Are Existing Irrigation Salinity Leaching Requirement Guidelines Overly Conservative or Obsolete?

Dennis L. Corwin
Research Soil and Environmental Scientist, United States Department of Agriculture-Agricultural Research Service, US Salinity Laboratory, 450 West Big Springs Rd., Riverside, CA 92507-4617 (corresponding author). Email: Dennis.Corwin@ars.usda.gov

Stephen R. Grattan
Plant-Water Relations Specialist, Dept. of Land, Air, and Water Resources, Univ. of California, 239 Veihmeyer Hall, Davis, CA 95616-8627. Email: sgrattan@ucdavis.edu

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Introduction

The accumulation of excess soluble salts in the root zone of arid and semiarid irrigated soils is a widespread problem that seriously affects crop productivity throughout the world. Squires and Glenn (2009) estimated the global extent of saline soils to be 412 Mha. The estimate of Szabolcs (1989) is more conservative at 352 Mha. Of the estimated 230 Mha of irrigated land worldwide, 20 to 50% may be salt affected (Szabolcs 1992; Ghassemi et al. 1995; Flowers 1999). Ghassemi et al. (1995) estimated that salinization of irrigated soils causes an annual global income loss of $12 billion. Recent estimates of income loss due to salinity within California gated soils causes an annual global income loss of $3.7 billion for 2014 (Welle and Mauter 2017). The estimate of Szabolcs (1989) is more conservative at 352 Mha.

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Introduction

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All irrigation waters contain salts and, except for nutrients and some specific elements, crop roots take up nearly pure water for transpiration, causing most of the remaining salts to concentrate in the root zone. Therefore, the predominant mechanism causing the accumulation of salt in irrigated agricultural soils is evapotranspiration. Periodic leaching by water to move excessive salts downward below the root zone is required to avoid reduced crop yields. Thus, a combination of irrigation and rainfall is required to meet surface evaporation, crop transpiration, and salt leaching needs. Application of water greater than the amount required for leaching salts and meeting evapotranspiration needs is not desirable because water is used inefficiently and nutrients and pesticides are also being leached. The fraction of the amount of applied irrigation and precipitation that drains below the root zone is defined as the leaching fraction (LF). Under steady-state conditions the leaching fraction is approximated by $EC_{dm}/EC_{dw}$, where $EC_{dm}$ is the electrical conductivity of the irrigation water (dS m$^{-1}$) and $EC_{dw}$ is the electrical conductivity of the drainage water (dS m$^{-1}$); consequently, the LF is an indication of the degree to which salts are leached from the root zone (US Salinity Laboratory Staff 1954). A leaching fraction equal to 1 indicates a uniform soil salinity profile through the root zone where sufficient leaching has occurred so that the drainage water has the same salinity level as the irrigation water. Leaching requirement (LR) is defined as the minimum LF that is required over a growing season for a particular quality of water to maintain crop yield at or near maximum. However, often a yield decrement of no greater than 10% from maximum yield is regarded as permissible due to the spatial variation that crop yield exhibits. Leaching requirement is a specific quantitative value that can be determined and is not simply an abbreviated way of stating that leaching is required.

Clearly, an accurate and reliable method of calculating the LR is important for the efficient utilization of irrigation water. An underestimate would result in salt accumulation in the root zone and yield reduction. An overestimate would result in excessive water utilization and nutrient removal producing detrimental environmental impacts on groundwater or degraded drainage waters. For instance, the importance of having correct information on the LR is critical in California where salinity (and Se or other harmful solutes) in agricultural drainage waters in the western San Joaquin Valley results in drainage water disposal problems. The amount of drainage water produced relates directly to the LF: as the LF increases, the drainage volume increases. Irrigation practices using a low LF would be a positive approach to mitigate partially the impact of salinity on drainage waters. At a very low LF, the precipitation of salts occurs below the root zone, which lowers the total amount of salts in the drainage water. A low LF also lowers total drainage volumes. However, this approach could salinize soils to levels that would reduce crop yields if the proposed LF was too low.

