An Approach to Develop Site-Specific Criteria for Electrical Conductivity to Protect Agricultural Beneficial Uses that Accounts for Rainfall

Daniel Isidoro-Ramirez, Ph.D., Maria Jose Berenguer-Merelo, Ph.D., and
Stephen R. Grattan, Ph.D.

Department of Land, Air and Water Resources
University of California, Davis
Davis, CA 95616

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Executive Summary

A model has been developed to determine how the electrical conductivity of a given irrigation water supply affects crop production while taking annual rainfall into account. The model builds upon the principles and assumptions described by Ayers and Westcot (1985) and relates the electrical conductivity of the irrigation water (ECw) to the seasonal average rootzone salinity, expressed as the electrical conductivity of the saturated paste (ECe). The model considers the timing and quantity of applied irrigation water, the quantity and distribution of rainfall, and realistic assumptions related to soil water principles based on soil type.

The program can be used to either quantify the extent by which an irrigation water supply with a given EC would decrease the yield potential for a given crop under site-specific conditions or to determine the maximum EC of an irrigation water supply, that if used as the sole source of irrigation water over the long term, is fully protective of crop production. Moreover, the program could also be used to determine what additional agricultural practices might be necessary to restore full yield potential (e.g., applying additional irrigation to increase leaching). The sort of information that this program produces is not only valuable to policy and decision makers but to irrigation managers as

well. This model can be used to develop site-specific results when information regarding rainfall history, crop and soil type and irrigation water quality is available.

This model was used to evaluate site-specific conditions for the Davis region based on consistently conservative assumptions. The specific goal of this work was to help the Regional Board and UC Davis determine an EC threshold value for Putah Creek (ECw) that protects downstream agricultural uses of the water. Beans were chosen for this analysis since this crop is potentially grown in the area downstream of the UC Davis wastewater treatment plant outfall and beans are salt-sensitive, having one of the lowest soil salinity thresholds (i.e., ECe = 1.0 dS/m or 1,000 umhos/cm). Protecting beans would, in turn, protect all other crops commonly grown in the Davis area.

Three scenarios were considered. The first scenario considered no rainfall while the others considered actual daily rainfall data over either a 5-year period or the entire 53-year period of historical rainfall records. The purpose of the first scenario was to compare our model with the relationship described by Ayers and Westcot (1985) by assuming no rainfall. In the absence of rainfall, our model predicts that irrigation water with an ECw of 0.7 dS/m (700 μmhos/cm) will result in an average seasonal rootzone salinity (ECe) of 0.95 dS/m. This result agrees very well with Ayers and Westcot (1985) estimate that such a water will produce an ECe of 1.0 dS/m, providing confidence that rainfall can now be added as an additional input into the model for the subsequent scenarios.

The second scenario introduced rainfall as an additional input while keeping all other factors and assumptions the same as in Scenario 1. The first part of this scenario used a 5-year period (1953-1957) representing a relatively dry period. The second part of this scenario used a 5-year period (1963-1967) representing a period of average rainfall. Simulation results indicate that the seasonal average rootzone salinity (ECe) over the 5-year period is about 1.0 dS/m when the EC of the irrigation water is 1.2 dS/m (compared to the 0.7 dS/m in the no-rainfall scenario). Interestingly, the wetter 5-year period resulted in mean seasonal ECe values equal to the dryer 5-year period, suggesting that rainfall distribution also plays a large role in determining the seasonal ECe.

A third scenario was examined to build upon the results obtained from the second scenario and evaluate how a given irrigation water affects crop yield over the long term. In this scenario, the entire 53-year record of historical daily rainfall was taken into account to determine the effect of irrigation waters with different ECw values on seasonal average ECe. With an ECw of 1.2 dS/m, the seasonal mean ECe for the 53-year period is 1.02 dS/m, while the range in seasonal ECe for individual years varied between 0.88 to 1.42 dS/m. A statistical analysis of the data indicated that there were no significant trends for an accumulation of EC in the soil over the years.

When an ECw of 1.1 dS/m is considered over the 53-year rainfall series, the model predicts that the seasonal mean ECe is 0.94 dS/m. In 80% of the years, the mean seasonal ECe is less than 1.0 dS/m, the yield threshold for salt-sensitive bean. For 50 of the 53 years, the seasonal mean ECe for individual years is 1.05 or lower, which would result in a predicted yield reduction of 1% or less. However, this predicted reduction in yield potential is less than the error associated with the yield threshold value itself.

Over the entire 53-year period of record, yield reduction for beans is predicted to be noticeably reduced during only 3 years when applying irrigation water with an EC of 1.1 dS/m. All three years occurred during a period of drought in the 1970s. These three outliers translate into reductions in the potential yield of 2, 4 and 6%. Again, however, these predicted values are within the statistical uncertainty of the salinity threshold value itself. Moreover, such losses, if real, could be avoided by winter leaching.

Given these results, and taking into account all the other factors that potentially impact crop yield (e.g., weather, water stress, and biotic stresses) and the conservative nature of all inputs into the model, the use of 1.1 dS/m as the threshold EC value for irrigation water is considered protective for beans, and thus all other agricultural uses of the water in the Davis area.

Introduction

A model has been developed to determine the maximum electrical conductivity of an irrigation water supply (ECw) that is fully protective of crop production while accounting for annual rainfall and other site-specific conditions. The ECw is an indicator of the salinity hazard of the irrigation water and increases in direct proportion to its salt concentration (i.e., total dissolved solids, TDS). The program can be used to either quantify the extent by which an irrigation water supply with a given ECw would decrease the yield potential for a given crop under site-specific conditions or to determine the maximum ECw of an irrigation water supply, that if used as the sole source of irrigation water over the long term, can be fully protective of crop production. Moreover, the program could also be used to determine what additional agricultural practices might be necessary to restore full yield potential (e.g., applying additional irrigation to increase leaching). The sort of information that this program produces is not only valuable to policy and decision makers but to irrigation managers as well. This model can be applied to other conditions in California provided site-specific information regarding rainfall history, crop and soil type and irrigation water quality are available.

