City of Davis - Site-Specific Study Workplan

Questions & Issues

The City of Davis has submitted a workplan (attached) to conduct a modeling study to establish site-specific salinity objectives to protect agricultural beneficial uses (AGR) for the receiving water bodies influenced by their wastewater treatment plant discharge.

In 2006, Dr. Stephan Grattan prepared a site-specific study in compliance with the City of Woodland's wastewater treatment plant NPDES permit. Because of the Woodland's proximity to Davis, the City of Davis has proposed to review and assess the applicability of that study to its discharge.

The following are the main technical issues and questions staff would like the Technical Advisory Committee (TAC) to consider and provide recommendations on:

1. **Applicability of Woodland data to City of Davis**

The workplan indicates that the City of Davis will rely on the City of Woodland study as a basis for the data to be used and build on that with any additional data needed. Staff is intending to request additional information regarding locations of irrigation water diversions downstream of the City of Davis' discharge in order to define the study area, historical cropping patterns and irrigation efficiency in the study area, and identification of salt sensitive crops in the study area and the growth cycle of those crops.
Question: Is there additional information staff should be requesting?

2. **Use of the Grattan and Hoffman models**

The Woodland study utilized the Grattan model. More recently, the State Board developed the Hoffman model. Although not clearly stated in the workplan, it appears that the City of Davis intends to rely on the Grattan model for their study. If this is the case, we plan on utilizing the Hoffman model to verify the results of the City of Davis model runs.
Question: Is this a sound approach and do you have any specific recommendations for staff in applying the Hoffman model to the City of Davis conditions?

3. **Running the model for boron, chloride, and sodium**

In addition to EC, the permit requires the City of Davis to study and provide recommendations for appropriate site-specific boron, chloride, and sodium objectives. The workplan proposes doing this by using a single model. However, the Woodland study report indicated that the Grattan model was not applicable to boron. In addition, it may not be applicable to sodium and chloride.
Question: If the model used by the City of Davis cannot be applied to boron, sodium and/or chloride, what is an appropriate method for determining objectives for those constituents?

4. **Determining leaching fraction**

Leaching fraction is one of the most sensitive inputs for both the Grattan and Hoffman models. It is, therefore, very important that the leaching fractions used for these studies are as representative of site-specific conditions as reasonably possible.
Question: What would be a reasonable approach for determining site-specific leaching fractions for this sort of study? Is the data needed to make the determination generally available?

5. **Other technical questions**

Question: Are there other technical (not policy) issues you think staff should be considering, and do you have any suggestions or recommendations regarding those issues?

Policy questions: City of Davis staff developing the workplan will also need clarification/guidance on two other issues that can have a significant influence on model outcomes. Although we consider these policy issues, we would also like to get recommendations from the TAC on how to address these issues:

1. *What is an appropriate way of determining the most salt-sensitive crops to be protected in the study area?*

2. *What is a reasonable level of crop protection (i.e. percent yield) that should be provided?*

Attachments:

City of Davis – EC, Boron, Sodium, and Chloride Study Workplan
City of Woodland Report

FEBRUARY 2011

CITY OF DAVIS

EC, Boron, Sodium and Chloride Study Workplan

submitted to

CENTRAL VALLEY REGIONAL WATER QUALITY CONTROL BOARD

prepared by

LARRY WALKER ASSOCIATES

Amended by

CITY OF DAVIS

Introduction

The City of Davis is required by NPDES Permit No. CA0079049 (Order No. R5-2007-0132-02) under Provision VI.C.2.d to submit reports on the results of site-specific investigations of EC, boron, chloride, and sodium levels to protect agricultural beneficial use in areas irrigated with water from the Willow Slough Bypass, Conaway Ranch Toe Drain, and/or Yolo Bypass that is diverted downstream from the City's discharge points.

Provision VI.C.2.d states,

> "the study for EC, boron, chloride, and sodium shall determine the sodium adsorption ratio of the soils in the affected area, the effects of rainfall and flood-induced leaching, and background water quality. The study shall evaluate how climate, soil chemistry, background water quality, rainfall, and flooding effect EC, boron, chloride, and sodium requirements. Based on these factors, the study shall recommend site-specific numeric values for EC, boron, chloride, and sodium that fully protect agricultural uses."

The work plan presented herein is submitted in compliance with Provision VI.C.2.d that requires submittal of a work plan for the study by 1 February 2011. The work plan describes the proposed technical approach and schedule for completing the required EC, boron, chloride, and sodium study.

Technical Approach

The technical approach proposed to complete the required EC, boron, chloride, and sodium study consists of the ten (10) work tasks described below.

TASK 1 – INITIATE PROJECT / ASSESS DATA NEEDS

The study will be initiated with a project scoping and data needs assessment, including an assessment and review of the City of Woodland's EC study and its applicability to the City of Davis. Data likely to be needed includes: historical climatological data (e.g. rainfall, temperature…) for the study area (i.e. the agricultural area irrigated with water influenced by the City of Davis effluent discharge); maps of the study area, including the locations of irrigation water ways and points of irrigation water diversion downstream of City of Davis WWTP discharges; quantitative history of crops grown in the study area for the period 1998-2010; chemical and physical properties of soils in the study area; effluent water quality and flow for the period 1998-2010; and receiving water quality and flow for the period 1998-2010. The data list will be reviewed to determine what needed data are available from existing data files, and will be compared to the data used in the City of Woodland's study to determine if the data are of similar quality and nature. If it is determined that the physical and site specific factors for the City of Davis' discharge locations are different as compared to those evaluated in the City of Woodland's study, then additional data needs will be identified.

