Leaching Requirement: Steady-State Versus Transient Models

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CHAPTER 26

LEACHING REQUIREMENT: STEADY-STATE VERSUS TRANSIENT MODELS

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INTRODUCTION

In the southwestern United States, irrigated agriculture is responsible for roughly 80% of the demand on surface and groundwater resources. Similar demand levels can be found in irrigated arid and semi-arid regions throughout the world. The sizable consumption of water to support irrigated agriculture is a growing concern, particularly in arid zone regions of the world. Greater scrutiny of irrigated agriculture's sizable demand on water resources grows as a consequence of water scarcity due to increased demand on finite water resources and increased frequency of drought conditions resulting from erratic weather attributable to climate change or alterations in historical weather patterns. Finite water resources that are stretched to their limits must be used judiciously. One means of diminishing demand on finite water resources is to decrease the volumes of irrigation water necessary to remove salts from the rootzone to maintain crop productivity.

Excess salts accumulate in the rootzone of arid and semi-arid irrigated soils largely as a result of the process of evapotranspiration (ET). In the ET process, plant roots remove pure water, thus concentrating any salts present in the irrigation water, resulting in salinity profiles that typically increase with depth, as shown in Fig. 26-1. The accumulated salts can cause a reduction in crop yields and even crop failure due to (1) osmotic effects that limit plant water uptake, (2) specific-ion toxicity effects (e.g., excess Na), (3) upsetting the plant nutrient balance (e.g., Ca in the presence of excess Na), and (4) salt composition effects [e.g., high sodium adsorption ratio (SAR) and low electrical conductivity (EC)] that influence soil physical properties such as soil permeability and tilth.

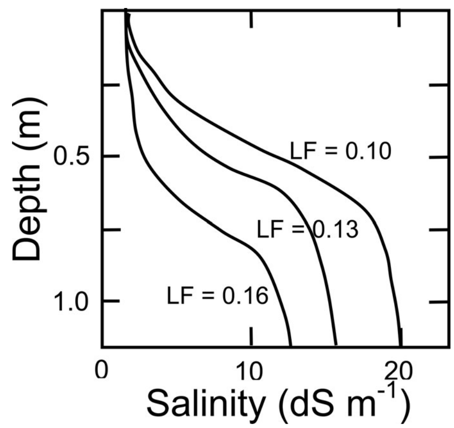

FIGURE 26-1. Typical salinity profiles resulting from the process of evapotranspiration (ET) for various leaching fractions (LFs).

The accumulation of excessive soluble salts in the rootzone, which threaten crop productivity on irrigated soils, can be prevented by applying water in excess of what is required to meet ET needs to leach excessive soluble salts. The water needed to remove excessive salts that cause a crop yield decrement is referred to as the leaching requirement (LR). Leaching requirement was originally defined as the fraction of infiltrated water that must pass through the rootzone to keep average rootzone soil salinity from exceeding a level that would significantly reduce crop yield, assuming steady-state conditions with associated good management and uniformity of leaching (U.S. Salinity Laboratory Staff 1954).

The original concept of LR developed by the U.S. Salinity Laboratory was based on the concept of leaching fraction (LF), where LF is defined as the fraction of the applied irrigation water that moves beyond the plant rootzone and represents the level of drainage and leaching of salts. As the LF increases, the level of leaching of salts increases and the salts accumulating in the rootzone decrease, which is graphically illustrated in Fig. 26-1. The LF is quantitatively defined by Eq. 26-1:

$$LF = \frac{D_{dw}}{D_{iw}} = \frac{EC_{iw}}{EC_{dw}} \tag{26-1}$$

where D_{dw} ($mm^3\ mm^{-2}$) and D_{iw} ($mm^3\ mm^{-2}$) are the unit depths 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 represents the lowest value of

LF that could be allowed without EC_{dw} (and thus, inferentially, soil salinity) becoming excessive for optimal 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. 26-1, resulting in Eq. 26-2, which is considered the original LR model:

$$LR = \frac{EC_{iw}}{EC^*_{dw}} \tag{26-2}$$

The LR is an estimate of what the LF must be to keep soil water salinity within tolerable limits for crop production. Equation 26-2 must still include a relationship between plant response and EC of the bottom of the rootzone.

Equation 26-2 only considers salt tolerance of the crop grown and salinity of the irrigation water while assuming steady-state conditions. Steady-state conditions do not exist under most field situations. In addition, LR is influenced by numerous factors, including irrigation nonuniformity, mineral precipitation-dissolution reactions, transient root water uptake distributions, preferential flow, climate, runoff, extraction of shallow groundwater, and leaching from effective precipitation, as well as the questionable appropriateness of the assumption of steady-state conditions. Based on the exclusion of these factors from consideration, recent publications by Corwin et al. (2007) and Letey and Feng (2007) have brought into question the appropriateness of Eq. 26-2 as a reasonable means of calculating LR, suggesting that a new paradigm may be needed, particularly for research applications.

