance parameters (i.e., intercept and slope) for alfalfa, wheat, and lettuce are: 2.0 dS/m and 7.3% per dS/m increase in EC_e, 6.0 dS/m and 7.1%, and 1.3 dS/m and 13.0%, respectively (Maas, 1990). Alfalfa is classified as a moderately sensitive crop, wheat as a moderately tolerant crop, and lettuce as a moderately sensitive crop. Thus, the chosen rotation will require a relatively high degree of leaching because the preponderance of water-use is by relatively salt-sensitive crops. Less leaching would be required, if more salt-tolerant crops were grown or their proportional use of the total water supply was greater.

While soil properties do not directly affect the LR, they do affect it indirectly by influencing the leaching efficiency. Soil properties directly affect irrigation management since water holding capacity, infiltration rate, and hydraulic conductivity properties of soils establish the timing and duration limits of irrigation. The dominant soil series of the Imperial Valley in terms of area and surface permeabilities are as follows: Imperial (44%; 0.15–0.5 cm/h), Holtville (15%; 0.15–0.5 cm/h), Glenbar (15%; 0.5–1.5 cm/h), Indio (6%; 1.5–5 cm/h), Meloland (8%; 1.5–15 cm/h), Niland and Rositas (4%; 15–50 cm/h). The shrink–swell character of the Imperial soil is classified as high, of the Glenbar soil as moderate, of the Holtville soil as high to low, and of the others as low. The dominant soils of the Valley have low infiltration rates and moderate to high shrink–swell properties. For purposes of the computer simulations, the water holding and transmission properties of the soils were assumed to be similar to those of the dominant Imperial silty-clay and Holtville silty-clay soil types, as given in Perrier et al. (1974) and based on unpublished data from a lysimeter study using Imperial silty-clay soil taken from the Brawley Experiment Station in California's Imperial Valley: a dry-weight moisture content of 0.45 g/g at field-capacity, a dry-weight moisture content of 0.20 g/g at permanent wilting, a bulk density of 1.5 g/cm³, an average infiltration rate of about 0.33 cm/h, and a field-capacity/saturation percentage ratio of 0.5. The hydraulic properties used in the UNSATCHEM simulations were those estimated using the sub-routines contained within the program based on soils with similar permeabilities. The initial condition for the electrical conductivity of salt in soil solution through the soil profile was assumed to be 1.4, 2.0, 3.0, and 4.0 dS/m for the depth increments of 0–0.3, 0.3–0.6, 0.6–0.9, and 0.9–1.2 m, respectively.

An approximation of representative preferential flow for Imperial silty-clay soil was also obtained from the lysimeter study. An analysis of time domain reflectometry and an optimized fit of TETrans to tracer data from the study indicated that preferential flow was dominated by flow through surface cracks extending to depths ranging from 15 to 45 cm. The preferential flow through surface cracks occurred until the cracks were swollen closed, after which preferential flow was substantially reduced and subsequently dominated by flow through macropores scattered throughout the profile. The assumed depth of penetration for the surfaces cracks was set at 30 cm, representing the mid-point of the range of cracks found in the lysimeter study, which was assumed to be representative of the Imperial silty-clay soil.

The average salinity levels and compositions of the Colorado River during the period 1990–1996 were established using monthly compositional data supplied by Mark Niblack of the Bureau of Reclamation-Yuma, AZ office. The average EC value was 1.23 dS/m. The corresponding average values of major solute concentrations were: 5.89 mmol$_c$/L (Na), 0.13 mmol$_c$/L (K), 4.30 mmol$_c$/L (Ca), 2.70 mmol$_c$/L (Mg), 2.97 mmol$_c$/L (alkalinity), 3.42 mmol$_c$/L (Cl), and 6.29 mmol$_c$/L (SO$_4$).

4. Results of leaching requirement assessments

The results obtained with each method for determining LR are presented and discussed separately in this section. First, the steady-state methods are discussed for the traditional, WATSUIT, and WPF models, followed by the transient methods for TETrans and UNSATCHEM, and finally the results are compared. In all cases rainfall was ignored since rainfall in the Imperial Valley is so low.

4.1. Traditional model

As shown in Table 1, the LR values determined by the traditional method from Eq. (4) for the individual alfalfa, wheat, and lettuce crops are 0.14, 0.04, and 0.23, respectively, assuming the EC of the irrigation water (i.e., Colorado River) is 1.23 dS/m, and the tolerable levels of average root zone soil salinity are 2.0, 6.0, and 1.3 dS/m, respectively. The weighted average LR for the 6-year rotation during crop growth and the 6-year rotation during growth and overall rotation periods were 0.14 and 0.13, respectively, assuming the ET$_c$ values for alfalfa, wheat, and lettuce are 5273, 668, and 233 mm, respectively (Table 1). Additional irrigation water must be added to compensate for the amount of ET$_c$ (actually, for E) that occurs during unplanted periods and for the depletion

(with reference to field-capacity) of soil water that occurred during cropping. These LRs are based on uniform water infiltration across the field.

4.2. WATSUIT model

The estimated LR values are 0.09, 0.03, and 0.13 for the individual alfalfa, wheat, and lettuce crops, respectively (Table 2). The corresponding weighted LR values for the crop growth period and overall rotation period are estimated to be 0.09 and 0.08, respectively (Table 2).

The relationships between soil salinity, soil depth, and LF predicted using WATSUIT are shown in Fig. 1a. The soil salinity-depth distributions shown in Fig. 1a apply to a steady-state condition, such as would occur if the crop were to be grown continuously for a period of several years without interruption (i.e., perennial crops). Similar distributions occur after approximately 2 years of a 4-year cycle of alfalfa production, but not during the wheat and lettuce crops.