TASK 2 – CONFIRM STUDY APPROACH / ASSUMPTIONS WITH RWQCB

The City will request to meet with RWQCB staff to present and discuss the technical approach and key assumptions and criteria to be used in the study to determine appropriate levels of EC, boron, chloride and sodium to reasonably protect agricultural beneficial uses of water in the study area of interest. One of the key issues to be decided will be what criteria defines a reasonable level of protection of beneficial agricultural water use considering all of the variables that can affect crop yield. Another key issue will be the extent and magnitude of influence of the City's discharge on the seasonal agricultural water supplies in the local region.

TASK 3 – COLLECT AVAILABLE EXISTING DATA

Based on the data needs list developed in Task 1, the information will be obtained from available existing sources. Data sources will include: UC Cooperative Extension, County Agricultural Commissioner's office, local Resource Conservation Districts, Natural Resources Conservation Service, City data files, DWR data files for wells, and local farmers' well water, crop data and knowledge of irrigation practices. Data compiled from noted sources by the City of Woodland may serve as an initial basis and built upon with newly retrieved data.

TASK 4 – COLLECT NEW FIELD DATA

If new data needs are identified in Task 1, the information will be obtained by collecting and analyzing water and/or soil samples as necessary. The magnitude of the monitoring effort needed to collect the data will be determined and a monitoring program will be developed as necessary to address the data needs.

TASK 5 – RUN CROP TOLERANCE MODEL FOR EC

The criteria and assumptions developed in Task 2 and the data obtained in Tasks 3 and 4 may be used as inputs to a transient model that predicts root zone EC under a range of conditions based on historical data. After consultation with RWQCB staff, the City of Davis may consider using another type of model besides a transient model that predicts root zone EC under a range of conditions based on historical data. The predicted root zone EC levels will then be used to estimate the level of irrigation water EC that is reasonably protective of the crops of concern grown in the study area. As required by the NPDES permit, any model used by the City will consider the effects of climate, soil physical properties, rainfall, flood-induced leaching (if appropriate for the study area), and background water quality on local soils and crop production.

TASK 6 – EVALUATE IMPACTS OF BACK GROUND WATER QUALITY

Under this task the impact of background water quality on the EC, chloride, sodium and boron levels of the blended water, that is diverted for irrigation downstream of the City of Davis WWTP discharge points, will be assessed. For example, through the use of a dilution model that considers the relative volume and quality of effluent discharged into the local agricultural water supply in comparison to the total supply derived from surface and pumped groundwater. Such a model will yield the range of EC, chloride, sodium and boron levels expected in the blended water that is diverted for irrigation in the study area.

TASK 7 – DETERMINE PRELIMINARY EFFLUENT EC LEVELS

The results of Task 6 combined with model results from Task 5 will be used to estimate a preliminary value of WWTP effluent EC that would be reasonably protective of crops grown within the study area boundary. A brief summary of the results of Task 7 will be prepared for RWQCB staff's review and comment.

TASK 8 – RUN CROP TOLERANCE MODEL FOR BORON, CHLORIDE AND SODIUM

The criteria and assumptions developed in Task 2 and the data obtained in Tasks 3 and 4 will be used as inputs to a transient model, or other type of model, described in Task 5. To the extent possible, the model selected will be used to estimate the levels of boron, chloride, and sodium in irrigation water that are reasonably protective for the identified crops of concern. The results from the selected model combined with soil-water principles and relations will be used to account for differences between EC, boron, chloride and sodium.

TASK 9 – DETERMINE PRELIMINARY EFFLUENT BORON, CHLORIDE AND SODIUM LEVELS

The results from Task 6 combined with results from Task 8 will be used to estimate a preliminary proposed value for WWTP effluent boron, chloride and sodium mass discharges that would be reasonably protective of crops grown in the area of concern.

TASK 10 – PREPARE REPORT

A draft report will be prepared that describes the process, criteria, assumptions, and models, as modified, to investigate effects of EC, boron, chloride and sodium levels in irrigation water diverted downstream of the City of Davis discharge points. The report will recommend site-specific numeric levels for EC, boron, chloride, and sodium in the City of Davis effluent that reasonably protect the AGR beneficial use designation of the receiving waters of concern. In addition, the report will address comments received from the RWQCB staff pursuant to Task 7. The study will be completed as required by Provision VI.C.2.d by 27 February 2015 and the study report submitted within three months of completion of the study.

Schedule

The tasks will be conducted according to a schedule shown in Table 1 that will result in the study being completed to meet the permit requirement for submittal to the Regional Board by 27 May 2015. This schedule is based on receiving RWQCB approval of this Work plan by May 2011. Delay in receiving approval beyond this date may require revision to the final submittal date.