Overall Description of the Salt and Water Balance Model

Our primary goal was to develop a model that will allow a decision maker or irrigation manager to relate the electrical conductivity of the irrigation water (ECw) to the seasonal average rootzone salinity (ECe), taking into account the timing and quantity of applied irrigation water, the quantity and distribution of daily rainfall and soil water properties based on solid scientific principles. It is the ECe that has been used as the standard by which crop yield and salt tolerance has been defined (Maas and Hoffman, 1977; Ayers and Westcot, 1985; Maas and Grattan, 1999). We have chosen bean as the crop to protect since it is potentially grown in the area downstream of the UC Davis wastewater treatment plant outfall and is salt-sensitive, having one of the lowest soil salinity thresholds of 1.0 dS/m (1,000 µmhos/cm) (Maas and Grattan, 1999). That is, the yield potential is not reduced provided the average rootzone salinity over the season does not exceed 1.0 dS/m. This model takes into account many site-specific factors such as crop type, rootzone depth, crop evapotranspiration and soil texture which defines the limits for the available soil water content, soil water potential and soil-water movement characteristics.

In the process of developing the model, we built upon the assumptions used and described by Ayers and Westcot (1985). Therefore, the rooting depth of the crop (RD) is divided into 4 equal quarter-layers. A daily mass balance (water and salt) is performed for each layer. The inputs for the first layer are the applied irrigation (I) and rainfall (P), and the outputs are the drainage (D, from layer 1 to layer 2) or saturated flow, and the evapotranspiration (ET) from the layer. For the underlying layers, the only input is the drainage from the overlying layer and the outputs are the drainage to the underlying layer and ET from that layer. For the fourth and deepest layer, the drainage represents the total drainage from the crop rootzone. Additionally, unsaturated flow (U) is considered between layers, calculated in daily steps whenever there is no saturated flow. It is related to the difference in the water content (more precisely the soil matric potential) between the layers and can be either an input or an output to a given layer, depending upon the soil-water-potential gradient.

Each soil layer is assigned a wilting point (WP), field capacity (FC) and total available water ($TAW = FC - WP$) according to the soil characteristics for the soil texture chosen. Each layer has a maximum storage capacity of TAW.

The evapotranspiration of the crop (ETc) is calculated in each layer using appropriate crop coefficient (Kc) values and historical reference evapotranspiration (ETo) data provided by Goldhamer and Snyder (1989), as well as taking into account the soil water content. The achievable ETc is calculated as $ETc = Kc\ ETo$. Between cropping seasons (September through April) all ET (or evaporation (E) since there is no crop) is assumed to take place from the upper layer and bare surface E is assumed to be relatively constant at 0.6 mm/day (Department of Water Resources, 1989). Similar to the assumptions by Ayers and Westcot (1985), during the crop growing season the extraction pattern for each quarter-layer is 40%-30%-20%-10% from each descending layer when complete growth development is achieved (i.e., when maximum ETc is achieved).

There are two crop-dependent parameters: the effective rooting depth (RD) and the ratio of readily available soil moisture to TAW (p = RAW/TAW) (Allen et al., 1998). The importance of this parameter is that not all of the TAW is equally available and that crops extract soil water more readily near the FC limit than that near the WP limit.

We found it important to include a root-water extraction (i.e., soil water depletion) function to make the model more realistic and to prevent the soil water content dropping below the WP. If the "previous" water content (L, explained below) of a layer is higher than WP + (1-p) TAW, the ET for that layer is taken as ETc. But if L < WP + (1-p) TAW, the lesser of ETc or $\frac{(1-p)\cdot TAW}{k}$ is taken as ET. The parameter k is a water depletion exponent (k > 1) that usually takes values of 2 to 30 and defines how quickly the water is depleted from the layer under crop water-stress conditions (the higher k, the lower the rate water is depleted). In any case, it is stated that if ETc > W – WP, then $ET = \frac{(1-p)\cdot TAW}{k}$. This caution should apply in cases when TAW of the layer is very low in relation to ETc (e.g., soils with very low TAW). The water content of every layer is always kept above the WP in this way, simulating root water extraction behavior. In addition, the frequency of irrigations can be increased to avoid using the water-stress function at all.

Some initial conditions are arbitrarily specified for each layer: an initial soil water content (W_0) and an initial salinity (EC_0). For short-term simulations, we have consistently adjusted the initial conditions close to those obtained at the end of the simulation so that the results obtained resemble steady state conditions. Next, a "previous" water content is calculated as $L_1 = W_0 + I_1 + P_1 - ET_1$ for the upper layer or $L_1 = W_0 + D_1 - ET_1$ where D_1 is the saturated flow from the overlying layer for the others. If this is higher than FC, the difference $L_1 - FC$ is assigned to excess Ex1. This excess is distributed that day and over the next two days as drainage from the layer in the sequential daily proportions of 60%, 30% and 10% and forms the drainage from the layer (D). The fraction of the excess remaining in the soil after drainage is called the distributed excess (EXd). For an excess EX_1 in day 1, the distributed excess and drainage in the following days are given by:

$$
\begin{array}{ll}
EXd_1 = 0.4 \cdot \left(EX_1\right) & D_1 = 0.6 \cdot \left(EX_1\right) \\
EXd_2 = 0.1 \cdot \left(EX_1\right) & D_2 = 0.3 \cdot \left(EX_1\right). \\
EXd_3 = 0 & D_3 = 0.1 \cdot \left(EX_1\right)
\end{array}
$$

If there is excess water produced the days that follow, it is assigned to EXd and D in the same fashion, such that EXd and D depend on the excess generated in the 2 or 3 previous days. Every layer gets rid of any excess water above FC reaching FC two days after the excess was produced. The excess water then percolates through the whole profile in nine days after the last excess took place with 95% of the excess being drained in the first five days. The actual water content of a layer is calculated as $W_1 = W_0 + EXd_1$.

The unsaturated flow (U) between layers allows for the redistribution of water from wetter to dryer layers so that the ET pattern for the layers can come closer to the 40%-30%-20%-10% root-water extraction pattern even when one layer (usually the upper) becomes water limiting [$W < WP + (1\text{-}p)\, TAW$]. Other features needed to establish the unsaturated flow are assigned to each layer from measured soil properties or are induced from its texture: the exponent (b) of the water potential relationship ($\psi = \psi_s \cdot \left(\theta/\theta_s\right)^{-b}$), the saturated water content (θ_s), the "saturated water potential" (ψ_s) and the saturated hydraulic conductivity (K_s) (Clapp and Hornberger, 1978). The flow between layers 1 and 2 is determined as $U_{1to2} = -K(\theta) \cdot \left(\frac{\psi_2 - \psi_1}{RD/4} - 1 \right)$ where $K(\theta)$ is the unsaturated hydraulic conductivity established between layers 1 and 2 as $K(\theta) = K_s \cdot \left(\theta/\theta_s\right)^{2b+3}$. For the determination of $K(\theta)$, the water content θ is taken as the harmonic mean of the water content of the layers between which the flow is established.