Fig. 1b and c show quite clearly that salt precipitation under steady-state conditions is a significant factor in reducing average soil salinity for this water composition. At steady-state, the soil water salinity will be predicted with WATSUIT to be reduced by salt precipitation by about 25% at a LF of 0.03, 20% at 0.05, 13% at 0.10, 9% at 0.15, and 5% at 0.20 (Fig. 1c). These removals of salt reduce the need for leaching. As shown in Tables 1 and 2 and Fig. 1b, the LR for alfalfa (EC$_e^*$ of 2.0 dS/m) is reduced from 0.14 to 0.09 by salt precipitation; the LR for lettuce (EC$_e^*$ of 1.3 dS/m) is reduced from 0.23 to 0.13, and the LR for wheat is reduced from 0.04 to about 0.03. The process of salt precipitation, in which the salts are made innocuous to plants and removed from the soil and drainage waters, significantly reduces the LR. To illustrate, the LR value for the crop rotation period obtained using the WATSUIT model is estimated to be about 0.08–0.09, compared to LR values of about 0.13–0.14 obtained using the traditional model.

Table 1 – Leaching requirements (LR) as determined by the traditional method					
Period	Leaching requirement estimates (traditional method)				
	ET$_c$[a] (mm)	LR[b]	V$_{iw}$[c] (mm)	V$_{dw}$[d] (mm)	Weighted LR
Alfalfa (Year 1)	1642	0.14	1909	267	
Alfalfa (Year 2)	1740	0.14	2023	283	
Alfalfa (Year 3)	1740	0.14	2023	283	
Alfalfa (Year 4)	1511	0.14	1757	246	
Wheat	668	0.04	699	31	
Lettuce	233	0.23	304	71	
Crop growth	7534		8715	1181	0.14[e]
Overall	7731		8912	1181	0.13[f]

[a] Crop evapotranspiration (ET$_c$) from Table A-2 (UCCE, 1996a).
[b] Leaching requirement (LR) obtained from Fig. 1b.
[c] Required irrigation, V$_{iw}$ = ET$_c$/(1 − LR).
[d] Required drainage, V$_{dw}$ = V$_{iw}$ − ET$_c$
[e] (Required drainage/required irrigation) during crop growth period.
[f] (Required drainage /required irrigation) during overall rotation period. Crop growth: 6-year rotation during crop growth period. Overall: 6-year rotation during crop growth and fallow periods. EC$_{iw}$: electrical conductivity of the irrigation water; EC$_e^*$: average electrical conductivity of the saturation extract for a given crop appropriate to the tolerable degree of yield reduction, generally 10%, and equivalent to the threshold electrical conductivity as defined by Maas (1990); V$_{iw}$: volume of irrigation water; V$_{dw}$: volume of drainage water.

Table 2 – Leaching requirements as determined by the WATSUIT model					
Period	Leaching requirement estimates (WATSUIT model)				
	ET_c[a] (mm)	LR[b]	V_{iw}[c] (mm)	V_{dw}[d] (mm)	Weighted LR
Alfalfa (Year 1)	1642	0.09	1804	162	
Alfalfa (Year 2)	1740	0.09	1912	172	
Alfalfa (Year 3)	1740	0.09	1912	172	
Alfalfa (Year 4)	1511	0.09	1660	149	
Wheat	668	0.03	685	17	
Lettuce	233	0.13	266	34	
Crop growth	7534		8239	706	0.09[e]
Overall	7731		8436	706	0.08[f]

[a] Crop evapotranspiration (ET_c) from Table A-2 (UCCE, 1996a).
[b] Leaching requirement (LR) obtained from Fig. 1b.
[c] Squared irrigation, $V_{iw} = ET_c/(1 - LR)$.
[d] Required drainage, $V_{dw} = V_{iw} - ET_c$.
[e] (Required drainage/required irrigation) during crop growth period.
[f] (Required drainage/required irrigation) during overall rotation period. Crop growth: 6-year rotation during crop growth period. Overall: 6-year rotation during crop growth and fallow periods. EC_{iw}: electrical conductivity of the irrigation water; EC_e^*: average electrical conductivity of the saturation extract for a given crop appropriate to the tolerable degree of yield reduction, generally 10%, and equivalent to the threshold electrical conductivity as defined by Maas (1990); V_{iw}: volume of irrigation water; V_{dw}: volume of drainage water.

4.3. Water-production-function model

The results obtained with the WPF model are summarized in Table 3. Simulations with the WPF model (data not shown) clearly indicated that relatively large increases in LF are required to obtain increases in yields greater than about 90% of the potential non-stressed yield. Thus, when using the WPF model to estimate LR, one should carefully consider water-use efficiency and economics in order to determine the most appropriate minimum value of LF to determine LR. Without benefit of such an analysis, we arbitrarily chose the LR values as the values of LF resulting in about 98% yield. The LR values are about 0.18, 0.04, and 0.23 for the individual crops of alfalfa, wheat and lettuce, respectively. The LR values for the entire crop rotation are 0.17 and 0.17 for the planted and overall periods (see Table 3).

4.4. TETrans model

In its present configuration, TETrans is designed to simulate solute transport in the root zone rather than to determine LR; consequently, the model requires considerable time to vary inputs to estimate LR. Because TETrans does not compute yield based on soil salinity, it must be used to estimate LR by iteratively running simulations using successively lower irrigation amounts (hence, reduced LF) until the predicted soil salinity reaches EC_e^*. The corresponding LF represents the LR. For the preceding operational limitation, TETrans was used to test whether the steady-state LRs determined from the traditional method would result in lower, comparable, or higher levels of soil salinity under transient conditions; consequently, irrigation timings and amounts for TETrans were adjusted to match those of the steady-state LRs

Table 3 – Leaching requirements as determined by the water-production-function model					
Period	Leaching requirement estimates (water-production-function model)				
	ET_c[a] (mm)	LR[b]	V_{iw}[c] (mm)	V_{dw}[d] (mm)	Weighted LR
Alfalfa (Year 1)	1642	0.18	2002	360	
Alfalfa (Year 2)	1740	0.18	2122	382	
Alfalfa (Year 3)	1740	0.18	2122	382	
Alfalfa (Year 4)	1511	0.18	1843	3329	
Wheat	668	0.04	696	28	
Lettuce	233	0.23	302	70	
Crop growth	7534		9087	1554	0.17[e]
Overall	7731		9284	1554	0.17[f]