Table 1. Schedule

Task	Task Description	Completed by
Task 1	Initiate Project/Assess Data needs	September 2011
Task 2	Confirm study approach/ assumptions with RWQCB	January 2012
Task 3	Collect available existing data	January 2013
Task 4	Collect new field data	November 2013
Task 5	Run crop tolerance model for EC	January 2014
Task 6	Evaluate impacts of background water quality	February 2014
Task 7	Determine preliminary effluent EC levels	April 2014
Task 8	Run crop tolerance model for boron, chloride and sodium	November 2014
Task 9	Determine preliminary effluent boron, chloride and sodium levels	December 2014
Task 10	Complete Study	February 27, 2015
	Prepare and submit final report	May 27, 2015

MAY 2006

An Approach to Develop Site-Specific Criteria for Electrical Conductivity, Boron and Fluoride to Protect Agricultural Beneficial Uses

prepared by

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DANIEL ISIDORO-RAMIREZ, PH.D

prepared for

CITY OF WOODLAND

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ABOUT THE AUTHORS

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Stephen R. Grattan received his B.S. in 1977 in Soil and Water Science at UC Davis and received his MS and PhD at UC Riverside in 1980 and 1984 while conducting his research at the USDA-ARS Salinity Laboratory. He has been a Plant-water Relations Specialist at the University of California, Davis since 1984. His area of expertise is in irrigation water management with particular emphasis on salinity, reuse of saline water for irrigation and crop-salinity relations. He has over 80 peer-reviewed publications and has written over 130 reports. Some of his more popular peer-reviewed papers are listed below.

- Grattan, S.R. and J.D. Rhoades. 1990. Irrigation with saline ground water and drainage water. (In K.K. Tanji, Editor) Agricultural Salinity Assessment and Management Manual. ASCE. pp 432-449.
- Maas, E. V. and S. R. Grattan. 1999. Crop yields as affected by salinity. In R. W. Skaggs and J. van Schilfgaarde (eds) Agricultural Drainage. Agron. Monograph 38. ASA, CSSA, SSA, Madison, WI pp. 55-108.
- Grattan, S.R. and C.M. Grieve. 1999. Salinity - Mineral nutrient relations in horticultural crops. Sci. Hort. 78:127-157.
- Grattan, S.R. and J.D. Oster. 2003. Use and reuse of saline-sodic waters for irrigation of crops. In: S.S. Goyal, S.K. Sharma and D.W. Rains (eds.), Crop Production in Saline Environments: Global and Integrative Perspectives. Haworth Press, New York. pp 131-162.
- Grattan, S.R., C.M. Grieve, J.A. Poss, P.H. Robinson, D.L. Suarez and S.E. Benes. 2004. Evaluation of salt-tolerant forages for sequential water reuse systems. III. Potential implications for ruminant mineral nutrition. Agric. Water Manag 70:137-150.
- Hanson, B.R., S.R. Grattan and A. Fulton. 2006. Agricultural Salinity and Drainage (Revised 2005 edition). Division of Agriculture and Natural Resources Publication 3375. University of California. 164pp.

Daniel Isidoro (Daniel Isidoro-Ramirez)

Dr. Isidoro is Agricultural Engineer by the Polythechnic University of Madrid (Spain). He specialized in Irrigation and Drainage and got a PhD degree in Agricultural Sciences by the University of Lleida (Spain) in 1999. Since 1994, Dr. Isidoro has worked mainly with the environmental impact of irrigation, especially the effect of agricultural activities on the quality of surface waters in irrigation schemes of NE Spain. During 2003 to 2005 he was a Fulbright Fellow in UC Davis, specializing in modeling of pollutant transport and in 2005 he collaborated with Dr. Grattan of UC Davis in developing a model to account for the effect of site-specific conditions on the allowable salinity of irrigation water. His most recent scientific (SCI) publications and reports focus on the effect of irrigation on surface water quality and the modeling of the effect of salinity on crop yields, as shown in the selected publications below.

- Daniel Isidoro and Ramón Aragüés (2006), Modeling survival of young olive trees (Olea europaea L., cv. Arbequina) in saline and waterlogging conditions, Agronomy Journal 98: 795-799.
- Daniel Isidoro, Dolores Quílez, and Ramón Aragüés (2006), Environmental impact of irrigation in La Violada district (Spain) I: Salt export patterns, Journal of Environmental Quality 35 (3): 766-775.
- Daniel Isidoro, Dolores Quílez, and Ramón Aragüés (2006), Environmental impact of irrigation in La Violada district (Spain) II: Nitrogen fertilization and nitrate export patterns in drainage waters, Journal of Environmental Quality 35 (3): 776-785.
- Stephen R. Grattan and Daniel Isidoro (2005), Evaluation of interim groundwater quality limits (EC, TDS, B, Cl and Na) for the Fresno Waste Water Treatment Plant to protect irrigated agriculture, report submitted to Carollo Engineers in reference to BTPC re-Evaluation of Site-specific Interim Groundwater Limits for the City of Fresno, 45 p.
- Daniel Isidoro, María José Berenguer, and Stephen R. Grattan (2004), An approach to develop site-specific criteria for electrical conductivity to protect agricultural beneficial uses that accounts for rainfall, Report for the Central Valley Regional Water Quality Control Board of California, 22 p.

EXECUTIVE SUMMARY

Site-specific criteria for electrical conductivity (salinity), boron and fluoride have been developed for irrigated agriculture both inside and outside the Yolo bypass. These criteria were developed to protect agricultural beneficial uses taking into account site-specific conditions including soil type, irrigation management practices, water quality, crop evapotranspiration (ET) and inputs from irrigation and rainfall, while protecting the most sensitive of the dominant crops in that area (i.e. those major crops that account for at least 90-95% of the cropped area). The two dominant crops in the area that are most sensitive to salinity are identified as corn and rice. The revised limits proposed are based on a transient model that predicts the average soil ECe (the electrical conductivity of the saturated soil paste) in the crop rootzone over the crop season taking into account site-specific conditions including, among other factors, soil type, water management and historical daily-rainfall and temperature records over the past 53 years. A different model was developed for rice because it is grown in flooded basins where standing water flows sequentially from basin to basin. Details of the models are described in the Appendix A and B of this report.