The questionable ability of Eq. 26-2 to accurately calculate LR stems from (1) the assumption of steady state, and (2) influencing factors that are not taken into account. Steady state occurs when water content and salt concentration remain constant over time at a given soil depth. The assumption of steady state is probably not reasonable in most situations, particularly over short time periods of a few years or less, because both water content and salinity continuously change over time within the rootzone due to the extraction of water by roots and replenishment by irrigation and precipitation. In addition, several factors can cause perturbations to steady-state conditions, including a change in the crop, variation in irrigation water quality, alteration in irrigation management, and transient water uptake by plant roots. Furthermore, osmotic and matric effects on roots will cause plants to uptake water from that area of the rootzone where the least energy is expended to extract water. The dynamic uptake of water by roots enables a greater ability to tolerate average rootzone salinities higher than the plant's salt-tolerance values, which are experimentally derived from the linearly averaged rootzone EC of the saturation extract (EC_e) of high-LF experiments producing nearly uniform rootzone salinity. By accounting for the transient uptake of water by roots, the LR will be lower than that calculated by Eq. 26-2.

Aside from not considering transient conditions, other factors that influence LR are often not taken into account. Depending on the chemical composition of the irrigation water and the minerals present in the soil, salts in the soil water can precipitate or minerals in the soil can dissolve, resulting in changes in the salinity in the soil water. A low LF will increase the salt concentration in the soil water, increasing the likelihood of salt precipitation. The original LR method (i.e., Eq. 26-2) ignores the chemical process of salt precipitation which can, in some cases, significantly reduce levels of soil salinity within the rootzone. The failure to account for precipitation can lead to an overestimation of the LR, whereas the failure to account for dissolution reactions will have the opposite effect. Climatic factors such as humidity can, in some cases, increase a plant's salt tolerance, which will lower the LR. The original LR method does not account for preferential flow, which influences water flow and the efficiency of salt leaching, resulting in an increase in LR. Runoff reduces the volume of infiltrating water, which reduces the leaching of salts raising the LR. If the plant can extract water from the groundwater, then salts accumulating in the rootzone have less of an effect, thereby lowering the LR. Leaching from effective precipitation will lower the volume of water necessary to remove salts from the rootzone, thereby lowering the LR. Furthermore, the estimation of LR does not include (1) the manner in which spatiotemporal variation in salinity within the rootzone affects crop response and water uptake, (2) scale issues, (3) horizontal leaching and subsequent redistribution of salts for cracking soils when flood irrigation is used, (4) basing the LR on the most salt-sensitive crop in a crop rotation, and (5) uncertainties in salt-tolerance data developed from experimental plots when applied to field situations. Some of these have been discussed in Rhoades (1999).

It is also noteworthy that LR does not provide sufficient information concerning optimal irrigation because optimal irrigation is the amount of water that maximizes profit, and maximum profit may not coincide at all times with maximum yield (Letey et al. 1985). The relationship between crop yield and seasonal amount of water required is essential to determine the optimal irrigation management (Letey et al. 1985). For this reason, crop-water production functions have been advocated as a means of determining the economically optimal 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 United States and many other irrigated arid and semi-arid regions of the world.

Transient models enable the simulation of complex processes with time-dependent variables. The development of transient models has been primarily facilitated by the development of high-speed computers. To evaluate the appropriateness of a steady-state approach for estimating LR, Corwin et al. (2007) compared a variety of steady-state and transient LR models to determine whether differences existed, the extent of the differences, and the reasons for the differences, and to analyze the implications of the differences with respect to irrigation management and salinity control. A compilation of the most significant results of Corwin et al. (2007) is presented below.

GENERAL DESCRIPTION OF MODELS USED TO ESTIMATE LEACHING REQUIREMENT

Four models are compared to evaluate the appropriateness of steady-state versus transient conditions and to evaluate the significance of precipitation-dissolution reactions, transient water uptake by roots, and preferential flow to the estimation of LR. Each is considered to have potentially significant effects on LR for the fine-textured soils of the arid southwestern United States. The four models selected to compare and contrast their estimation of LR are (1) the traditional LR model, which is a~~n~~ LR model by Rhoades (1974) based on the original LR developed by the U.S. Salinity Laboratory Staff (1954), (2) *WATSUIT* (Rhoades and Merrill 1976), (3) *TETrans* (Corwin and Waggoner 1990a,b; Corwin et al. 1990), and (4) *UNSATCHEM* (Šimůnek and Suarez 1994). These models reflect a spectrum of categories of models ranging from steady-state to transient models and from functional to mechanistic, which provide potential insight into the influence of physical and chemical processes on the estimation of LR. The traditional LR and *WATSUIT* models are steady-state models, whereas *TETrans* and *UNSATCHEM* are transient models. The *WATSUIT* and *UNSATCHEM* models account for precipitation and dissolution reactions but the traditional LR and *TETrans* models do not. The *UNSATCHEM* model determines ET and plant yield as a function of matric and osmotic stresses, while the traditional LR model, *WATSUIT*, and *TETrans* do not. Finally, *TETrans* is the only model within the group that accounts for preferential flow. Table 26-1 provides a summary of the four models, which includes the type of model (steady-state or transient) and the processes included in the model (salt effects on plant growth, osmotic and matric effects on root water uptake, precipitation-dissolution reactions, and preferential flow).