[a] Crop evapotranspiration (ET_c) from Table A-2 (UCCE, 1996a).
[b] Leaching requirement (LR) calculated from Letey et al. (1985).
[c] Required irrigation, $V_{iw} = ET_c/(1 - LR)$.
[d] Required drainage, $V_{dw} = V_{iw} - ET_c$.
[e] (Required drainage/required irrigation) during crop growth period.
[f] (Required drainage/required irrigation) during overall rotation period. Crop growth: 6-year rotation during crop growth period. Overall: 6-year rotation during crop growth and fallow periods. EC_{iw}: electrical conductivity of the irrigation water; EC_e^*: average electrical conductivity of the saturation extract for a given crop appropriate to the tolerable degree of yield reduction, generally 10%, and equivalent to the threshold electrical conductivity as defined by Maas (1990); V_{iw}: volume of irrigation water; V_{dw}: volume of drainage water.
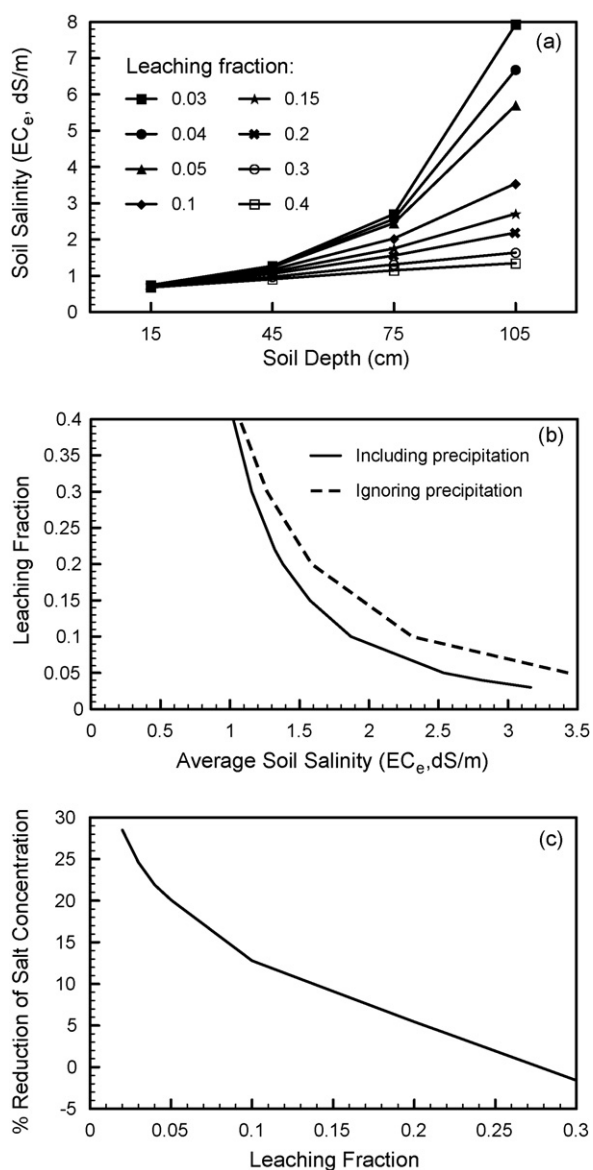
Fig. 1 – WATSUIT simulated results when irrigated with Colorado River Water: (a) soil salinity as a function of soil depth for various leaching fractions (LF), (b) average soil salinity (0–120 cm) with and without salt removal by precipitation as related to LF, and (c) percent reduction in salt concentration in soil water due to salt precipitation as a function of LF.

determined using the traditional method. Pre-season irrigations were given only in amounts sufficient to return the soil to field-capacity water content; no special irrigations, such as reclamation leachings, were included in the simulations. The cumulative LFs that actually were obtained in the simulations were 0.14, 0.04, and 0.17 for alfalfa, wheat, and lettuce, respectively. These results and their time trends are shown in Fig. 2. The simulations reveal that, when bypass is 40% or less, soil salinity is less than the threshold EC_e levels of each crop grown in the rotation, even though the LFs were based on steady-state traditional LR model. At most, the yield of alfalfa would be reduced by 1.5% during the first season. Even under

the extreme conditions of 80% bypass, alfalfa yield would be reduced by only 3% during the first year of production; no loss would occur in the next 3 years of production. Wheat yield would not be reduced under such extreme conditions of bypass; lettuce yield would be reduced no more than 5%. The results show that the LRs estimated from the steady-state traditional model are not too low, but they are probably too high.

The data also demonstrate that the simulated pre-season and early-season conventional irrigations were sufficient (i.e., reclamation was not needed) to provide the leaching needed to keep salinity from ever becoming excessive during the rotation period for the growth of these crops. This is due, in part, to the fact that the higher levels of salinity that develop over time are found in the lower depths of the soil profile (see Fig. 3). Thus, each successive crop is not exposed to the salts residing deeper in the soil profile, especially during crop establishment when the crops are most salt-sensitive but shallow in their rooting. Some of the salts accumulated during the production of each crop are subsequently leached out during the time when the pre- and early-season irrigations are applied to the following crop. During this period the soil is returned to field-capacity and essentially unavoidable leaching events occur because the soil permeability is the greatest during the period of the initial irrigations and more water must be applied with surface irrigation methods to get the water across the field. Excessive levels of soil salinity did not develop by prediction with the TETrans model under the assumed conditions of leaching (LF $\sim$ 0.14) even during the 4-year period of continuous alfalfa production.