Water scarcity and increased frequency of drought, 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 methods or guidelines for the calculation of the crop-specific leaching requirement of irrigated soils have fallen under the microscope of scrutiny and criticism because they are believed to erroneously estimate LR due to the assumption of steady-state conditions and disregard for processes such as transient conditions, precipitation-dissolution reactions, preferential flow, and rainfall. The goal of this paper is to stimulate discussion and rethink the current approach for determining LR. To achieve this goal, there are two objectives: (1) to evaluate the appropriateness of the traditional steady-state method for estimating LR in comparison to the transient method; and (2) to discuss the implications that these findings could have on irrigation guidelines and recommendations.

Determination of the Leaching Requirement

Crops have different degrees of tolerance to salinity that lead to different values of LR. Extensive research conducted in the past assessed crop salt tolerance. Much of the work summarized by Maas and Hoffman (1977) was expanded and updated to a list of over 100 crops compiled by Grieve et al. (2012). Maas and
Hoffman (1977) reported salt tolerance information using a two-piece linear salt tolerance model

\[ Y_r = 100 - b(\overline{EC}_e - a) \]  

where \( Y_r \) = relative crop yield; \( a \) = salinity threshold (dS m\(^{-1}\)); \( b \) = slope expressed in yield decrement percentage per decisiemens per meter; and \( \overline{EC}_e \) = mean electrical conductivity of the saturation extract for the root zone (dS m\(^{-1}\)). This response function is characterized by two linear lines, one a tolerance plateau with a slope of zero and the other a concentration-dependent line whose slope is the yield reduction per unit increase in salinity above the threshold. Consequently, Maas and Hoffman salt tolerance information is represented by two coefficients: (1) the salt tolerance threshold value; and (2) the percent yield decline per unit increase in salinity beyond the threshold value. The point where both lines intersect is the salinity threshold value (\( EC_e \)), which represents the maximum soil salinity that does not reduce yield. The Maas and Hoffman coefficients continue to provide the scientific basis for irrigation management guidelines throughout the world.

The Maas and Hoffman coefficients relate to the seasonal average root zone electrical conductivity of the saturated soil extract (\( \overline{EC}_e \)). Maximum yield is expected if the average root zone \( EC_e \) is equal to or less than the Maas and Hoffman threshold value \( a \) or \( EC_e \). However, plants respond to the salinity of the water surrounding the root (\( EC_s \)). Since soils are typically at field capacity (i.e., water content of the soil when free drainage has stopped, which is approximately at \(-1/3\) bar of soil tension) or have a lower water content during the growing season, it has been commonly assumed that \( EC_e \) is approximately equal to \( 2EC_s \).

There is a direct connection between crop salt tolerance, irrigation water salinity, and leaching requirement. Guidelines developed by Ayers and Westcot (1985) have been used internationally as an estimate of LR (these guidelines are referred to herein as A&W). Ayers and Westcot (1985) also presented the following equation developed by Rhoades (1974) as a means for calculating LR based on irrigation water salinity and crop salt tolerance:

\[ LR = \frac{EC_{iw}}{(5EC_s - EC_{iw})} \]  

where \( EC_{iw} \) = electrical conductivity of the irrigation water (dS m\(^{-1}\)).

Rhoades (1999) presented two graphs showing the linear relationship between average root zone \( EC_e \) and \( EC_{iw} \) for LF values between 0.05 and 0.50. These two graphs were reproduced by Hanson et al. (2006) in their handbook Agricultural Salinity and Drainage. One graph was for conventional surface and sprinkler irrigation (UC1) and the other for high frequency irrigation (UC2) such as drip.

These four methods or guidelines [A&W, Eq. (2), UC1, and UC2], established several decades ago, were based on steady-state conditions. Mathematically a steady-state flow analysis does not include a time variable, whereas a more complex transient-flow analysis does. Considering flow analysis of water and solute, the water content and solute concentration at a given point remain constant with time in a steady-state system but can vary in a transient system. The assumption used to justify steady-state conditions was that, over time periods of several years or more, under the same irrigation management, crop, weather patterns, and irrigation water quality, the salinity profile distributions reach a pseudo-steady-state condition. In reality, the compelling reason for assuming steady-state conditions was the lack of sufficient accessible computer processing power to solve the complex solute transport equations under transient conditions using numerical analysis techniques. The assumption of steady-state conditions resulted in significantly simpler analytical solutions to mechanistic solute transport models or functional models that did not require any computer processing power.