Steady-State Leaching Requirement Models

Steady-state LR models are based on simple salt-balance concepts and an assumption of long-time average conditions that will result in steady state.

TABLE 26-1. Summary of Leaching Requirement Model Type and Processes Included in Each Model

	Type of Model		Processes Included in Model			
Leaching Requirement Model (1)	Steady-State Model (2)	Transient Model (3)	Salt Effects on Plant Growth and Evapo-transpiration (4)	Osmotic and Matric Effects on Plant Water Uptake (5)	Precipitation-Dissolution Reactions (6)	Preferential Flow (7)
Traditional	X					
WATSUIT	X				X	
TETrans		X				X
UNSATCHEM		X	X	X	X	

Traditional model

The determination of LR, as originally formulated in Eq. 26-2, required the selection of the appropriate value of EC^*_{dw} for the crop in question. Such crop-related values were not known. However, data obtained from salt tolerance studies conducted in test plots utilizing relatively uniform soil conditions and optimal irrigation and crop management were available at that time (Bernstein 1974; Maas and Hoffman 1977). These studies related the response of many crops to average rootzone soil salinity in terms of the 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 rootzone 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. 26-2 to estimate LR. No direct evidence supports the appropriateness of this substitution or the corresponding LR values, nor is there any direct evidence to support the assumption that plants respond primarily to average rootzone soil salinity.

Based on empirical distribution of soil salinity by depth, Rhoades (1974) introduced a procedure for approximating values of EC^*_{dw} for use in Eq. 26-2 using Eq. 26-3:

$$EC^*_{dw} = 5\ EC^*_e - EC_{iw} \tag{26-3}$$

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. 26-3 into Eq. 26-2 yields Eq. 26-4, which has become referred to as the traditional LR model:

$$LR = \frac{EC_{iw}}{5EC_e^* - EC_{iw}} \tag{26-4}$$

Equation 26-4 ties LR to irrigation water salinity and crop tolerance. 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.

WATSUIT

In contrast to the traditional steady-state model previously described, *WATSUIT* considers the chemical composition of the irrigation water [i.e., major cations and anions and presence or absence of soil lime ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$)] and includes the processes of mineral precipitation (salt deposition) and mineral weathering (salt pickup). The assumption is made that plant water uptake occurs from successively deeper quartile-fractions of its rootzone in the ratios of 40/30/20/10. The concentrations of the major cations and anions in the soil water within an irrigated rootzone are predicted at equilibrium by *WATSUIT* as a function of the irrigation water composition, quartile 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 rootzone 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.

The effect of salinity on ET (mm) is not taken into account. It is assumed that there will be no loss in yield due to salinity and, concomitantly, no loss in ET, provided the average rootzone 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. Further details regarding *WATSUIT* can be found in Rhoades and Merrill (1976).

Transient Leaching Requirement Models

Steady-state conditions are the exception rather than the rule. Perturbations to the system result in transient conditions that can reduce the general applicability of the traditional LR model approach, rendering a temporal tracking of the system with transient approaches more appropriate.

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 rootzone (Corwin et al. 1990; Corwin and Waggoner 1990a,b). In *TETrans*, transport through the rootzone 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 an integration of simultaneous processes. Other assumptions include (1) the soil is composed of a finite series of discrete depth intervals with each depth interval having homogeneous properties, (2) drainage occurs through the profile to a depth-variable field capacity water content, (3) the depletion of stored water by ET within each depth increment does not go below a minimum water content that will stress the plant, (4) dispersion is either negligible or part of the phenomenon of bypass, and (5) 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 of California). 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, which requires additional water to leach the salts, thereby increasing the LR.

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). Additional details regarding *TETrans* can be found in Corwin et al. (1990).

UNSATCHEM

The *UNSATCHEM* model is a sophisticated mechanistic, 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 rootzones, 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, ET, 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 (mineral) 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. Additional details regarding *UNSATCHEM* can be found in Šimůnek and Suarez (1994) and Šimůnek et al. (1996).

MODEL INPUTS

In order to estimate LR using the previously described steady-state and transient models, a database is needed for the following: climate, crops grown, crop rotations, soil physical and chemical properties related to solute transport (e.g., soil salinity initial conditions, field capacity, wilting point, bulk density, infiltration rate, texture, and hydraulic conductivity properties), irrigation management practices, drainage conditions, irrigation scheduling and amounts, ET, root water uptake, irrigation water composition, crop salt-tolerance parameters, and a schedule of events (e.g., planting and harvesting dates, dates and amounts of irrigation and rainfall, root development, mature root penetration depths, root water extraction patterns, and stages of plant growth). For comparative analysis a set of realistic conditions representative of California's Imperial Valley was developed and was used as input for the LR models. Details describing the development of the dataset from available data sources can be found in Corwin et al. (2007).