The results presented in Figs. 2d–f and 3 clearly show that the relatively high levels of salinity that develop over time in the lower portion of the root zone are subsequently displaced to deeper depths and eventually out of the root zone as the subsequent crop is irrigated. The effect of bypass is also illustrated in these figures. The levels and distributions of soil salinity are not much affected by bypass up to at least 40%. This level of bypass slightly increases salinity levels in the relatively shallow soil profile depths in the early period of the crop season, but not enough to reduce yield. The predicted salinity levels when the bypass is very high (i.e., 80%) are higher, especially during the periods of wheat and lettuce production (see Fig. 2f). These levels are not high enough to reduce wheat yield, but they could slightly reduce lettuce growth during the early part of its growing season. While the extent of bypass occurring in the Imperial Valley soils has not been established, it is doubtful that it reaches the level of 80%. Thus, it is doubtful that crop yields would be reduced by the levels of soil salinity resulting under the conditions of simulated crop rotation, even considering the bypass phenomenon.

Simulations using TETrans show that the LRs of the crops in rotation are not greater than those estimated using the traditional model. This is because the estimate of LR by the traditional model is slightly more conservative than by TETrans, i.e., the maximum levels of salinity predicted to occur at steady-state do not result under transient conditions. Because TETrans does not account for salt precipitation, predictions of salinity distributions in the root zone are still higher than would be expected.
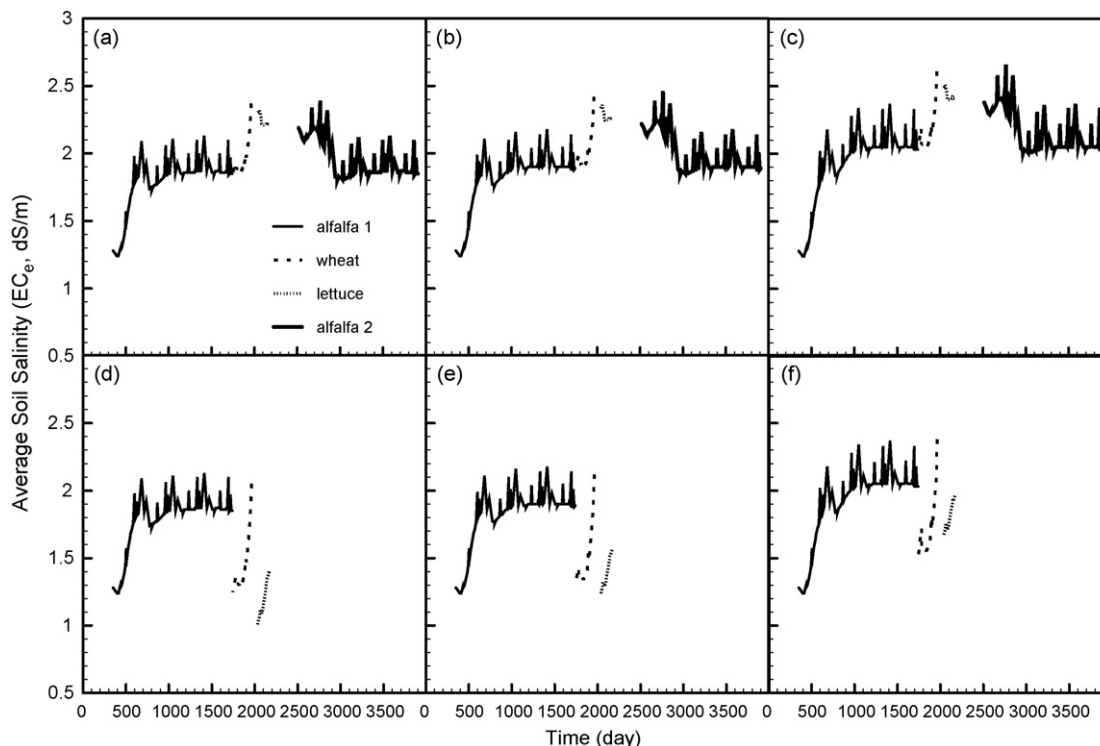
Fig. 2 – Time trend in average salinity (EC_e, dS/m) for the soil profile (0–120 cm) over the period of a 10-year cycle of crop rotation (a–c) and for the crop root zone (alfalfa: 0–120 cm, wheat: 0–90 cm, lettuce: 0–60 cm) over the period of a 6-year cycle of crop rotation (d–f) as predicted by TETrans for various levels of bypass: (a and d) 0% bypass, (b and e) 40% bypass, and (c and f) 80% bypass.

4.5. UNSATCHEM model

Similar to TETrans, simulations were made with UNSATCHEM for the purpose of evaluating whether soil salinity would become excessive during the transient conditions that occur under crop rotation, so as to require either a period of special reclamation or the adoption of the LR of the most salt-sensitive crop grown in the rotation. Several simulations were performed using UNSATCHEM. The first was undertaken using the same modified input as was employed in the TETrans simulations so that the results of the two models could be directly compared. In this simulation, pre-season irrigations were given to return the soil to field-capacity water content; otherwise no additional special irrigations, such as reclamation leachings, were included in the simulation. Because of salt precipitation, the salinity levels obtained with UNSATCHEM were always lower than the corresponding levels predicted by TETrans at bypass levels of 0 and 40%. The salinity levels were never yield limiting under the assumed conditions of irrigation and leaching. Thus, the LR values are concluded to be less than the LFs used in this simulation (i.e., 0.14, 0.05, and 0.17 for alfalfa, wheat, and lettuce, respectively). The results also showed that the salinity conditions that resulted at the end of the 4 successive years of alfalfa production were essentially the same in both the first and second cycles of the 6-year rotation; thus, those for wheat and lettuce would necessarily also be the same in both cycles. From these results, one can conclude that the ultimate

long-term conditions of salinity for the rotation under evaluation will be the same as those found in the second cycle of the rotation. These data further substantiate that the LR values estimated using the traditional model for the individual crops, as well as for the rotation, are conservative.