Discussion is provided regarding the inappropriate use of soil salinity 'yield threshold' values, introduced by Maas and Hoffman (1977), for developing limits on electrical conductivity (ECw) in the irrigation water. From a plant physiological perspective, "thresholds" have no scientific justification. Consequently, other expressions have been developed more recently using a curvilinear approach and fit the salt tolerance data better. These methods provide a continuous function of yield loss with increases in root zone soil salinity and therefore do not provide a "threshold" value. Although the report describes results considering 100% yield potential using published "threshold" values, we also considered salinity levels that would maintain the yield potential above 90 and 95% as reasonable levels of protection.

Of the dominant crops in the area, results from our model indicate that irrigation with water containing an ECw of 1.4 dS/m, as the sole source of irrigation water, is fully protective of corn and rice in all of the dominant soil types under which they are grown both inside and outside the Bypass. Computer model simulations indicate that the yield potential for both these salt-sensitive crops can be maintained at 100% over 89% of the years even under the worse case scenario. These limits could be raised to 2.1 dS/m and protect both crops such that yield potentials >90% are maintained >90% of the years. However with this ECw, grain yields in some of the lower rice basins (checks) drop below the 90% yield potential due to evapoconcentration of salts. In the process of fully protecting rice and corn by setting the maximum ECw of 1.4 dS/m, the other dominant crops are protected as well.

Fluorine (F) is an element that can be toxic to plants but the main concern is not the adverse affect on plants, but rather the potential negative impact to livestock that consume forages with high levels of F in its tissue. The availability of fluorine in soil solutions to plants depends not so much on the total concentration in the soil, but rather it's ionic species which depends upon the soil type, pH and presence of ions that fluoride can complex with. Fluorine is generally not a concern in neutral and alkaline soils where HF^{o}, the dominant species entering plants, is at very low levels. The recommended maximum concentration in irrigation water for the long-term use for the protection of animals and plants was set at 1.0 mg/L, but that recommendation only applies to areas with acid soils (Ayers and Westcot, 1985). In neutral and alkaline soils, fluoride complexes with magnesium and calcium and HFo concentrations are substantially reduced so it is uncertain to what extent above the 1.0 mg/L limit fluoride should be increased and still be protective of crops in the Bypass. However, since total fluoride concentration in the City of Woodland WWTP of 0.24 mg/L is far below the 1.0 mg/L upper limit for long-term irrigation on acid soils, it will clearly not be problematic in this study area since soils in the Yolo bypass have a pH between 6.1 to 8.4. Therefore, irrigation of crops with undiluted WWTP effluent from the City of Woodland will not pose a potential fluoride concern with respect to irrigated agriculture both inside or outside the Yolo bypass.

Of the dominant crops within the study area, sunflower emerges as the crop most sensitive to boron (B). No research to our knowledge has been conducted on boron tolerance to rice or some other dominant crops in the study area. However considering that sunflower ranks among the most sensitive of crops to boron, developing criteria to protect it will protect all others.

There are only 17 crops where research has been conducted to determine yield reductions with increasing soil boron concentrations. Of those, the boron concentrations where yields are maintained above 90% (B_{90}) vary between 1.8 to 14.1 mg/L. Of those grain crops, B_{90} values varied between 4.0 to 9.5 mgL.

We tried to adapt the model to account for the behavior of boron in the soil. Boron has a higher affinity to the soil than does common salts so soil adsorption processes become critical. After consulting with soil chemists at the US Salinity Laboratory in Riverside, CA, with expertise in boron's behavior in soil, it became clear that adsorption/desorption processes are highly dependent upon soil mineralogy, clay content, surface area, organic matter content and pH. We therefore concluded that incorporating boron into the model was going to be far too complex of an exercise and that such an activity falls beyond the scope of this study.

Although the model could not be applied for boron, boron reclamation curves could be applied indicating the extent by which flooding of the Yolo Bypass would reduce the previous season's soil boron concentration. The analysis indicates that when flooding for more than 20 days occurs (i.e. about half of the time), soil boron concentrations are reduced by 86 to 98% suggesting that this event alone would protect irrigated agriculture from boron related problems.

Balancing factors such as Yolo Bypass flooding, the dominant crops in the Yolo Bypass, and specific unknowns about yield losses with increases in soil boron, a conservative limit of 1.5 should not be exceeded until more research on boron tolerance has been conducted.

The SAR from samples collected from of the Woodland Waste Water Treatment Plant (WWTP) was assessed along with ECw to determine if water infiltration problems were likely. The average SAR values were adjusted to account to precipitation with calcite and resulting values were 4.3. This value, along with the calculated ECw from the WWTP (i.e. 1.65 dS/m), indicate that water infiltration problems are unlikely.

INTRODUCTION

The federal Clean Water Act requires that wastewater dischargers obtain a National Pollutant Discharge Elimination System (NPDES) permit for discharge of effluent waters. The City of Woodland is required, by its NPDES permit, to complete a "site-specific" investigation to develop appropriate EC, boron and fluoride limits to protect agricultural in areas irrigated with Tule (or Toe) Canal waters diverted downstream from the city's effluent outfall. This study was conducted to provide such a site-specific limit.