In fact, true steady-state conditions never exist in the field. Steady state specifies that applied irrigation water is continuously flowing downward at a constant rate, irrespective of irrigation frequency. In addition, steady state specifies that evapotranspiration is constant over the growing season. Steady-state solutions assume that the salt concentration of the soil solution at any point in the soil profile is constant at all times. None of these general assumptions are real. Steady-state conditions are an idealized assumption for agricultural systems. Nevertheless, steady-state analyses often provide acceptable approximations of more complex transient-state analyses. Indeed, until modern computers were developed that could rapidly perform the time-step calculations required in a transient analysis, only steady-state analysis was feasible.

Evaluation of the Steady-State Leaching Requirement Guidelines

Two pivotal research papers published almost concurrently by different groups of authors (Corwin et al. 2007; Letey and Feng 2007) have created considerable doubt in the application of the traditional steady-state approach for estimating LR. Both papers pointed out that the failure to account for transient conditions in the determination of LR results in an erroneous estimation of the LR that can have significant environmental implications and impacts on water demands. Present guidelines based on these steady-state assumptions overestimate the LR and underestimate the level of salinity in the irrigation water that can be effectively utilized (Letey et al. 2011). In other words, present guidelines indicate that more irrigation water is needed to control salinity and that lower levels of salinity in irrigation water are required than necessary to achieve a 100% yield potential.

There are several significant implications to the findings of Corwin et al. (2007), Letey and Feng (2007), and Letey et al. (2011). First and most obvious, overestimating the LR requires more irrigation water, which places a greater demand on limited freshwater resources. Second, overestimating the LR will result in a greater volume of drainage water and therefore more salts and other potentially harmful constituents (e.g., Se, Mo, B, and NO\(_3\)) passing below the root zone. Drainage water with potentially harmful constituents poses a disposal problem. Evaporation ponds are the current means of disposal of drainage water, which takes 1 ha of land out of production for the evaporation pond for every 10–20 ha of irrigated land. In instances where no tile drains are present to collect the water leaving the root zone, then groundwater is impacted by this degraded water, which contains salts and other harmful constituents leached from the root zone. Third, underestimating the level of salinity permissible in the irrigation water to obtain maximum yield creates a need for the use of high-quality irrigation water, which is in limited supply, and curtails the use of degraded water, which is in growing supply.

Based on this research, do the current recommended guidelines on leaching requirements (based on steady-state analyses) need to be revised? This information is important to producers but is of the greatest need for regulatory agencies that apply or establish water quality salinity recommendations for irrigation water designed to protect irrigated agriculture production (NAS 1973). A summary of the analysis of the weaknesses that create skepticism concerning traditional LR determination follows.

Analysis of Ayers and Westcot

Ayers and Westcot (1985) assumed that the depth distribution of plant root water uptake is 40, 30, 20, and 10% of total...
transpiration, corresponding with the first- through the fourth- quarter sections of the root zone, respectively. Plant water uptake can range from an exponential to a uniform uptake depending on the crop and irrigation management practices, but the 40-30-20-10 uptake is customarily regarded as representative. Using mass-balance considerations, the salt concentration in the soil solution ($EC_s$) at the four quarter positions in the root zone were computed for LF values of 0.05–0.80 for a 1 dS m$^{-1}$ irrigation water. These numbers were divided by 2 as an estimate of $EC_e$ at each point (this assumes $EC_f$ at field capacity equals 2 × $EC_e$) (US Salinity Laboratory Staff 1954), and a linear average of $EC_e$ through the root zone was calculated. The calculated salinity distribution for each value of LF is illustrated in Fig. 1. Because the Maas and Hoffman threshold tolerance coefficients are reported in terms of average root zone $EC_e$, Ayers and Westcot (1985) calculated a linear average of $EC_e$ and determined the value of LF that would produce a value equal to or less than $EC_e$ for a particular crop and irrigation water salinity ($EC_{iw}$). The salt concentration increases with decreasing values of LF and with depth. The greatest increase in concentration with decreasing LF occurs at the lower part of the root zone, with only moderate increase in the upper part of the root zone where most of the roots exist. Therefore, one might expect that a linear average would result in an overestimate of the negative effects of reducing the LF.