For the preceding reasons, another simulation was undertaken with UNSATCHEM assuming lower amounts of leaching could be used. The LR values obtained using the steady-state WATSUIT model (0.09 for alfalfa, 0.03 for wheat, and 0.13 for lettuce) were used in this simulation. The salinity levels predicted with UNSATCHEM for these conditions of leaching are given in Figs. 4–6. These results show that soil salinity is kept within essentially acceptable conditions during all periods of the crop rotation, without the provision of any special leaching or reclamation (see Fig. 4). The estimates of LR obtained with the steady-state WATSUIT model (0.09, 0.03 and 0.13 for alfalfa, wheat and lettuce, respectively) appear to provide reasonable estimates of LR for salinity control under transient conditions, as well. However, the LR values of 0.09 for alfalfa and of 0.13 for lettuce appear to be close to the minimum. The LR value of 0.03 for wheat is about as low as feasible, though the salinity level is still much below that tolerable by this crop.

The manner in which the distribution of salinity within the soil profile (0–120 cm) changes during the crop rotation is clearly shown in Figs. 5 and 6. The relatively low levels of salinity maintained within the root zones of these crops during most of their cropping seasons, especially in the upper
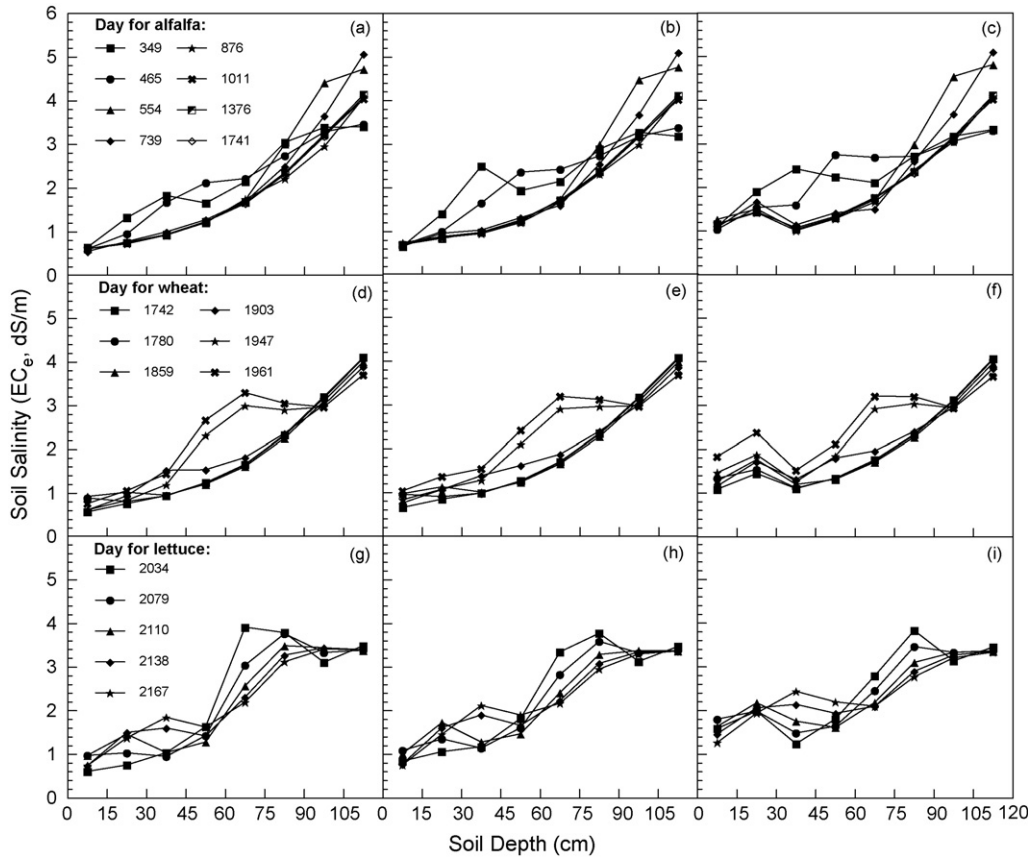
Fig. 3 – Soil salinity levels (EC_e, dS/m) by depth at selected times for alfalfa (a–c), wheat (d–f), and lettuce (g–i) as predicted by TETrans for various levels of bypass: (a, d, and g) 0% bypass, (b, e, and h) 40% bypass, and (c, f, and i) 80% bypass.

one-half of the root zones, clearly illustrates the adequacy of the simulated irrigation/leaching management for salinity control.

The amounts of irrigation, precipitation, crop ET (i.e., ET_c), and the levels of resulting leaching and deep percolation for each crop and for the entire rotation, as estimated from the input data and from UNSATCHEM, are summarized in Table 4

in three ways. The fraction of applied infiltrated water (precipitation + irrigation) that passed through the root zone (i.e., LF) over the entire period of the crop rotation was 0.08. Since no loss in yield was obtained under these conditions, it may be concluded that the LR may be as low (or possibly lower) as 0.08 for the overall crop rotation and about 0.10 for alfalfa, 0 for wheat, and 0.13 for lettuce.

5. Discussion of results

A summary of the values of LR obtained by the various methods is given in Table 5. Higher estimates were obtained using the WPF model for all crops and for the entire rotation period compared to the other two steady-state model (i.e., traditional and WATSUIT) and the two transient models (TETrans and UNSATCHEM). Although estimated LR from the traditional and WPF model were nearly comparable (i.e., the same for wheat and lettuce), WPF was higher for alfalfa and for the entire rotation. Among the steady-state models, it was anticipated that lower values would be obtained by WATSUIT because it accounts for the removal of salts by salt precipitation while the traditional and WPF models do not. However, the slightly higher values obtained with the WPF model relative to the traditional method were not anticipated. Some insight into the higher WPF model values is gained by examining the relationship between relative crop yield and
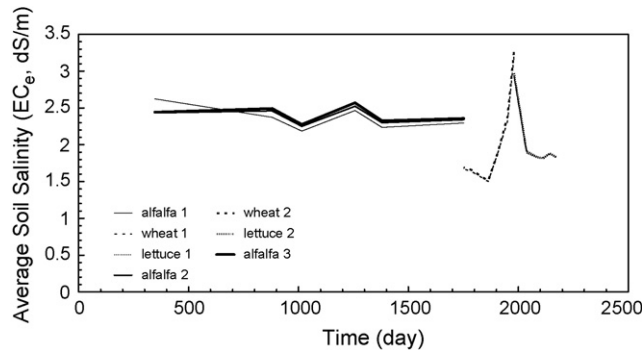