To estimate the LR for the entire Imperial Valley, a primary consideration is the crop sequence grown. 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, with alfalfa as the most dominant field crop, followed by wheat. Next, the garden crops were dominant, with lettuce as the most-grown garden crop. Consequently, a representative crop rotation for the Imperial Valley is a 6-year crop rotation consisting of 4 years of alfalfa, followed by 1 year of wheat and 1 year of lettuce in sequence (i.e., alfalfa/alfalfa/alfalfa/alfalfa/wheat/lettuce). This rotation was selected as a basis for evaluating the various models for estimating LR for the Imperial Valley.

MODEL LEACHING REQUIREMENT ESTIMATES

As shown in Table 26-2, the LR values determined by the traditional method from Eq. 26-4 for the individual alfalfa, wheat, and lettuce crops are 0.14, 0.04, and 0.23, respectively, assuming the EC of the irrigation water (the Colorado River) is 1.23 dS/m, and the tolerable levels of average rootzone 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 only and the 6-year rotation during growth and fallow periods (referred to as the overall rotation period) were 0.14 and 0.13, respectively, assuming the ET_c [estimated crop evapotranspiration = ET_0K_{cb}, where ET_0 is the potential reference evapotranspiration (mm) and K_{cb} is the crop coefficient] values for alfalfa, wheat, and lettuce are 5,273, 668, and 233 mm, respectively (Table 26-2). The overall rotation period refers to the growth period of all the crops plus all fallow periods between crops. Additional irrigation water must be added to compensate for the amount of ET_c (actually, for evaporation only) that occurs during unplanted periods and for the depletion (with reference to field capacity) of soil water that occurred during cropping.

The estimated LR values from *WATSUIT* are 0.09, 0.03, and 0.13 for the individual alfalfa, wheat, and lettuce crops, respectively (Table 26-3). 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 26-3).

TABLE 26-2. Leaching Requirements (LR) as Determined by the Traditional Method

Leaching Requirement Estimates (Traditional Method)					
Period (1)	ET_c[a] (mm) (2)	LR[b] (3)	D_{iw}[c] (mm) (4)	D_{dw}[c] (mm) (5)	Weighted LR (6)
Alfalfa (Year 1)	1,642	0.14	1,909	267	
Alfalfa (Year 2)	1,740	0.14	2,023	283	
Alfalfa (Year 3)	1,740	0.14	2,023	283	
Alfalfa (Year 4)	1,511	0.14	1,757	246	
Wheat	668	0.04	699	31	
Lettuce	233	0.23	304	71	
Crop growth	7,534		8,715	1,181	0.14[e]
Overall	7,731		8,912	1,181	0.13[f]

[a]Crop evapotranspiration (ET_c) from Table A-2 in UCCE (1996).
[b]Leaching requirement (LR) calculated from $LR = EC_{iw}/(5EC_e^* - EC_{iw})$.
[c]Required irrigation, $D_{iw} = ET_c/(1 - LR)$.
[d]Required drainage, $D_{dw} = D_{iw} - ET_c$.
[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
D_{iw} = unit depth of irrigation water ($mm^3\ mm^{-2}$)
D_{dw} = unit depth of drainage water ($mm^3\ mm^{-2}$)

From Corwin et al. (2007) with permission.

Figure 26-2a,b shows quite clearly from *WATSUIT* simulations 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 an LF of 0.03, 20% at LF 0.05, 13% at LF 0.10, 9% at LF 0.15, and 5% at LF 0.20 (Fig. 26-2b). These depositions of salt reduce the need for leaching. As shown in Tables 26-2 and 26-3 and Fig. 26-2b, 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 to 0.09,

TABLE 26-3. Leaching Requirements as Determined by the *WATSUIT* Model

Leaching Requirement Estimates (*WATSUIT* Model)					
Period (1)	ET_c[a] (mm) (2)	LR[b] (3)	D_{iw}[c] (mm) (4)	D_{dw}[d] (mm) (5)	Weighted LR (6)
Alfalfa (Year 1)	1,642	0.09	1,804	162	
Alfalfa (Year 2)	1,740	0.09	1,912	172	
Alfalfa (Year 3)	1,740	0.09	1,912	172	
Alfalfa (Year 4)	1,511	0.09	1,660	149	
Wheat	668	0.03	685	17	
Lettuce	233	0.13	266	34	
Crop growth	7,534		8,239	706	0.09[e]
Overall	7,731		8,436	706	0.08[f]

[a]Crop evapotranspiration (ET_c) from Table A-2 in UCCE (1996).
[b]Leaching requirement (LR) obtained from Fig. 26-1b.
[c]Required irrigation, $D_{iw} = ET_c/(1 - LR)$.
[d]Required drainage, $D_{dw} = D_{iw} - ET_c$.
[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.
D_{iw} = unit depth of irrigation water ($mm^3\ mm^{-2}$)
D_{dw} = unit depth of drainage water ($mm^3\ mm^{-2}$)

Taken from Corwin et al. (2007) with permission.

compared to LR values of about 0.13 to 0.14 obtained using the traditional LR model.