The Food and Agricultural Organization (FAO) of the United Nation's Irrigation and Drainage paper 29 "Water quality for agriculture" by Ayers and Westcot (1985), has been used by Regional Board staff as the basis for establishing water quality criteria to support permit effluent limits. This classical reference has been widely used to evaluate water quality and assist irrigation engineers and managers all over the world. The "Guidelines for interpretations of water quality for irrigation" presented in table 1 (p.8) in FAO 29, originally developed by the UC Committee of Consultants (1975), were produced as a "management tool" and are a conservative, first-step in identifying possible limitations or restrictions on it's use when no knowledge regarding the crop, soil, climate or site conditions are given.

Unfortunately, the guidelines in this table are far too general to be used to develop limits for particular regions since it provides no reference to the crops in question, no specifics on irrigation methods and management, and no allowances for site-specific soil and climatic conditions. These "guidelines" were not intended to serve as rigid limits.

Many of the assumptions listed for the guidelines (FAO 29, p.9) caution against strict interpretation. For example, the term "restriction on use" does not imply that a particular water source is unsuitable for irrigation. Rather it implies that changes in irrigation practices may be required or that some salt-sensitive plants cannot be grown without a reduction in the yield potential. Although the guidelines are applicable for a broad range of soil types provided they are well drained, they assume that winter rainfall does not account for leaching, which is inappropriate for most irrigated areas in northern California. Therefore it is important that such considerations be accounted for in "fine tuning" these guidelines to account for site specific conditions as is suggested by Ayers and Westcot (1985).

A model was developed by Isidoro-Ramirez et al. (2004) and further modified here that determines seasonal average rootzone salinity taking into account a number of site-specific factors including crop type, soil type, climate (daily rainfall and temperature), irrigation practices, soil water movement, root water extraction, ET and leaching. Our goal was to build upon the concepts and assumptions by Ayers and Westcot (1985) by developing a dynamic model accounting for daily changes in the water content and salinity in the crop rootzone. This site-specific approach has obvious advantages over the current, steady-state approach where such specifics are not considered. Therefore there is an opportunity for Regional Water Quality Control Boards to utilize a more scientific approach that uses scientifically-based principles to develop site-specific limits taking into account the crop types that require protection and soil types, climatic conditions and irrigation management practices used in the region.

The purpose of this report is propose new criteria for EC, boron and fluoride taking into account site-specific conditions that will protect dominant crops in the area affected by the City of Woodland wastewater treatment plant (WWTP) discharges (i.e. the Yolo Bypass and areas just out side of the Bypass).

STUDY AREA

The study area both inside (green shaded area) and outside (pink shaded area) the Yolo Bypass is outlined on the land use map developed by the Department of Water Resources in Figure 1.

The 1968 soil survey by the National Resources Conservation Service (NRCS, 1968) of Yolo County was used to determine and describe the dominant soil types both inside and outside the Yolo bypass.

After examining the report, we found that there were three major soil types where crops are grown inside the Yolo bypass. They are described in the NRCS soil survey report as:

- Capay soils, flooded (Cc)
- Clear Lake soils, flooded (Cn)
- Sacramento soils, flooded (Sg).

These major soil types are not prime agricultural soils and are listed as Class 4 soils (NRCS, 1968). Class 4 soils have severe limitations that restrict the choice of plants that can be grown and/or require very careful management. These soils also have a relatively low Storie-Index rating of 30-34. The Storie Index is based on soil characteristics such as soil depth, soil texture and surface relief (NRCS, 1968). It is an indicator of the relative degree of suitability of a soil for general intensive agricultural uses. In general, these level soils are silty clay-loams to clays and are moderately to poorly drained. Physical characteristics of these soils include a high bulk density ranging from 1.3-1.6 g/cm^3, high montmorillonitic clay contents (30-70%), a saturated hydraulic conductivity of 8-23 cm/day and have an available water content of 0.15 to 0.18 cm^3/cm^3.

The Cn series is described in the soil survey as having two different conditions; long duration flooding and brief duration flooding. Of these two, only the long duration flooding Cn soil was considered because its properties were more restricting and represents the worse case scenario.

There are three major soil types where crops are grown outside of the Bypass that can be irrigated with Tule (Toe) drain water.

- Sycamore soils silty-clay loam, drained (St)
- Sacramento silty-clay loam, drained (Sb)
- Sycamore soils silty loam (Sp).