Fig. 4 – Time trends in average soil salinity of the crop root zone (alfalfa: 0–120 cm, wheat: 0–90 cm, lettuce: 0–60 cm) over the period of 16 years (i.e., 4 years of alfalfa, 1 year of wheat, 1 year of lettuce, 4 years of alfalfa, 1 year of wheat, 1 year of lettuces, and 4 years of alfalfa) as predicted by UNSATCHEM.
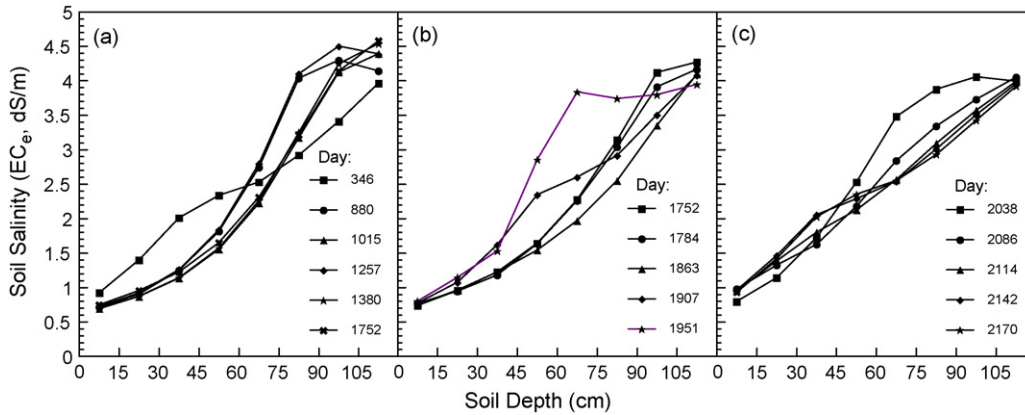
Fig. 5 – Soil salinity levels (EC$_e$, dS/m) by depth at selected times as predicted by UNSATCHEM for (a) alfalfa, (b) wheat, and (c) lettuce.

LF given from WPF simulations. First, relative losses in crop yields predicted by the WPF model are small (i.e., only ∼3–5%) at LF values equivalent to the LR values obtained by the traditional method. Second, maximum crop yields for the two salt-sensitive crops (i.e., alfalfa and wheat) are approached asymptotically as the LF increases. Essentially identical values of LR to those obtained by the traditional method can be obtained by the WPF model by substituting a more water-efficient value of acceptable relative crop yield, such as 95%, in place of the value of 98% that was used. This is easily justified, since relatively large increases in LF are required to obtain relatively small increases in crop yield, according to the WPF model. Furthermore, the LR values obtained with the WPF model at a 98% relative crop-yield reference are concluded to be too high because the levels of average root zone soil salinity predicted with TETrans (which used leaching amounts based on the LR values obtained with the traditional method) were below the threshold levels associated with the initiation of yield loss.

The traditional, WPF, and TETrans models are the most directly comparable of the various methods evaluated because they are based on the same water–salt balance relations and exclude the effects of salt precipitation. They allow a comparison of steady-state (i.e., traditional and WPF) and transient (i.e., TETrans) models. The notion that steady-state models over-estimate LR is supported, but only to a minor extent. Estimates of LR by steady-state models were found to be slightly conservative. The actual levels of root zone salinity will be slightly less than the predicted steady-state levels for the cases of annual crops and time-varying cropping since there is insufficient time to develop the maximum levels found under steady-state conditions, which result only after longer periods of continuous cropping, such as with perennial crops. This is supported by results obtained with the transient models, TETrans and UNSATCHEM.

The estimates of LR were significantly reduced when the effect of salt precipitation was included in the salt-balance calculations. For example, the LR for the overall crop rotation was reduced from 0.13 (traditional method) to 0.08 (WATSUIT method) by accounting for salt precipitation (Table 5). The magnitude of the effect of salt precipitation can be appreciated
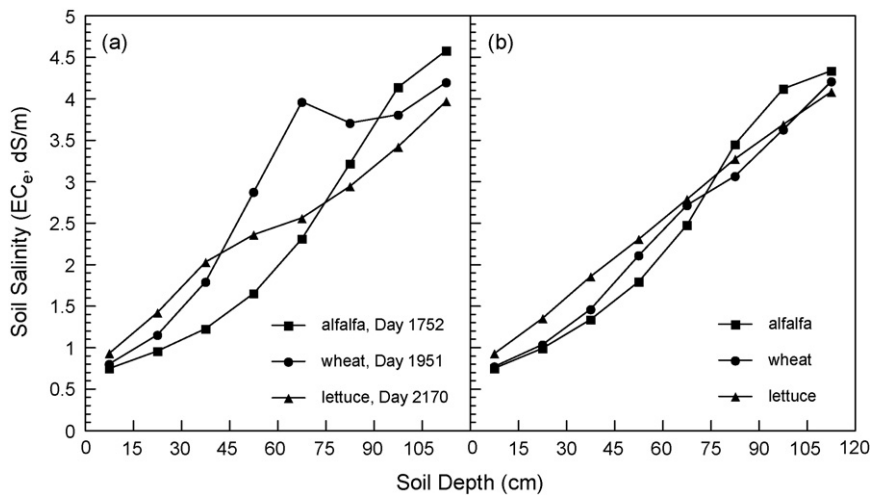

Fig. 6 – Soil salinity levels (EC$_e$, dS/m) by depth for alfalfa, wheat, and lettuce as predicted by UNSATCHEM for (a) single selected days late in each crop season (i.e., alfalfa: Day 1752, wheat: Day 1951, and lettuce: Day 2170) and (b) an average over the entire crop season (i.e., 4 years for alfalfa, 1 year for wheat, and 1 year for lettuce).