**Comparison of Four Steady-State Approaches to Calculate LR**

A comparison of the four methods for calculating LR using a steady-state approach is presented in Table 1. The numbers represent the ratio of the average root zone $EC_e$ to $EC_{iw}$, thus quantifying the salt concentrating factor associated with each listed value of LF. These ratio values can be used to assess maximum allowable irrigation water salinity values such that the soil salinity concentration will not exceed the $EC_e$ value for the specific crop (i.e., highest salinity that still achieves maximum crop yield). For example, consider a salt-sensitive crop with an $EC_e$ value of 1 dS m$^{-1}$ that is irrigated with an LF of 0.15. The Ayers and Westcot concentrating factor of 1.6 would indicate that the salinity of the applied water cannot exceed 0.62 dS m$^{-1}$ to achieve maximum yield. By comparison, the irrigation water salinity must be 0.31 dS m$^{-1}$ or less to achieve maximum yield if the LF is 0.05. The A&W, UC1, and UC2 models predict that maximum yield will be achieved using an LF of 0.3 when the irrigation water salinity is equal to $EC_e$ (Table 1).

These guidelines have previously served the agricultural industry well when irrigation practices frequently resulted in high LF values. However, advanced irrigation technology provides the farmer the opportunity to irrigate with very low LF values. Based on the numbers in Table 1, water of very low salinity is required to irrigate a field if a LF of 0.05 is applied.

**Transient Considerations**

Soil water salinity in a field continually changes with time. The soil salinity at two depths (i.e., 40 and 80 cm) and soil-water potential at one depth (i.e., 60 cm) as measured by Rhoades (1972) in an alfalfa field is illustrated in Fig. 2. After an irrigation, the soil becomes drier (more negative soil-water potential) and the salinity increases. Irrigation rewets the soil and decreases the soil salinity. The cycle is repeated for all irrigations. Transient behavior is clearly illustrated.

Computers facilitate the development of models based on transient analyses. These models allow simulations that include temporal changes in crop maturity, in crop salt tolerance through the growing season, in water salinity, including precipitation and dissolution reactions, and in the amount of irrigation and rainfall that are consistent with actual conditions. Several steady-state and transient models have been published in the literature. Steady-state models include the original LR model (US Salinity Laboratory 1954), WATSUIT (Rhoades et al. 1974), and water-production-function model (Letey et al. 1985), while transient models include UNSATCHEM (Šimůnek and Suarez 1994; Šimůnek et al. 1996; Suarez and Šimůnek 1997), TETrans (Corwin et al. 1991; Corwin and Waggoner 1990a, b), ENVIRO-GRO (Pang and Letey 1998; Feng et al. 2003), HYDRUS (Šimůnek et al. 2008;}

![Fig. 1. Distributions of electrical conductivity of the saturation extract ($EC_e$) with depth through the root zone for various leaching fractions for an irrigation water of 1.0 dS m$^{-1}$. (Adapted from Ayers and Westcot 1985.)](image)

![Fig. 2. Change in electrical conductivity of soil water ($EC_{iw}$) and soil water potential between irrigations of alfalfa due to evapotranspiration of stored water. (Adapted from Rhoades 1972.)](image)
Comparison of Transient Model to Experimental Results