The *TETrans* model 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 determined using the traditional method. Preseason irrigations were given only in amounts sufficient to return the soil to field-capacity water content; no special irrigations, such as reclamation leaching, 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, and an overall rotation LR of less than 0.13. These results and their time trends are shown in Fig. 26-3. The simulations reveal that, when bypass is 40% or less, soil

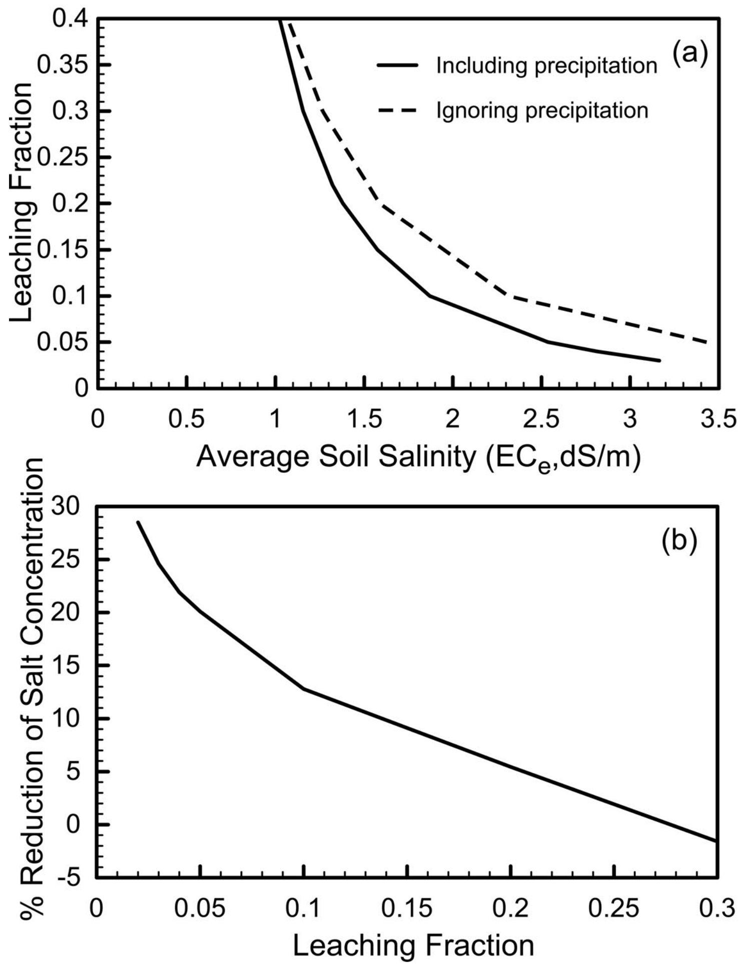

FIGURE 26-2. WATSUIT-*simulated results when irrigated with Colorado River water. (A) average soil salinity (0–120 cm) with and without salt removal by precipitation as related to LF, and (B) percent reduction in salt concentration in soil water due to salt precipitation as a function of LF. From Corwin et al. (2007) with permission.*

salinity is less than the threshold EC_e levels of each crop grown in the rotation, even though the LFs were based on the 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

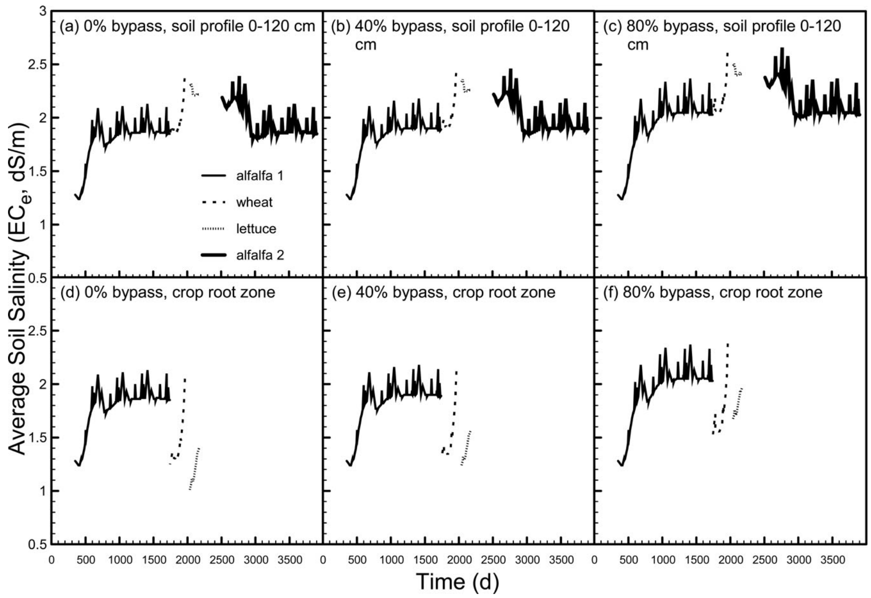

FIGURE 26-3. Time trend in average salinity (EC_e, dS/m) for the soil profile (0–120 cm) over the period of a 10-year cycle of crop rotation (A–C), and for the crop rootzone (alfalfa: 0–120 cm, wheat: 0–90 cm, lettuce: 0–60 cm) over the period of a 6-year cycle of crop rotation (D–F) as predicted by TETrans *for various levels of bypass: (A and D) 0% bypass, (B and E) 40% bypass, and (C and F) 80% bypass. From Corwin et al. (2007) with permission.*

be reduced under such extreme conditions of bypass; lettuce yield would be reduced by 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 results presented in Figs. 26-3d–f and 26-4 show that the relatively high levels of salinity that develop over time in the lower portion of the rootzone are subsequently displaced to deeper depths and eventually out of the rootzone 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 (~80%) are higher, especially during the periods of wheat and lettuce production (see Fig. 26-2f). These levels are not high enough to reduce wheat yield