Table 4 – Estimates of deep percolation and leaching fraction (LF) obtained with the UNSATCHEM model

Time period	Crop	No. of days	Adjusted ET_c (cm)	Precipitation (cm)	Irrigation (cm)	ΔSW (cm)	DP (cm)	LF
Simple water balance results								
349–1752	alf	1403	668.8	25.4	714.8	0	71.4	0.10
1752–1980	wh	228	70.6	5.5	40.7	−14.7	−9.6	0
1980–2170	let	190	35.8	1.2	53.8	14.6	4.6	0.08
349–2170	rot	1821	775.2	32.1	809.4	0.1	66.4	0.08
Water balance data distributed between cropping and fallow periods								
349–1752	alf	1403	668.7	25.4	714.8	0	71.5	0.10
1752–1814	bare	62	3.8	1.8	6.2	0	4.2	0.53
1814–1980	wh	166	66.8	3.7	34.5	−14.7	−13.8	0
1980–2038	bare	58	6.1	0	20.6	14.7	−0.2	0
2038–2086	bare	48	9.4	0.6	10.3	0	1.5	0.14
2086–2170	let	84	20.4	0.6	23.0	0	3.2	0.14
349–2170	rot	1821	775.1	32.1	809.4	0	66.4	0.08
Water balance data, redistributed ascribing irrigations and consumptive use to the appropriate crop								
349–1814	alf	1465	672.5	27.2	721.0	0	75.7	0.10
1814–2038	wh	224	72.8	3.7	55.1	0	−14.0	0
2038–2170	let	132	29.8	1.2	33.2	0	4.7	0.14
349–2170	rot	1821	775.1	32.1	809.4	0	66.4	0.08

alf: alfalfa; wh: wheat; let: lettuce; rot: alfalfa/alfalfa/alfalfa/alfalfa/wheat/lettuce rotation; bare: fallow; ET_c: crop evapotranspiration; ΔSW: change in soil water content; DP: deep percolation: precipitation + irrigation-ET_c-change in soil water content.

Table 5 – Summary table of leaching requirements as estimated by various methods

Model	Tables[a]	Leaching requirement (LR)				
		Crop or cropping period				
		Alfalfa	Wheat	Lettuce	Crop growth[b]	Overall rotation[b]
Traditional	Table 1	0.14	0.04	0.23	0.14	0.13
WATSUIT	Table 2	0.09	0.03	0.13	0.09	0.08
WPF	Table 3	0.18	0.04	0.23	0.17	0.17
TETrans		<0.14	<0.04	<0.17		<0.13
UNSATCHEM	Table 4	<0.1	0	<0.13		<0.08

WPF: water-production-function model.
[a] Table number where data were obtained.
[b] Crop growth refers to period included in crop simulation and overall rotation includes entire rotation with fallow periods.

by comparing the EC_{dw} – LF relation obtained with the WPF model to that obtained with the WATSUIT model (Fig. 7). Simulated data from WATSUIT show that the concentration of soil water salinity is reduced by about 13 and 25% at LFs of 0.1 and 0.04, respectively, as a result of salt precipitation. The average soil salinity levels predicted with UNSATCHEM were essentially the same as those obtained with WATSUIT (Table 5). These two methods may be compared because both include salt precipitation, although WATSUIT assumes steady-state conditions while UNSATCHEM simulates transient conditions. Both models clearly show that with salt precipitation lower LR would be expected.

The predicted levels of salinity simulated by UNSATCHEM within the root zones of alfalfa, wheat, and lettuce never exceeded levels that would cause crop-yield losses at any time during the transient conditions of crop rotation. These and other results obtained with UNSATCHEM indicate that (i) reclamation and the use of less water than that estimated by the traditional LR method could control soil salinity in the alfalfa/wheat/lettuce crop rotation selected as representative
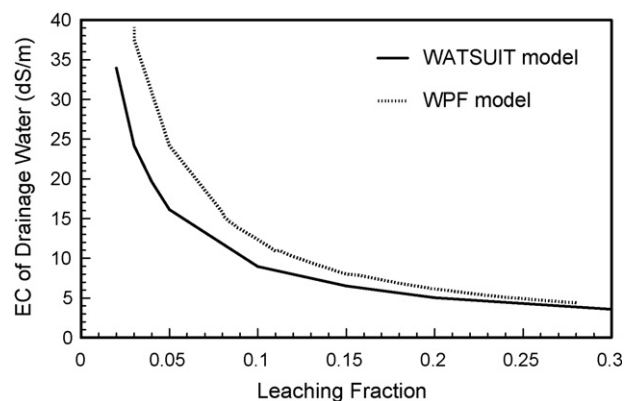

Fig. 7 – Comparison of simulated electrical conductivities (EC) of the drainage water as a function of leaching fraction for WATSUIT (salt precipitation) and water-production-function (WPF; no salt precipitation) models, showing the effect of salt precipitation on salinity levels in the drainage water.

of Imperial Valley conditions and (ii) the LR is lower than that determined using the traditional method.

6. Conclusions

The two transient models, TETrans and UNSATCHEM, estimated the LR to be lower than the traditional steady-state approach. The weakness of the traditional LR approach is that steady-state conditions seldom exist except over long time periods and processes such as preferential flow and precipitation–dissolution reactions are not taken into account. The difference between the traditional steady-state and transient approaches is expected and adds credence to the recommendation that any estimation of LR first consider the use of a transient model, particularly for research applications. The same general conclusion recommending the use of a transient over a steady-state approach for estimating LR was also found by Letey and Feng (this issue) when focusing on the influence of plant water uptake using the transient ENVIRO-GRO model compared to two steady-state models. Similarly, Schoups et al. (2006) demonstrated the need for transient modeling of salt leaching.