This water balance yields the daily water content of each layer [$W_i^{(x)}$]. It can be checked by comparing the increase in water content in the whole profile for the year (or growing season) [the sum of $W_{365}^{(x)} - W_0^{(x)}$ for x = 1, 2, 3 and 4] with the sum of inputs and outputs to the soil profile along the year [$P + I - D^{(4)} - (ET^{(1)} + ET^{(2)} + ET^{(3)} + ET^{(4)})$, where P and I represent the annual precipitation and irrigation amounts].

The salt balance is performed with the flows between layers and their assigned soil water electrical conductivities (ECsw in dS/m). The EC of precipitation (NADP, 2004) and irrigation are variables but are given constant values EC_p and EC_I. The salt balance for the first layer [$^{(1)}$] for day 1 results:

$$\left(W_1 + D_1\right) \cdot EC_1 = W_0 \cdot EC_0 + P_1 \cdot EC_P + I_1 \cdot EC_I - U_1 \cdot EC^*$$

where $EC^* = EC_1^{(1)}$ if $U_1 > 0$ and $EC^* = EC_0^{(2)}$ if $U_1 < 0$. Evapoconcentration is accounted for as it is removed from W_0 to get W_1.

The salt balance can also be checked by comparing the increase in salts (EC*W) in the soil from day 0 to day 365 by summing all the salt inputs and outputs during the year. The net salt accumulation or removal from the profile is also obtained. A long-term (more than one year) simulation can be run to determine if there will be a tendency towards long-term salinization or whether a stable or quasi-steady state value will be achieved.

The mean EC of the soil profile is obtained from the EC in each layer ($EC_{sw}^{(x)}$) either as the arithmetic mean or as a weighted mean (weighted based on the crop water use from each layer: $ET^{(x)}/ET$). The EC of the saturation extract (ECe) is calculated from the EC of soil water (EC_{sw}) through $ECe = \left(\theta / \theta_S\right) \cdot EC_{sw}$ and the results are compared with the crop's threshold for 100% yield (Ayers and Westcot, 1985; Maas and Grattan, 1999; Maas and Hoffman, 1977). These means taken over the growing season will determine whether crop yield will be adversely affected under the simulation conditions or not. The mean and daily maximum EC of the profile (both weighted and arithmetic mean of the 4 layers) for the whole year and for the growing season are presented.

Accounting for Rainfall and Irrigation Schedules

Among the entries to the model are the daily values of precipitation (rainfall) and irrigation. The main goal of this work is to establish how precipitation will affect crop yields when using irrigation water of a given constant quality (i.e., ECw). The historical rainfall record over the past 53 years for the Davis area was taken from the National Climate Data Center (2004) and was numerically sorted from the minimum (driest year) to the maximum (wettest year). If the rainfall of the mth year in the ordered row is P_m, the probability that rainfall is lower than Pm is given by the order number (m) of a year divided by the total number of years (n) plus 1 [$Prob(P \leq P_m) = m/(n+1)$]. The actual rainfall distribution of the mth can be used to determine the results of the simulation with a P_m probability in the conditions of the location. In order to get a more accurate estimate for a given probability value (say 20%) several years with P_m around 20% may be used and the mean results taken as the 20% probability is the outcome from performing such an irrigation schedule under such weather conditions.

An irrigation schedule can also be specified in several ways. First, we can define a leaching fraction (LF) and make I = ETc/(1-LF) where I is the depth of applied (infiltrated) water. Furthermore "I" may be distributed in a given number of daily irrigations similar to actual farmers' irrigation practices or "I" may be applied at a frequency to prevent water stress. Any given schedule can be shifted a few days before or after so as to find which actual dates provide a better water schedule for the crop (such that actual ET is the closer to the achievable ETc).

Therefore, this model allows numerous irrigation schedules to be tested under a range of actual rainfall situations that could take place with a given probability. The results indicate whether soil salinity gets high enough to reduce yields of a particular crop under the given rainfall patterns and irrigation practices or whether there is a net salinization of the soil profile over time such that salinity will eventually affect crop yields. When this occurs, the EC of the irrigation water must be decreased until such favorable soil salinity conditions (i.e., the ECe threshold, the maximum seasonal rootzone salinity of a particular crop above which yields decline) are achieved.

Also, the simulation can be applied to multi-year historical rainfall series. If irrigation water quality were to remain constant over this same period, the resulting simulated series of ECe thresholds for various crops can be used to establish the probability of obtaining below/above the threshold values of ECe. The result is the distribution function of seasonal average rootzone salinity (ECe) for the entire period. This model can be used in other locations within the state given information on crop types, soil types and regional climatical data including historical rainfall records.

Results and Discussion

The water and salt balance model has been applied under several different rainfall scenarios in order to predict the evolution of soil salinity in the crop rootzone and its potential adverse effects on yield as irrigation water with a higher salinity is introduced. The analyzed scenarios were developed for the Davis region based on direction given to UC Davis by the Central Valley Regional Water Quality Control Board. In all scenarios, the parameters and assumptions required by the model were kept constant. The parameters derived from the soil and crop characteristics have been chosen from actual soil and crop data. The soil evaluated is the *Yolo silt loam* series (SCS, 2004) which represents the dominant soil type in the study area. The crop evaluated was dry bean because it is grown in the area and represents one of the most salt-sensitive crops to salinity. Therefore, protecting dry bean from salinization will also protect all other crops that either have equal sensitivity or more tolerance to salinity.

The main features of the *Yolo silt loam* series important for our model are the total available water (TAW), saturated hydraulic conductivity (Ks) and the porosity or saturated soil-water content (θ_s). These are taken as $TAW = 0.19 cm^3/cm^3$, $K_s = 86.4$ cm/day and $\theta_s = 0.51$ cm^3/cm^3 from the available soil data. Field capacity ($FC = 0.35 cm^3/cm^3$) and wilting point ($WP = 0.17 cm^3/cm^3$) are inferred from TAW and the exponent *b* and the ψ_s coefficient are determined from FC and WP ($b = 5.2$ and $\psi_s = 40.4$ cm). The soil water depletion constant is taken as $k = 12$, to account for the difficulty for the crop to extract water from such a fine-textured soil.