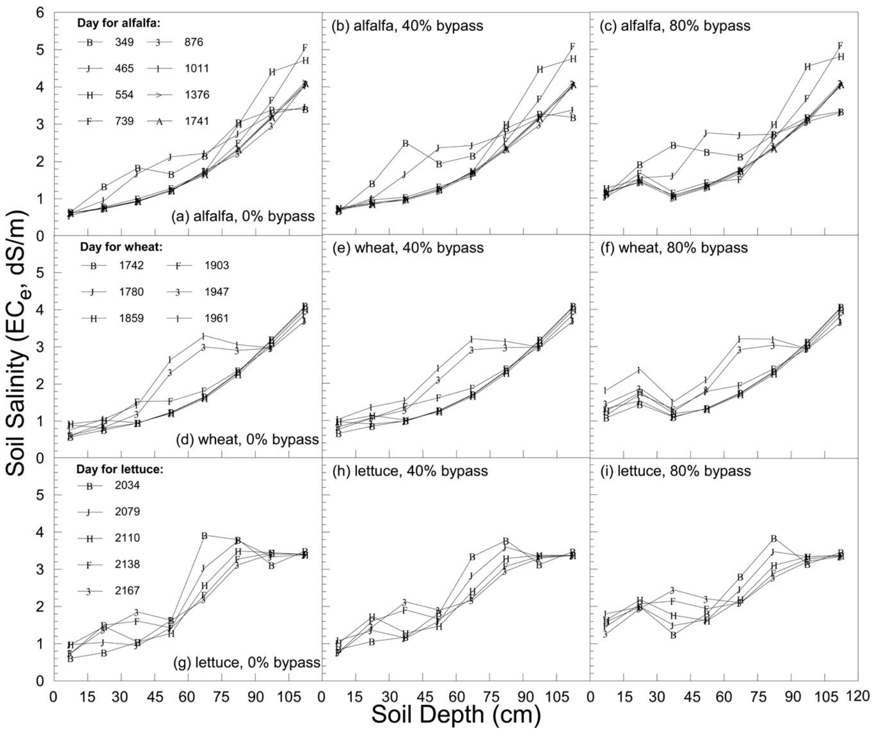

FIGURE 26-4. Soil salinity levels (EC_e, dS/m) by depth at selected times for alfalfa (A–C), wheat (D–F), and lettuce (G–I) as predicted by TETrans *for various levels of bypass: (A, D, and G) 0% bypass, (B, E, and H) 40% bypass, and (C, F, and I) 80% bypass. From Corwin et al. (2007) with permission.*

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*, that is, 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 rootzone are still higher than would be expected.

The amounts of irrigation, precipitation, crop ET (i.e., ET_c), and the levels of resulting leaching and deep percolation predicted from *UNSATCHEM* for each crop and for the entire rotation are summarized in Table 26-4. The LRs estimated from *UNSATCHEM* are 0.10 for alfalfa, 0 for wheat, 0.13 for lettuce, and an overall rotation LR of less than 0.08. The estimates of LR obtained with the steady-state *WATSUIT* model (i.e., 0.09, 0.03, and 0.13 for alfalfa, wheat and lettuce, respectively, and an overall rotation LR of 0.08) appear to provide estimates of LR for salinity control as reasonable as those of the transient model *UNSATCHEM*. 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 as determined by *UNSATCHEM* is still much below that tolerable by this crop. 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.

The manner in which the distribution of salinity within the soil profile (0–120 cm) changes during the crop rotation is shown in Figs. 26-5 and 26-6. The relatively low levels of salinity maintained within the rootzones of these crops during most of their cropping seasons, especially in the upper half of the rootzones, illustrates the adequacy of the simulated irrigation/leaching management for salinity control.