Models are only useful to the extent that they accurately simulate observed behavior in the field. Comparison between model simulations and experimental data from field experiments is essential for model validation. Unfortunately, because of the complexity and cost associated with field experiments that include salinity and other variables, not many extensive field experiments have been conducted. Among the few, one was conducted on corn at the Gilat Agricultural Experimental Station in the northern Negev of Israel (Shalhevet et al. 1986). Five irrigation water salinities of 1–10 dS m\(^{-1}\) were used along with four irrigation intervals of 3.5–21 days. Feng et al. (2003) compared the experimentally measured yield to the simulated yields using the ENVIRO-GRO model (Pang and Letey 1998). A comparison of the measured and simulated relative yields is shown in Fig. 3. The mean simulated relative yield was 0.70, and the measured mean relative yield was 0.68. The Willmott’s index of agreement between simulated and measured yield was 0.96, where a value of 1.0 represents perfect agreement. Based on these results, the authors concluded that the ENVIRO-GRO model can be used with confidence in simulating the consequences of irrigation management options under saline conditions.

Another frequently used transient model is HYDRUS-2D. This model was used by Hanson et al. (2009) to compare results with field experiments on processing tomatoes under shallow water table conditions for drip irrigation for a range of irrigation water salinities. Replicated experiments were conducted to investigate relationships among yield, irrigation water salinity, and applied water. Both field and model results showed that seasonal fieldwide water applications should be about equal to potential crop evapotranspiration for tomatoes, thereby providing adequate localized leaching at the crop root zone scale and preventing the shallow saline water table from rising.

The transient model TETrans has been validated at field scale but with respect to salt loads draining into tile drains over a 2,396-ha area of California’s Broadview Water District rather than to yield (Corwin et al. 1999). TETrans is a “tipping bucket” functional model explicitly developed for field-scale application, which uses less spatially variable capacity input parameters rather than the highly spatially variable rate parameters that are required for mechanistic models. Table 2 compares measured and simulated salt loads at various drainage sumps. The authors concluded that TETrans reliably predicted salt loads when used in combination with stream tubes (i.e., noninteracting spatial domains of similar solute transport properties) defined from apparent soil electrical conductivity (\(EC_s\)) directed soil sampling (Corwin et al. 1999). The stream tubes served as a means of delineating the spatial structure of the variability of properties influencing the leaching of salt into tile drains.

Comparison of Steady-State and Transient Analyses

Corwin et al. (2007) compared three steady-state LR models, including the traditional LR model of the US Salinity Laboratory Staff (1954), WATSUIT (Rhoades et al. 1974), and water-production-function model (Letey et al. 1985), and two transient models, including TETrans (Corwin et al. 1991) and UNSATCHM (Šimůnek and Suarez 1994). Corwin et al. (2007) reported that the calculated LR was lower when determined using a transient approach than when using a steady-state approach. They calculated that the reduced LR using the transient analyses as compared to the commonly used traditional method for the Imperial Valley of California would result in an annual diminished drainage volume of approximately 3.9 × 10\(^3\) m\(^3\) (100,000 acre ft).

Letey and Feng (2007) compared results of transient-state analysis using ENVIRO-GRO with steady-state analyses for irrigating corn. The results presented in that paper are expanded here to include all of the steady-state models that are reported in Table 1. The results are presented in Table 3 for irrigating corn with water salinity values of 1 or 2 dS/m. The \(EC_s\) for corn grain was assumed to equal 1.7 dS m\(^{-1}\) (Maas and Hoffman 1977). All steady-state methods predicted the application of more water to achieve maximum yield as compared to ENVIRO-GRO. The differences were greater at the higher water salinity.

![Fig. 3. Comparison of measured and simulated relative corn yield. (Adapted from Feng et al. 2003.)](image-url)
Rainfall was ignored in all of the analyses presented. Rainfall at any time of the year, including fallow periods, would partially mitigate the impacts of irrigating with saline waters. Simulations using transient-state models for actual field conditions require input of all waters, including rain. Thus, the impact of rain cannot be ignored using these models.