The root depth (RD) for dry beans was assumed to be 60 cm (Hanson et al., 1999) and the ratio of water depletion to TAW under which the crop is water stressed is taken as $p = 0.45$ from available information (Allen et al., 1998). Irrigation practices are reproduced from the usual local practices for dry bean (Long et al., 1999): a pre-sowing irrigation and four in-season irrigations are applied. The dates of application are arranged each year to obtain the maximum possible water use by the crop. The leaching requirement is assigned at 15 % (0.15) such that the irrigation application amount is 1.15 times the seasonal ETc. In all cases, the initial soil water contents and soil EC are adjusted so that the water contents in the beginning and the end of the season are similar and that there is no significant salt leaching or accumulation in the profile. The results therefore resemble a stable condition, which is particularly important for short (one year) simulations.

The scenarios considered are:

(1) Irrigation water with ECw = 0.7 dS/m (700 µmhos/cm); No rainfall and therefore no ET from non-cropped fields except during the irrigation season; this is the situation considered by Ayers and Westcot (1985);

(2) Calculate maximum ECw to maintain mean ECe <=1 with assumed annual rainfall; Two five-year series were analyzed representing a dry and average rainfall series: the 20th and 50th percentile of the 53-year precipitation series (i.e., those years representing a probability of 80% or 50% that the 5-year precipitation series will be higher than the one presented here);

(3) Irrigation water with an ECw = 1.2 dS/m and 1.1 dC/m over the entire 53-year series of available rainfall data.

Scenario 1. Irrigation water with ECw = 0.7 dS/m (700 µmhos/cm): No rainfall and therefore no ET before and after the irrigation season.

This first simulation is particularly important since it compares our model with the assumptions and approach described by Ayers and Westcot (1985). Under Ayers and Westcot (1985), rainfall is not considered, the rootzone is divided into four equal quarters where the rootzone water extraction pattern is 40%-30%-20%-10% in descending quarters and a leaching fraction of 15-20% below the fourth layer is assumed. Using these assumptions, Ayers and Westcot (1985) predict that an irrigation water of 0.7 dS/m (700 µmhos/cm) will produce an average rootzone salinity (ECe) of 1.0 dS/m, a soil salinity that will not limit productivity of any crop, regardless of salt sensitivity.

We developed our model to adopt and build upon the assumptions of Ayers and Westcot (1985). Below are results that describe soil water content, irrigation and drainage volumes, and ECe values for the different layers (i.e., rootzone quarters) in relation to time of year both within and outside of the growing season.

In this first scenario, the only change that takes place out of the irrigation season is the redistribution of water within the soil profile (between the soil layers) as no rainfall or drainage is taking place (Fig. 1.1). Whenever the water content in a layer exceeds field capacity, there is a saturated flow to the underlying layer. When the water content in the fourth layer exceeds field capacity, drainage takes place out of the rootzone, and with it the leaching of salts. The simulations show that drainage takes place after each of the 5 irrigation events of the year (Fig 1.2). After the season (August 15), the water redistributes in the soil towards equal soil-water potential in the layers (Fig. 1.1) since no rainfall is considered.

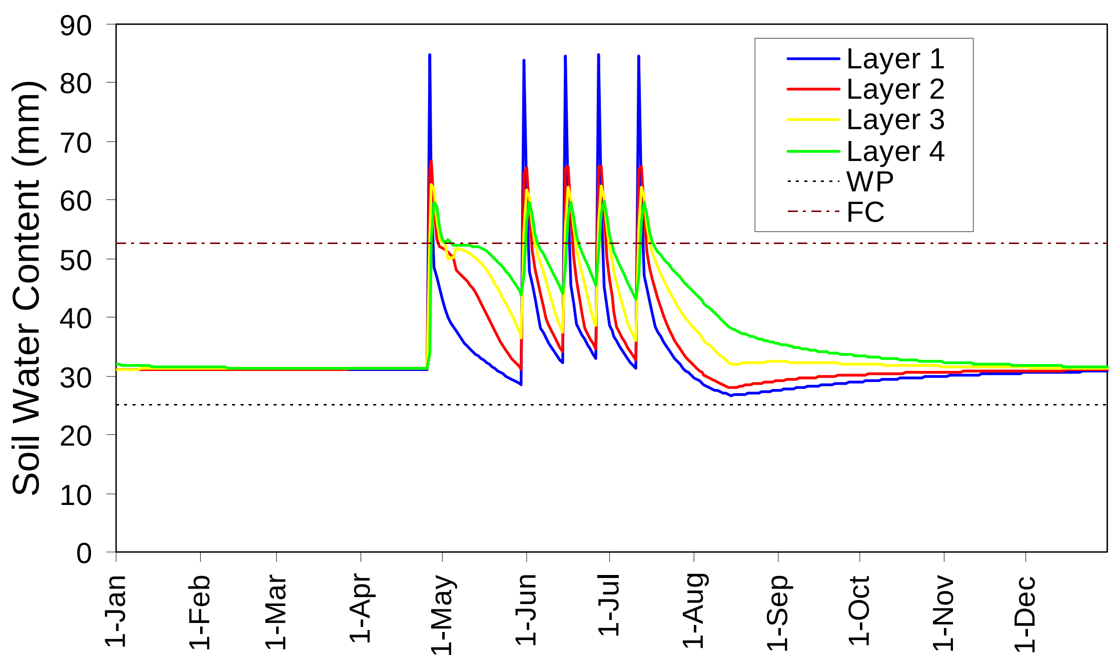

Figure 1.1. Simulated soil water content (in mm) of the four soil layers over the year in relation to the mean field capacity (FC) and wilting point (WP) of the four layers.