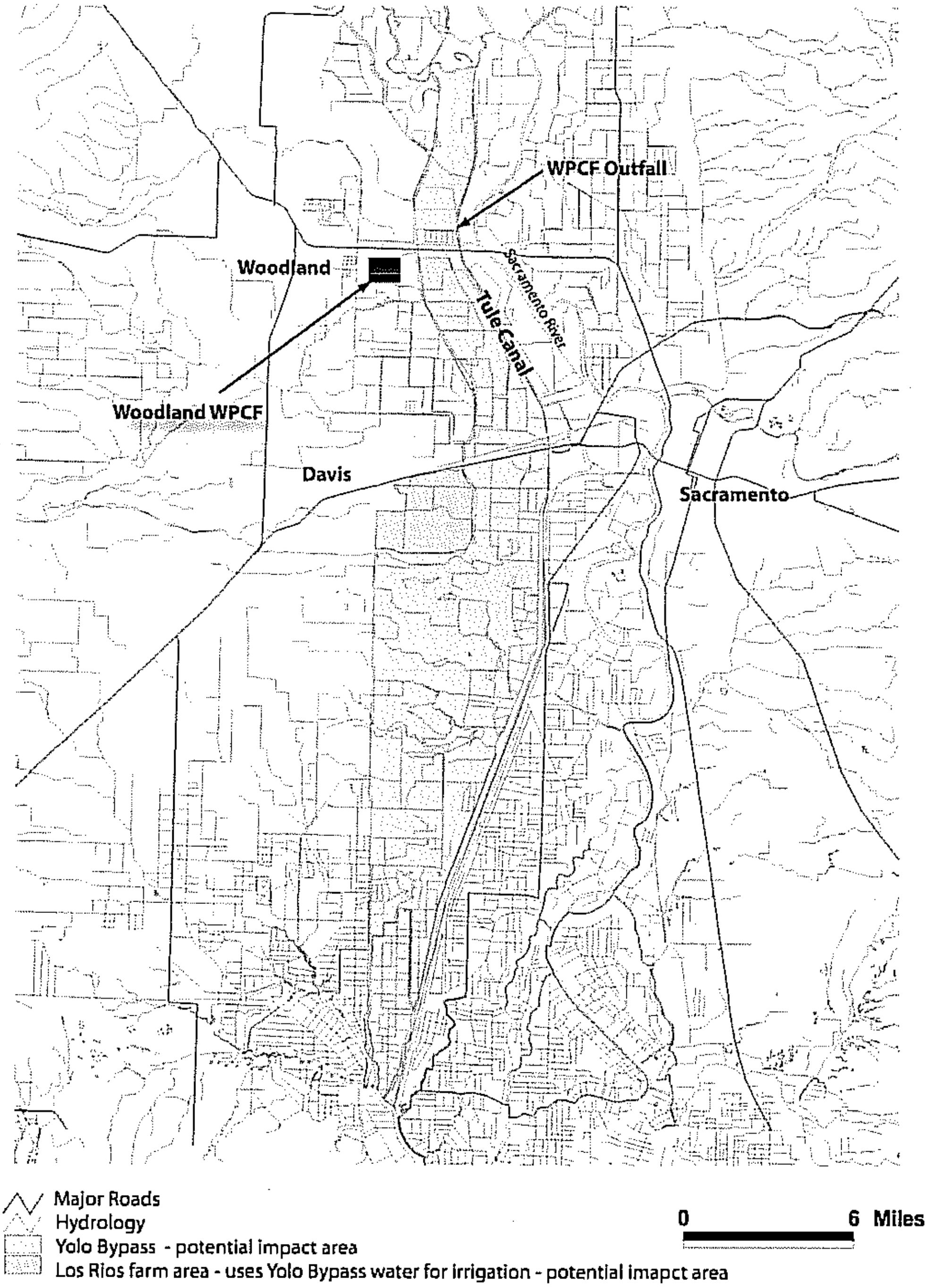

Figure 1. The study area inside and outside the Yolo Bypass

The Sycamore silty clay loam, drained (St) and the Sacramento silty clay loam, drained (Sb) have the same properties as the series Sg and the Sycamore silty loam, drained (Sp). Also the Sycamore complex Sv has some presence in the area, but its properties are those of St (if silty-clay loam) or Sp (if silty clay). The analysis for Sb soils is similar to that of Sg soils inside the Yolo Bypass without flooding. Therefore, only two different soils were considered here: Sycamore silty-clay loam (referred to as St) and the Sycamore silty loam (referred to as Sv).

Unlike those within the Bypass, these soils are considered prime agricultural land by the NRCS (1968) and are described as Class 1 soils. These soils have little to no limitations that restrict their use for crops. These soils have a Storie-Index rating between 61 and 90. Physical characteristics of these soils include a bulk density ranging from 1.3-1.6 g/cm^3, montmorillonitic clay contents (21-45%), saturated hydraulic conductivity of 23-78 cm/day and have an available water content of 0.13 to 0.19 cm^3/cm^3. Although these soils are also relatively heavy, they have considerably less clay and drain better than those in the Bypass.

In addition to the soil properties described above for various rootzone depths, we deduced other properties from information in the NRCS (1968) survey. For example the sand and silt fractions were deduced from the textural class and clay fraction. They were used, along with texture and clay fraction, to determine other soil parameters needed for the model such as volumetric water contents at saturation, field capacity and wilting point) (Table 1).

Table 1. Volumetric water content at saturation (θSat), field capacity (θFC), and wilting point (θWP)

Volumetric fraction of sand (S), clay (C), and silt (Si) in the soil matrix; saturated hydraulic conductivity (Ks, in cm/day); and texture for each of the 4 layers (rootzone quarters) considered in each soil type in and outside the Yolo Bypass: Sycamore Si-C-L (St), Sycamore Si-L (Sv) Sacramento (Sg), Clear Lake (Cn), and Capay (Cc).