TABLE 26-4. Estimates of Deep Percolation and Leaching Fraction (LF) Obtained with the *UNSATCHEM* Model

Time Period (Day Numbers) (1)	Crop (2)	No. of Days (3)	Adjusted ET_c (cm) (4)	Precipitation (cm) (5)	Irrigation (cm) (6)	ΔSW (cm) (7)	DP (cm) (8)	LF (9)
349−1814	alf	1,465	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	1,821	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

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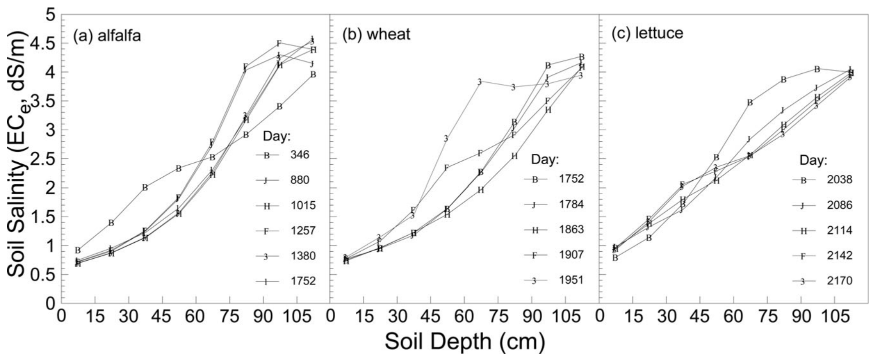

FIGURE 26-5. Soil salinity levels (EC_e, dS/m) by depth at selected times as predicted by UNSATCHEM *for (A) alfalfa, (B) wheat, and (C) lettuce. From Corwin et al. (2007) with permission.*

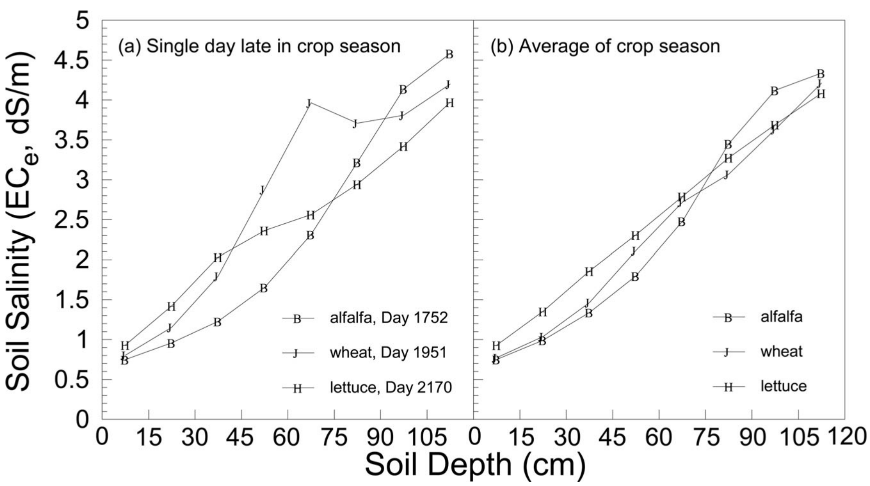

FIGURE 26-6. Soil salinity levels (EC_e, dS/m) by depth for alfalfa, wheat, and lettuce as predicted by UNSATCHEM *for (A) single selected days late in each crop season (i.e., alfalfa: Day 1752, wheat: Day 1951, and lettuce: Day 2170); and (B) an average over the entire crop season (i.e., 4 years for alfalfa, 1 year for wheat, and 1 year for lettuce). From Corwin et al. (2007) with permission.*

IMPLICATIONS OF LEACHING REQUIREMENT MODEL ESTIMATES

A summary of the values of LR obtained by the various methods is given in Table 26-5. Comparing steady-state models to transient models supports the notion that steady-state models overestimate LR, but only to a minor extent. Estimates of LR by steady-state models were found to be slightly conservative. The steady-state traditional model and transient *TETrans* model are directly comparable because they are based on the same water-salt balance relations and exclude the effects of salt precipitation. Similarly, the steady-state model *WATSUIT* is directly comparable to the transient model *UNSATCHEM* since both take mineral precipitation-dissolution reactions into account. In both comparisons, there is only a slight difference in estimated LRs (see Table 26-5). The actual levels of rootzone 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.

The estimates of LR were significantly reduced when the effect of salt precipitation was included in the salt-balance calculations, regardless of whether the model was steady-state or transient. For example, the LR for

TABLE 26-5. Summary Table of Leaching Requirements as Estimated by Various Methods

		Leaching Requirement (LR)				
		Crop or Cropping Period				
Model (1)	Table[a] (2)	Alfalfa (3)	Wheat (4)	Lettuce (5)	Crop Growth[b] (6)	Overall Rotation[c] (7)
Traditional	26-2	0.14	0.04	0.23	0.14	0.13
WATSUIT	26-3	0.09	0.03	0.13	0.09	0.08
TETrans	Corwin et al. (2007)	<0.14	<0.04	<0.17	<0.13	
UNSATCHEM	26-4	<0.1	0	<0.13	<0.08	

[a]Table number in this chapter where data were obtained.
[b]Crop growth refers to period included in crop simulation.
[c]Overall rotation includes entire rotation with fallow periods.

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the overall crop rotation was reduced from 0.13 for the traditional model to 0.08 for the *WATSUIT* method by accounting for salt precipitation (Table 26-5). 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 (Fig. 26-2b). The average soil-salinity levels predicted with the transient *UNSATCHEM* model were essentially the same as those obtained with the steady-state *WATSUIT* model (Table 26-5). Both models clearly show that with salt precipitation lower LR would be expected.