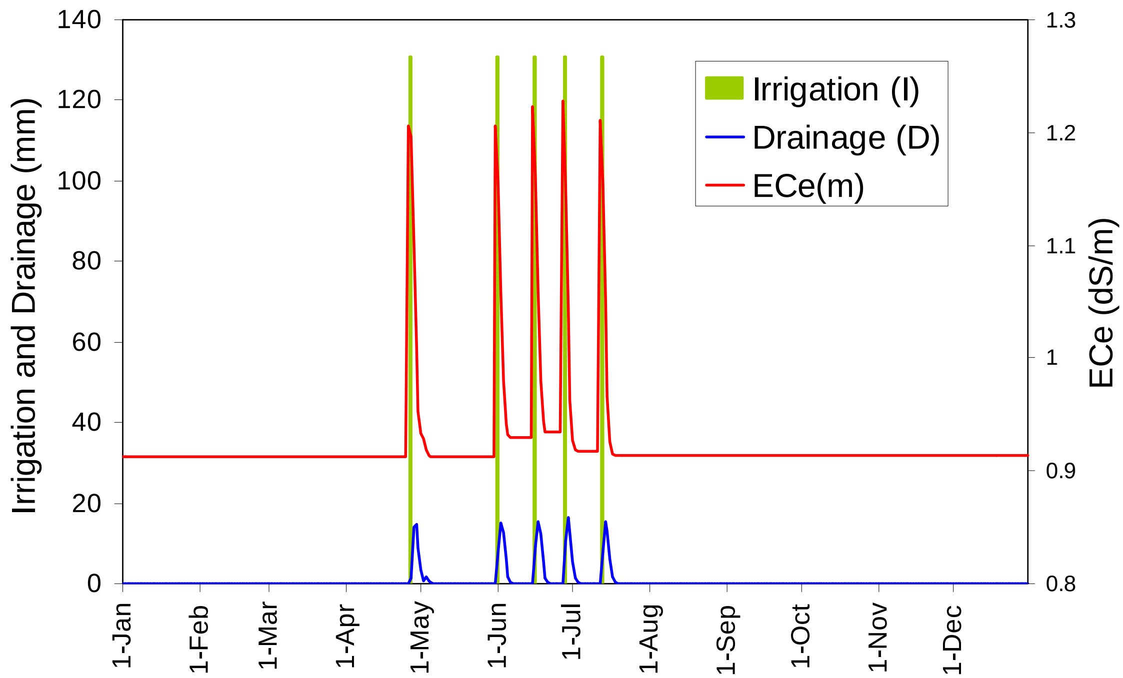

Figure 1.2. Irrigation volumes applied and drainage (in mm) and mean EC of the saturation extract obtained by simulation in the absence of rainfall.

It is also important to note that the soil water content in each of the four layers varies depending upon whether they are examined before or just after an irrigation event. Immediately after each irrigation the water content in the top layer (layer 1) is higher than that in layer 2 and so on. During most of the time between irrigations, the water content is least in the top layer and is progressively wetter with each descending layer which reflects the root-water extraction pattern being highest in the top layer and decreases with depth.

There are no salt inputs (no rainfall) or outputs (leaching) previous to the first irrigation. When the first irrigation takes place (April 26), the mean salinity of the saturation extract in the profile (ECe) increases as a result of the salt input (Fig. 1.2), but it decreases the following days as drainage takes place. In this scenario, as the initial and final water contents are made equal and there are no salt outputs or inputs outside of the irrigation period, all the salts introduced by irrigation are leached at the end of the season.

In the other scenarios that follow, there is an actual increase in soil salinity over the season which has to be leached by the winter rains.

The ECe remains below 1 dS/m (the threshold limit beyond which yields decline) during the non-irrigation season yet shows an increase-decrease pattern after each irrigation event during the irrigation season. Leaching is effective enough to reduce salinity below the 1 dS/m after each event (Fig. 1.3), but that is not the case necessarily in the simulation of actual years.

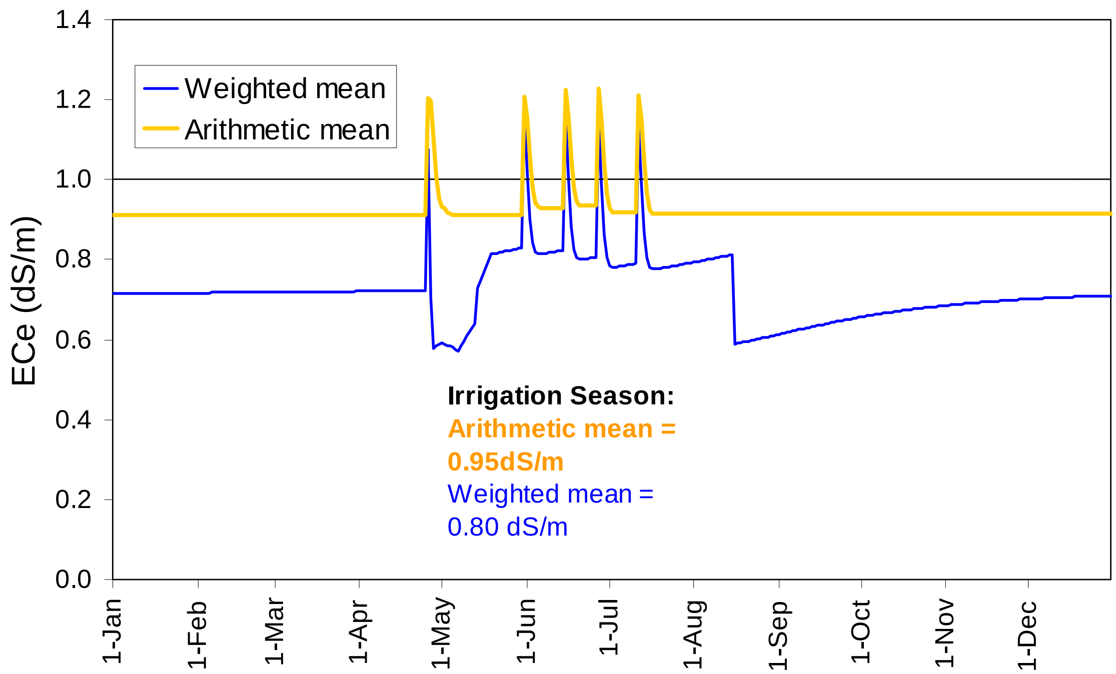

Figure 1.3. Simulated mean EC of the saturation extract of the four soil layers (ECe) at various times over entire year.

The mean ECe obtained in this scenario was 0.95 dS/m for the irrigation season (May 1 – August 15) (Figure 1.3). Therefore, our simulation is essentially the same as that calculated by Ayers and Westcot (1985). That is, irrigation water with an ECw of 0.7 dS/m will result in a seasonal ECe of 1.0 dS/m (0.95 dS/m). In this scenario as well as each that follows, the annual ECe is slightly lower than the seasonal ECe due to the salt leaching by rains before the season begins and accumulation of salts by irrigation during the season.

The mean ECe of the soil profile weighed by each layer's contribution to total ET is also lower than the arithmetic mean for the irrigation season (i.e., ECe = 0.80 dS/m) and for the entire year (i.e., ECe = 0.72 dS/m). Although the model calculates both the weighted mean and arithmetic mean, we have consistently used the arithmetic mean (i.e., the higher value) to characterize salinity following Ayers and Westcot (1985). The arithmetic mean is more appropriate to characterize soil salinity for infrequently furrow-irrigated crops such as bean, while the weighted mean is more appropriate for characterizing crop response to high-frequency, drip irrigated crops (Pratt and Suarez, 1990).