Soil type	Corn Root depth (75 cm)	θ_{Sat}	θ_{FC}	θ_{WP}	S	C	Si	Ks	Soil Texture
St	1	0.52	0.36	0.19	0.1	0.31	0.59	23.3	Si-C-L
	2	0.52	0.36	0.19	0.105	0.307	0.587	29	Si-C-L
	3	0.51	0.36	0.19	0.15	0.285	0.565	77.8	Si-C-L
	4	0.51	0.36	0.19	0.15	0.285	0.565	77.8	Si-C-L
Sv	1	0.5	0.32	0.15	0.15	0.21	0.64	77.8	Si-L
	2	0.5	0.32	0.15	0.15	0.212	0.638	77.8	Si-L
	3	0.5	0.32	0.15	0.15	0.225	0.625	77.8	Si-L
	4	0.5	0.32	0.15	0.15	0.225	0.625	77.8	Si-L
Sg	1	0.52	0.26	0.2	0.1	0.35	0.55	23.3	Si-C-L
	2	0.52	0.26	0.2	0.1	0.35	0.55	23.3	Si-C-L
	3	0.51	0.34	0.21	0.1	0.6	0.3	10.5	C
	4	0.5	0.34	0.21	0.1	0.65	0.25	7.9	C
Cn	1	0.49	0.31	0.16	0.325	0.375	0.3	23.3	C-L
	2	0.49	0.31	0.16	0.325	0.375	0.3	23.3	C-L
	3	0.49	0.31	0.16	0.325	0.375	0.3	23.3	C-L
	4	0.5	0.32	0.17	0.279	0.452	0.269	13.8	C
Cc	1	0.53	0.36	0.22	0.075	0.475	0.45	7.9	Si-C
	2	0.53	0.36	0.22	0.075	0.475	0.45	7.9	Si-C
	3	0.53	0.36	0.22	0.075	0.475	0.45	7.9	Si-C
	4	0.53	0.36	0.22	0.075	0.475	0.45	7.9	Si-C

This table describes the properties assigned to each of the soil series used to perform the water and salt balances. Soil salinity, which depends on the extent of leaching under the conditions simulated, is generally lower in soils more prone to leaching (lighter textured soils with higher hydraulic conductivities, Ks) such as Sycamore silty loam (Sv). This characteristic is reflected by lower overall soil salinities in the simulation results. Particular management practices such as installing tile drains that could improve leaching in the finer textured soils are not considered in this report.

PROTECTING DOMINANT CROPS

A method is needed that identifies the crops to be protected in a particular region. Although a couple suggestions are provided here, the importance is that a method needs to be adopted by the Regional Board that it is consistent, non-labor intensive given the limited Regional Board Staff resources, and flexible for changing cropping patterns in the future.

It makes little sense to protect ALL crops within a particular region. First, it would be difficult to identify all crops in a region and it is likely that there will be small areas of a particular crop that fall outside the norm of the dominant crops in the region. Second, is there a lower limit in crop acreage that constitutes "a crop"? For example, would a 10 acre plot of beans dictate the water quality limits in a 10,000-acre region dominated by safflower, rice and corn and other more tolerant crops given that beans are more sensitive to salinity and boron than the major crops in the area, yet only represent 0.1% of the total acreage? It would make more sense to identify those dominant crops that comprise a certain percentage of cropped land within the region (i.e 90 or 95%).

In some regions it appears that the Regional Board follows such an approach while in others it does not. The Regional Boards could unite and develop a consistent method that defines "major crops" that require protection. For example they could adopt the criteria where all major crops that comprise at least 90% of the current, cropped area require protection. In this way if a new crop is introduced in a region, limits may require adjusting but only in the future if that crop becomes a dominant player in the region and if it is more sensitive to salinity or specific ion in the effluent than the current dominant crops. The actual criteria needs to and should be decided by the Board and it is important that this method be consistent and readily adopted in other regions.

It would also make little sense to set limits based on "potential" crops that could be planted in the region. This is particularly true for the Class 4 soils in the Bypass where the NRCS indicates limitations regarding the types of crops that can be grown. It would be very difficult to determine what is actually "potential" since many factors such as climate, soil type, market potential, disease susceptibility and other factors would play a key role.

We define the dominant or major crops in the study area as those that comprise 90-95% of the cropped area. For the purposes of this report, only the major crops in the study area were considered. Based on a 1997 survey of the Yolo county and the 1994 survey of Solano county by the California Department of Water Resources (DWR) (E. Morris, personal communication, 2006), there are five dominant crops in the Yolo bypass; corn, pasture, rice, safflower and tomatoes (Table 2). The acreage of these crops sum to 93% of the cropped acreage.

Since the data in Table 2 represent only one survey in each of the counties, we decided that it was important to consult growers in the Yolo Bypass for their input to determine if other potential crops should also be considered. Based on interviews with several growers[1], sunflower was considered a dominant crop as well. Growers mentioned that melons are also grown at times but acreage was very limited and they indicated that it was not a dominant crop.

Of those dominant crops listed in Table 2, rice and corn emerge as the two most sensitive to salinity. Therefore by protecting these sensitive crops, all other dominant crops listed in table 2 will be protected (i.e. alfalfa and other pasture crops, safflower and tomato). Sunflower, the other dominant crop not listed in table 2 based on grower interviews, is moderately tolerant to salinity and yields are not affected until soil salinities (average rootzone ECe) exceed 4.8 dS/m.