The small difference in the estimated LR between WATSUIT and UNSATCHEM shows that accounting for salt precipitation under conditions representative of the Imperial Valley was even more important than whether the model was a steady-state or transient. This suggests that in some instances accounting for all the dominant mechanisms influencing the leaching of salts may be nearly as important as capturing the temporal dynamics of the leaching process. This fact suggests that there may be certain instances where steady-state models can be used as long as the steady-state model accounts for all the dominant mechanisms (e.g., bypass flow, precipitation–dissolution reactions, plant water uptake, etc.) that are affecting the leaching of salts and there few or no perturbations that have occurred over a long time period that would prevent steady-state conditions or nearly so. For instance, in situations where precipitation–dissolution reactions are dominant and temporal dynamic effects are minimal, LR could be adequately estimated using WATSUIT. Or, in situations where irrigation water of quality and amount that minimized the temporal dynamic effects of plant water uptake, LR could be adequately estimated using the exponential water uptake, steady-state model by Hoffman and van Genuchten (1983).

Our findings indicate that the most rigorous method for determining LR is with UNSATCHEM except that it does not consider bypass. To apply this method on a valley-wide basis would require that the exact crop rotation practiced on each field within the entire Imperial Valley be known and that simulations be carried out for every one of these combinations. The overall weighted average of all these combinations and fields would provide the correct value of LR for the Imperial Valley. However, this approach is impractical. An alternative would be to determine the area of every crop and to estimate the LR for each crop using the WATSUIT model. The valley-wide LR would then be the weighted average of these crop areas and LRs or the weighted average of the yearly irrigation requirements of these crops. Jensen and Walter (1998) obtained a value of 0.14 for the entire Imperial Valley

using this latter approach and the traditional method of estimating LR for individual crops. In addition, field studies by Oster et al. (1986) showed a similar steady-state estimate of LR of 0.12. The LR value obtained herein for the representative crop rotation using the traditional method of estimating LR was 0.13. The three results are essentially the same.

Thus, the valley-wide LR can be reasonably estimated using the selected representative crop rotation and either the WATSUIT or UNSATCHEM models. Based on the results obtained with these models, a LR value of 0.08 is concluded to be reasonable for the entire Imperial Valley. This conclusion is based on the fact that both models predict that soil salinity will not accumulate to levels that would cause losses to any crop grown in rotation at the ascribed level of leaching. Furthermore, the 6-year crop rotation is made up of the dominant crops grown in the Imperial Valley and of crops that are dominantly salt-sensitive (i.e., alfalfa and lettuce). The LR would be proportionately lower, if the assessment was based on more salt-tolerant crops. The validity of a valley-wide LR of 0.08 is supported by the results of a field experiment carried out in the Imperial Valley in which a succession of crops were successfully grown in two different rotations (cotton/wheat/alfalfa and wheat/sugar beets/cantaloupes) with a LF of about 0.1, even while substituting water that was four-times as saline as Colorado River (i.e., Alamo River water) in place of Colorado River for between 30 and 50% of the total irrigation supply (Rhoades et al., 1989). The field studies by Bali and Grismer (2001) and Grismer and Bali (2001) also support the notion that a valley-wide LR for Imperial Valley of 0.08 is reasonable from results that showed no decrease in the yield of alfalfa and Sudan grass hay at a LF of 0.10 or less.

The salient points to be derived from the model simulations that are specific to the conditions representative of the Imperial Valley include: (i) for cracking soils representative of the Imperial Valley, preferential flow does not appear to be a significant factor influencing LR and (ii) salt precipitation is a primary factor reducing LR for the Imperial Valley. The implication is that reducing the estimated LR from 0.13 to 0.8 will reduce irrigation water needs that deplete scarce surface water supplies and will reduce drainage volumes that impact the environment when disposed. Each year an estimated 2.46×10^9 m^3 (2,000,000 ac-ft) of water infiltrates into the cropped soil of Imperial Valley; consequently, reducing the LR from 0.14 to 0.08 would reduce the drainage volume by approximately 1.23×10^8 m^3 (100,000 ac-ft).

However, there are cautionary notes that should be weighed when considering the practicality and validity of a valley-wide LR of 0.08 for the Imperial Valley. First, the effect of irrigation uniformity has not been addressed in this study nor has runoff been considered. The lack of irrigation uniformity caused by uneven application of irrigation water and/or within-field spatial variability results in a greater application of irrigation water to attain maximum yield. The issues of non-uniformity effects on LR are discussed in detail by Rhoades (1999). The inability to more precisely control the spatial distribution of irrigation application also causes runoff. However, site-specific irrigation technology may eventually overcome the problems of application distribution associated with flood irrigation and within-field spatial variability through site-specific, sprinkler irrigation. The use of level

basins may also ameliorate to some extent the non-uniformity of infiltration seen with flood irrigation. A second cautionary note pertains to the small effect of bypass on EC values, especially at deeper depths, suggesting that bypass will not significantly influence LR estimates. This is the consequence of the observation in soil lysimeters containing Imperial silty-clay soil that bypass primarily occurred between the soil surface to 30–45 cm below the surface, which may not be a realistic assumption in the field. The effect of bypass is small because it occurs only in the top 30 cm of the soil profile, where concentrations are relatively small and downward fluxes are large. Had the bypass been active in deeper layers, where concentrations are large and fluxes small, the effect would be significantly larger. Third, the ability to control a 0.05 reduction in leaching fraction will require a change from current irrigation management that results in significant runoff and will not be realized until more efficient site-specific irrigation management is adopted.

An inherent limitation in our LR model comparison using representative data is that it is an indicator and not a confirmation that transient models results are better. Confirmation that transient models provide a more robust estimation of LR than steady-state models can only be shown through more controlled experimental conditions. Our lower estimates of LR by transient models suggest the need for a reevaluation of the traditional means of estimating LR, but caution must be taken in regarding the transient model approach as the new paradigm until experimental data can provide direct evidence of its enhanced accuracy for determining LR since there still remain many issues that confound our knowledge of applying models, such as issues related to temporal and spatial scales, the complexities of uniformity of irrigation water application, and issues related to spatial variability, just to mention a few. However, this cautionary note should not preclude the use of transient models in place of steady-state models as a tool to help develop irrigation management guidelines and recommendations as long the transient models are not misused, which is an essential caveat. Furthermore, our cautionary note points to the need for continued field research to experimentally substantiate what has been theoretically postulated.

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