Scenario 2. Calculate maximum ECw to maintain mean ECe <=1 with assumed annual rainfall.

The second scenario was used to calculate the maximum ECw allowable to maintain a mean ECe <=1 over the growing season after taking rainfall into account. Two different 5-year rainfall series were analyzed. The first 5-year rainfall series represents an average rainfall period and the second 5-year series represents a dry period where there is an 80% or more probability that any randomly selected 5-year period has a higher annual rainfall record.

The 5-year series of 1953 to 1957 (P = 18.4%) was taken for the 80% probability rainfall. That is, in at least 80% of 5-year periods, rainfall (and therefore leaching) will be higher than that selected here in this series. The same is applicable to the series 1963 to 1967 (P = 49.0%) with a 50% probability (i.e., an average rainfall period). These series represent the given quantities of the annual precipitation (January 1 to December 31) but it has been shown that the precipitation of the hydrologic year (October of the previous year to October of the current year) has a closer relationship with ECe.

After several trial ECw values, an ECw of 1.2 dS/m was found to satisfy the objective of maintaining a mean seasonal ECe = 1 over the 5-year period (Figure 2.1). The seasonal mean ECe for the 80% (dry) series was 1.03 dS/m and the mean ECe of the average rainfall series was 1.02 dS/m. As for the individual years, all years but one resulted in an ECe < 1.03 dS/m in the 1953-57 series, with the maximum ECe being 1.09

dS/m. In the 1963-67 series, three years had an ECe < 1.00 dS/m while the other two had higher ECe values (1.13 dS/m and 1.14 dS/m). This shows that though the ECe is quite low expressed as a mean for the 5-year series (at either the P > 80% or the P > 50% level) there can be individual years with higher seasonal salinity, even during the more rainy P > 50% series. While this simulation indicates that rainfall will reduce the mean seasonal ECe, it suggests that annual rainfall distribution is at least equally if not more important than the annual rainfall amount in regards to its impact on ECe. This finding was further studied in Scenario 3.

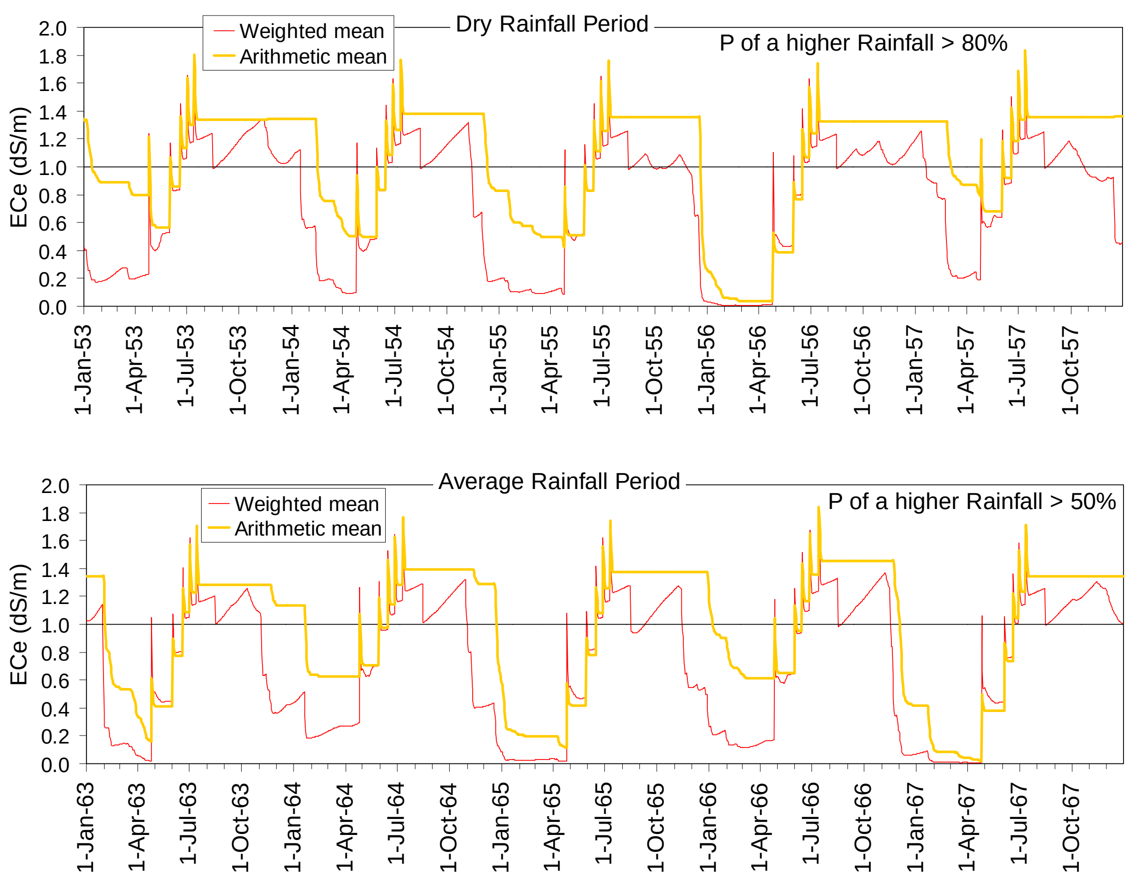

Figure 2.1. Mean simulated rootzone-salinity (ECe) in relation to the 5-year run using a probability of at least 80% (a) or at least 50% (b) of having a higher precipitation. The weighted mean is obtained by weighing each layer's ECe by the layer's contribution to total ET.

For all of the years analyzed in Scenario 2, the highest seasonal average rootzone ECe was 1.14 dS/m. The potential impacts of this worst-case year were further quantified to put the results in perspective. For beans, the expected yield reductions by salinity that results in seasonal average rootzone ECe value of 1.14, considering a yield reduction slope of 19 % per unit increase in ECe above the threshold of 1.0 dS/m (Maas and Grattan, 1999), is 3%. This slight reduction in yield potential is less than the error associated with the yield threshold value itself. As previously noted, all of the other crops commonly grown in the Davis region are less salt-sensitive than beans. Thus, the model results indicate that an ECw of 1.2 dS/m would be protective for all crops under both the average and dry rainfall periods analyzed.

There is a consistent increase in rootzone salinity as the irrigation season progresses in all the years simulated (Fig. 2.1). The feature that determines whether the mean salinity (ECe) will increase above 1.0 dS/m or not, is the starting point for that increase (i.e., the ECe at the beginning of the season) which depends on the leaching (i.e., the amount of rainfall the preceding winter). The ECe at the end of each season is very consistent at about 1.3-1.4 dS/m, but in very rainy winters it may drop as low as 0.03 dS/m (1966-67 winter) whereas in dry winters in may drop to only 0.80 dS/m (1956-57 winter).