The information presented in Table 1 determines LR without considering rain. The effect of rain can be estimated assuming using the weighted-average salinity of combined rain and irrigation water. However, the other deficiencies of the steady-state analyses are not corrected by this procedure. For example in a model developed by Isidoro and Grattan (2010), simulations indicate that rainfall occurring mostly in the winter produced lower ECw values in the root zone than did rainfall evenly distributed throughout the year. This result suggests that temporal distributions of rain may have an important influence on seasonal root zone salinity.

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### Conclusion

The present guidelines based on steady-state analyses overestimate the LR and exaggerate the negative consequences of irrigating with saline waters. An overestimation of the LR results in the application of excessive amounts of irrigation water and increased salt loads in drainage systems or underlying aquifers, which can detrimentally impact the environment and reduce water supplies. This error is particularly large at low leaching fractions. This is a fortuitous finding because irrigating to achieve low leaching fractions is desirable for reducing the transport of chemicals that degrade groundwater quality and provides for a more efficient use of limited water supplies. The feasibility of using saline waters for irrigation is also enhanced. Thus, these positive goals can be pursued without an erroneous overestimate of developing soil salination. However, soil salination is still a potentially negative consequence of irrigation and should not be ignored.

The lower estimates of LR by transient models suggest the need for a reevaluation of the traditional means of estimating LR. Even so, Corwin et al. (2007) point out that “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. . . . 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.”

Steady-state methods for determining LR are overly conservative, but are they necessarily obsolete? Obsolescence is based on whether or not there is a model consistently better with which to replace steady-state LR methods. Because steady-state models are more conservative than transient models, they can be used as a first, quick approximation to determine the suitability of water for irrigation. If the water is suitable for irrigation for a particular crop in a particular location, a more rigorous assessment may not be necessary. However, transient models provide improved estimates of LR but not without considerable difficulty. First, transient models do not directly calculate LR. Instead, model simulations are conducted for a series of seasonal water applications, from which the lowest application is selected that maintains maximum crop yield. Consequently, transient models must be reprogrammed to calculate LR directly. Second, most transient models are not user-friendly nor are the input parameters readily available and easy to establish. TETrans is the most user-friendly transient model, but it lacks the solution chemistry and combined matric and osmotic effects that make UNSATCHM such an appealing transient model for arriving at a more accurate estimate of the LR. For any transient model to become a replacement for the traditional steady-state approaches, it must have the user-friendliness of TETrans and the sophistication of UNSATCHM built into it. Unfortunately, no transient model currently meets these requirements.

Traditional means of determining LR are overly conservative, but their obsolescence depends on whether a practical approach for their replacement exists. The replacement of traditional LR approaches depends on simplifying complex transient solute transport models sufficiently for cooperative extension specialists and advisors, irrigation specialists, agricultural consultants, and producers to utilize profitably.

### Acknowledgments

The authors wish to dedicate this paper to the memory of Prof. Dr. John Letey, Jr. The senior author initially collaborated with Dr. Letey on this paper prior to his death on September 14, 2014. The decision to complete this paper was motivated by the desire to fulfill John’s vision of reestablishing the approach for calculating LR by accounting for the transient nature of solute transport. This vision was one of many that stimulated thought and discussion during John’s career. John’s integrity, self-effacing manner, and positive and generous attitude have forever touched the lives of those who knew him. John was a gentleman and a scholar with a keen and searching intellect. His extensive contributions to soil science are appreciated. He is deeply missed both personally and professionally by his many students and colleagues. The senior author was fortunate to be both a student and colleague of Dr. Letey.

### Notation

The following symbols are used in this paper:

- $EC_a$: apparent soil electrical conductivity (dSm$^{-1}$);
- $EC_e$: electrical conductivity of saturation extract (dSm$^{-1}$);
- $EC_v$: average root zone $EC_e$ (dSm$^{-1}$) for given crop appropriate to tolerable degree of yield depression usually 10% or less and equivalent to threshold $EC$ values as defined by Maas and Hoffman (1977);
- $EC_{iw}$: electrical conductivity of irrigation water (dSm$^{-1}$);
- $EC_s$: electrical conductivity of soil water surrounding root (dSm$^{-1}$); and
- $Y_r$: relative crop yield.

### References