The predicted levels of salinity simulated by *UNSATCHEM* within the rootzones 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 (1) 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 of Imperial Valley conditions, and (2) the LR is lower than that determined using the traditional method.

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 (2007) when focusing on the influence of plant water uptake using the transient *ENVIRO-GRO* model compared to two steady-state models.

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 more important than whether the model was a steady-state or transient model. 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 models account for all the dominant mechanisms (e.g., bypass flow, mineral precipitation-dissolution reactions, plant water uptake) that are affecting the leaching of salts and that 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 the irrigation water ~~of~~ quality and amount 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).

Using the area of every crop and an estimate of the LR for each crop with the traditional model to obtain a valley-wide LR based on the weighted average of the crop areas and LRs, Jensen and Walter (1998) obtained a~~n~~ LR value of 0.14 for the entire Imperial Valley. In addition, field studies by Oster et al. (1986) showed a similar steady-state estimate of LR of 0.12. The LR value obtained from Corwin et al. (2007), as discussed herein for the representative Imperial Valley crop rotation using the traditional method of estimating LR, was 0.13. The three results are essentially the same.

However, the valley-wide LR is more accurately estimated using the selected representative crop rotation and either the *WATSUIT* or *UNSATCHEM* model. Based on the results obtained with these models, a~~n~~ 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 (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~~n~~ LF of about 0.1, even while substituting water that was four times as saline as Colorado River water (i.e., Alamo River water) in place of Colorado River for 30% to 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 the Imperial Valley of 0.08 is reasonable from results that showed no decrease in the yield of alfalfa and Sudan grass hay at a~~n~~ LF of 0.10 or less.

The salient points to be derived from the LR model simulations that are specific to the conditions representative of the Imperial Valley include: (1) for cracking soils representative of the Imperial Valley, preferential flow does not appear to be a significant factor influencing LR; and (2) salt precipitation is a primary factor for reducing LR for the Imperial Valley. The implication is that reducing the estimated LR from 0.13 to 0.08 will reduce irrigation water needs that deplete scarce surface-water supplies and will reduce drainage volumes that affect the environment when disposed. Each year an estimated 2.46×10^9 m^3 (2 million 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, cautionary notes 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 nonuniformity 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 nonuniformity 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 Valley silty-clay soil that bypass primarily occurred from the soil surface to 30 to 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 LF 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 the LR model comparison by Corwin et al. (2007), using representative data, is that it is an indicator but 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 considering the transient model approach as the new paradigm until experimental data can provide direct evidence of its enhanced accuracy for determining LR. Many issues still remain 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 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 as the transient models are not misused, which is an essential caveat.

SUMMARY

Calculations of the LR and LF can be made using a number of either steady-state or transient models, each of which describes one or more of the following processes:

- Salt effects on plant growth and ET
- Osmotic and matric effects on plant water uptake
- Precipitation-dissolution reactions
- Preferential flow

Each of the four models described produces a different LR. The original or traditional model describes the LR in terms of the relative EC of water at irrigation infiltration depth and drainage-water depth, and generally provides the highest LR value. ~~The other traditional model (~~*WATSUIT*~~)~~ accounts for irrigation water quality and effects on two important soil chemicals (calcite and gypsum) as irrigation water flows through the soil. This provides additional insight into the conditions in the soil being evaluated. Both the traditional model and the *WATSUIT* model are steady-state models, that is, they do not account for incremental changes in soil conditions over time. The two transient models (*TETrans* and *UNSATCHEM*) use different methods to capture incremental changes in soil processes and conditions over time.

LR simulations using the four models (Table 26-5) vary by as much as ~40%. The implications of these simulations are that (1) estimates of LR are subject to substantial variation, depending on the method, (2) the more recent transient models can capture and evaluate more of the variables that may affect LR, and (3) the traditional models may overestimate the LR. Given the complexities of irrigation and drainage, and the economic and ecological consequences of excessive drainage, it is probably appropriate to develop more accurate tools for estimating LR.

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NOTATION

D_{dw} = unit depth of drainage water ($mm^3\ mm^{-2}$)
D_{iw} = unit depth of infiltrating water ($mm^3\ mm^{-2}$)
EC_{dw} = electrical conductivity of the drainage water ($dS\ m^{-1}$)
EC_e = electrical conductivity of the saturation extract ($dS\ m^{-1}$)
EC_{iw} = electrical conductivity of the irrigation water ($dS\ m^{-1}$)
EC^*_{dw} = maximum permissible salinity level of EC_{dw} ($dS\ m^{-1}$)
EC^*_e = average electrical conductivity of the saturation extract ($dS\ m^{-1}$) for a given crop appropriate to the tolerable degree of yield depression, usually 10% or less and equivalent to the threshold electrical conductivity values defined by Mass (1990)
ET = evapotranspiration (mm)
ET_c = estimated crop evapotranspiration (mm) = ET_0K_{cb} where ET_0 is the potential reference evapotranspiration (mm) and K_{cb} is the crop coefficient
LF = leaching fraction
LR = leaching requirement