The results from these short-term simulations (5 years) may be somewhat affected by the imposed condition of stability: that the salinity at the beginning of the period matches the salinity at the end. For example, if there is little drainage between September and December the fifth year of the simulated record, the resulting salinity will be high. Therefore the soil salinity of first year will then be adjusted upward to reflect this final salinity level and the simulation is run again. In light of short-term variations in soil salinity, a third scenario is introduced in which the entire 53-year rainfall series is taken into account. Therefore results from this simulation are more suitable as individual years are less likely to be affected by the stable condition imposed under the previous simulation.

Scenario 3. Evaluation of the entire 53-year rainfall series using ECw values of 1.2 dS/m and 1.1 dS/m to evaluate long-term impacts.

Simulations that consider irrigation waters with variable salinities (ECw) under the entire 53-year series of meteorological data provide the best insight into the changes in soil salinity over this long-term duration. If an irrigation water with an ECw of 1.2 dS/m is used as the sole source of irrigation water and the simulation is run for the 53 years with available historical rainfall data (1951 to 2003), the mean seasonal ECe ranges from 0.88 dS/m to 1.42 dS/m with a mean value of 1.02 dS/m (Figure 3.1). However, 50 of the 53 years (about 94% of the years), the seasonal ECe is maintained below 1.2 dS/m; a seasonal average root zone salinity that translates into a yield potential of over 95% (Maas and Grattan, 1999).

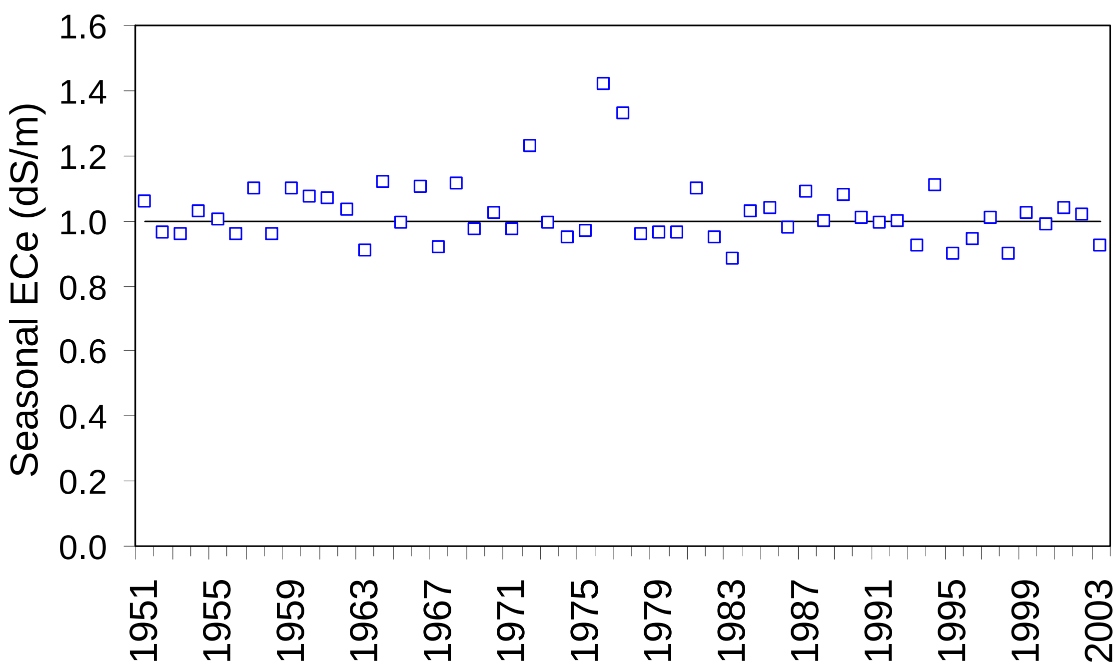

Figure 3.1. Trend of the mean ECe of the irrigation season obtained by simulation for the study period using irrigation water with an ECw of 1.2 dS/m.

The possibility that the ECe increases or decreases along the 53-year history due to the cumulative effect of leaching from rain water was considered. Fig. 3.1 shows that there is a slight apparent decrease in ECe with time. However, after running the Mann

Kendall procedure (Gilbert, 1983), it was concluded that irrigation with an ECw of 1.2 dS/m will not lead to a progressive increase or reduction in soil salinity under the analyzed precipitation patterns.

To evaluate the sensitivity of the results to changes in ECw, the model was run again with an ECw of 1.1 dS/m over the same 53-year rainfall record (see Fig 3.2). As expected, the resulting ECe values were less than those found using an ECw of 1.2 dS/m. The long-term seasonal mean ECe was reduced from 1.02 to 0.94 dS/m. Moreover, the seasonal mean ECe for individual years is less than 1.0 dS/m for 80% of the years compared to 50% using an ECw of 1.2 dS/m.

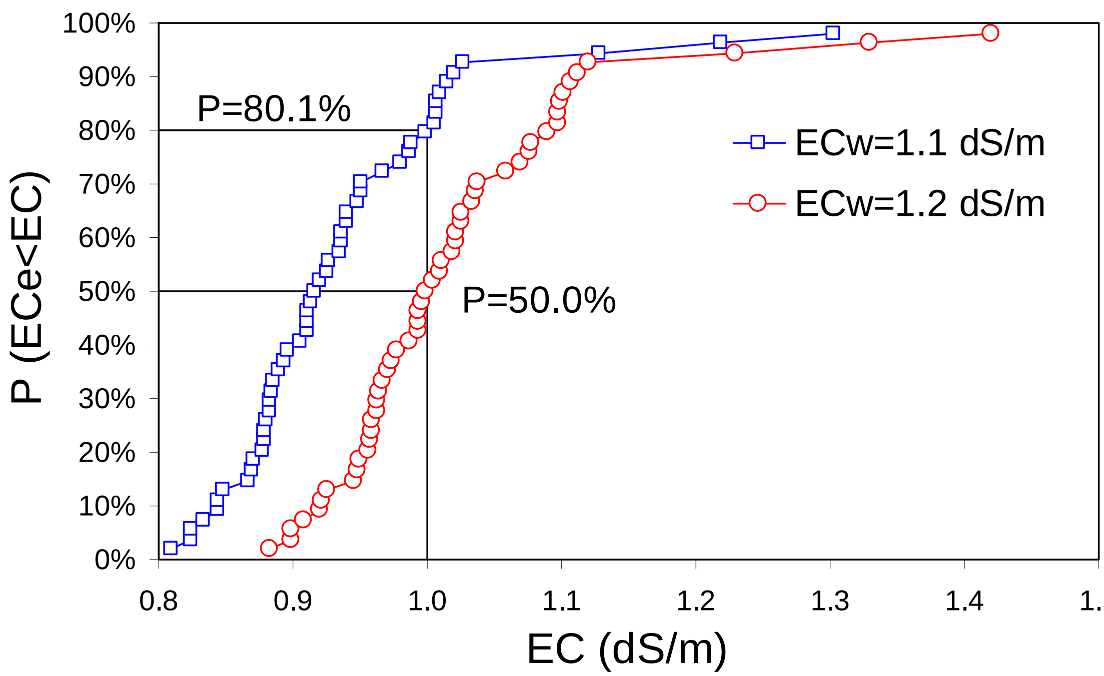

Figure 3.2. Sample probability distribution function of the mean seasonal ECe obtained after the simulation of the 53 year series assuming an ECw of 1.1 dS/m and 1.2 dS/m.

The frequency distribution of the ECe obtained by simulation is skewed to the left, meaning that there are far more values to the left of the mean than to the right, with both ECw of 1.2 dS/m (Fig 3.3 (a)) and 1.1 dS/m (Fig. 3.3 (b)). For both ECw cases, only a few years (7 for ECw = 1.2 dS/m and 3 for ECw = 1.1 dS/m) would present an appreciable yield loss (> 2 %).

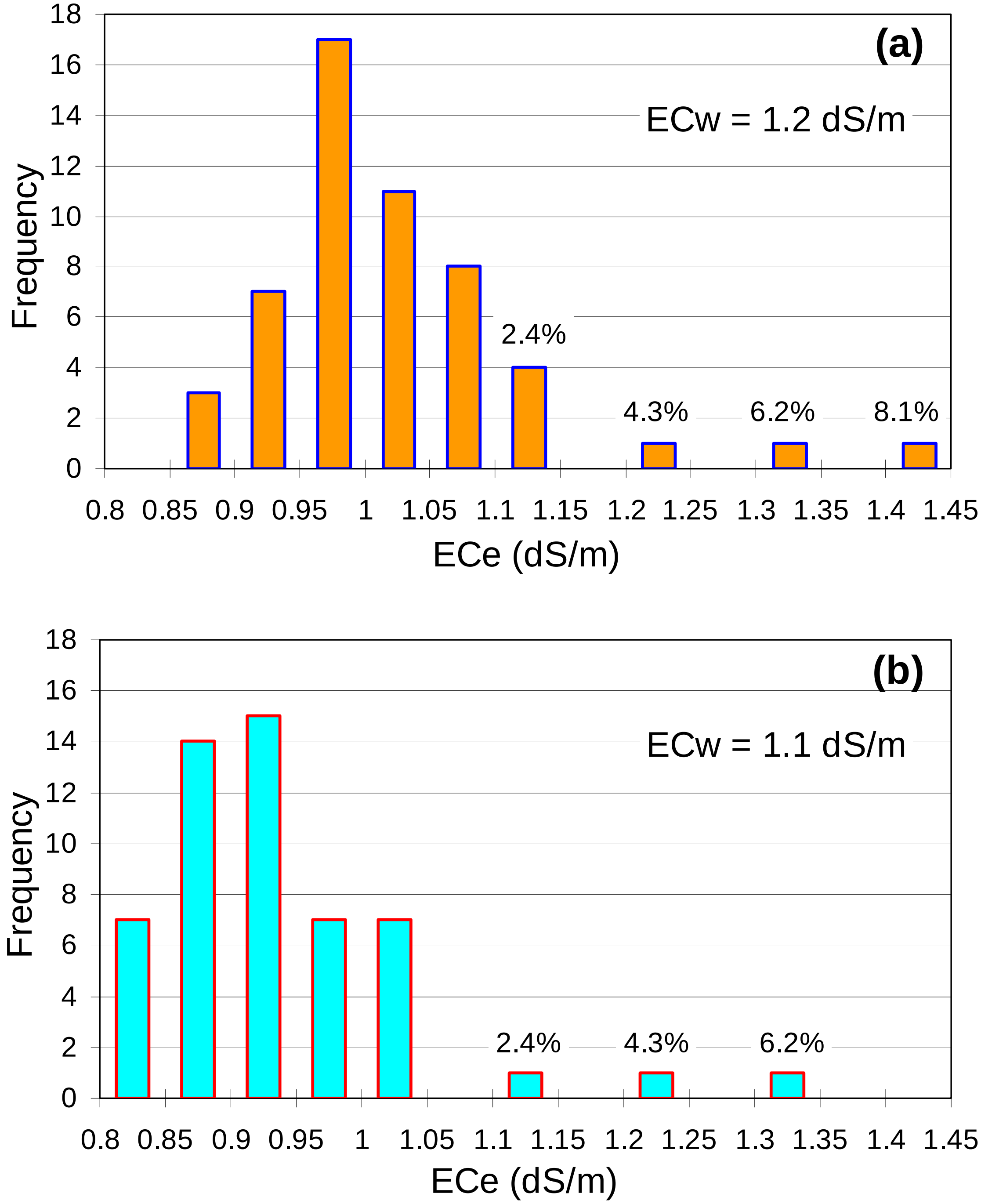

Figure 3.3. Frequency distribution of the seasonal mean ECe obtained by the simulation of the 53 year series assuming the ECw is 1.2 dS/m (a) and ECw is 1.1 dS/m (b). The numbers on top of the bars indicate the predicted yield reduction for that ECe, for yield reductions higher than 2%.

There were only three years where the seasonal mean ECe exceeded 1.1 dS/m when the simulation was run for the 53-year period with ECw of 1.1 dS/m. All three years occurred during the drought period in the 1970s. These three outliers translate into reductions in the potential yield of 2, 4 and 6% (Fig. 3.3b). These predicted values are within the statistical uncertainty of the salinity threshold value itself. Moreover, such losses, if real, could be avoided by winter leaching.

Given these results, and taking into account all the other factors that potentially impact crop yield (e.g., climate, water stress, and biotic stresses) and the conservative nature of all inputs into the model, the use of 1.1 dS/m as the threshold EC value for irrigation water is considered protective for beans, and thus all other agricultural uses of the water in the Davis area.

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