The traditional method of categorizing salt tolerance of a crop is by expressing yield potential (as a percentage) in relation to the seasonal average rootzone salinity. Maas-Hoffman salinity

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[1] Yolo Bypass growers interviewed: Rogina Cherovsky, Conway Ranch; Jack Dewit and Ron Tadlock, August, 2005

coefficients have historically used (Maas and Hoffman, 1977) to develop such expressions. Using these coefficients, yields of corn are reduced when the seasonal average soil salinity (ECe; electrical conductivity of the saturated soil paste) exceeds the "yield threshold" of 1.7 dS/m, indicating that the crop can tolerate a seasonal average of at least 1.7 dS/m and still maintain its full yield potential *(see important discussion in section below regarding the interpretation of yield 'threshold' values).* For rice, yields begin to decline when the seasonal EC of the field water exceeds about 1.9 dS/m (Grattan et al., 2002). Both of these crops vary, however, regarding the extent of yield losses with increases in salinity above their calculated "yield threshold" levels. Yields of rice decrease proportionally more with incremental increases in salinity. A yield potential of 90% or more can be achieved provided the seasonal average EC is at or below 3.0 and 2.5 dS/m for rice and corn, respectively (Table 2).

Wild rice is a dominant crop in the Bypass along with traditional rice. Little information exists regarding its' salt tolerance. The one report that we were able to find with the assistance of a UC Farm advisor (D. Marcum, personal communication, 2006) was one from 1905. In this study, the investigator concluded that "the salt water limit of wild rice is approximately 0.03 N sodium chloride" (Scofield, 1905). This translates into a field-water EC of about 3 dS/m. This is equivalent to the yield threshold for conventional rice reported by Maas and Hoffman (1977) and Ayers and Westcot (1985). Since a more recent field study indicates that rice yields are adversely affected at salinities above 1.9 dS/m, we chose the more restricting scenario.

Table 2. List of the crops grown in the Yolo bypass including the percent acreage planted.

Also listed are the rootzone tolerances to achieve 90, 95and 100% yield potential (data from Maas and Grattan, 1999). Crop acreage totaled nearly 36,000 and data are from the 1997 and 1994 surveys by California Department of Water Resources for Yolo and Solano Counties; courtesy of Ed Morris, DWR). A hyphen indicates no salinity or boron tolerance data.

Crop	Percent cropped area in the Yolo Bypass (1997)	Maximum rootzone salinity (ECe) to achieve 100% yield potential	Maximum rootzone salinity (ECe) to achieve >95% yield potential	Maximum rootzone salinity (ECe) to achieve >90% yield potential	Maximum Boron concentration (mg/L) in soil water
Corn	24	1.7	2.1	2.5	2.0-4.0
Melon and other cucurbits	2	1.0 - 4.9	1.6	2.2	2.0-4.0
Pasture** (native and mixed)	9	2	2.7	3.4	4.0-6.0
Rice (planted and fallow)*	18	1.9	2.4	3	-
Safflower***	29	>3.0	-	-	-
Sorghum (plus other grains)	3	6.8	7.1	7.4	7.4
Sudan grass	4	2.8	4	5.1	-
Tomato	9	2.5	3	3.5	5.7
Others	2	-	-	-	-

* Based on mean field water EC (Grattan et al., 2002)

** Based on alfalfa

*** Classified as moderately tolerant

Of the dominant crops listed in Table 2, corn is the most sensitive to boron. Studies indicate that the plant can tolerate between 2 to 4 mg/L in the soil water before yield are adversely affected. However, when sunflower is also considered as a dominant crop after interviews with growers, it emerges as the most sensitive of the dominant crops to boron (B)) with a maximum tolerance of 1.0 mg/L in the soil water (Maas and Grattan, 1999). No data are provided that describe how yields decrease with increasing boron. Furthermore, no information on boron tolerance is provided for rice and a few others on the list but it is unlikely that they would be more sensitive since sunflower ranks among one of the most sensitive to boron.

Because corn and rice are the most sensitive of the dominant crops to salinity and sunflower is the most sensitive to boron, based on the current research data base (Maas and Grattan, 1999), developing limits that protect these crops will in turn fully protect the other crops.

DETERMINING A REASONABLE LEVEL OF CROP PROTECTION

In addition to identifying the crops required for protection, there is a need to define a reasonable level of protection from salinity. In most cases, protecting the most sensitive of the identified dominant crops in a region at 100% yield potential is impractical or scientifically unfounded.

Historically, yield potential has been determined based on the Maas-Hoffman salinity-coefficients (Maas and Hoffman, 1977). They described 'salt-tolerance' by plotting the relative yield of a crop as a continuous function of average rootzone soil salinity (ECe). They proposed that this response function could be represented by two line segments; one, a tolerance plateau with a zero slope and the second, a concentration-dependent line whose slope indicates the yield reduction per unit increase in soil salinity (Figure 2).

For soil salinities exceeding the threshold of any given crop, relative yield (Yr) or "yield potential" can be estimated using the following expression:

$$Yr\ (\%) = 100 - b(ECe - a)$$

where a = the 'salinity threshold' soil salinity value expressed in dS/m; b = the slope expressed in % yield decline per dS/m; and ECe = seasonal average rootzone salinity of the saturated soil extract. The most current up-to-date listing of specific values for "a" and "b", called "salinity coefficients", are found in a publication by Maas and Grattan (1999). The greater the threshold value and lower the slope, the greater the salt tolerance.

Relationships between ECw (electrical conductivity in the irrigation water) and ECe (average rootzone salinity expressed as the EC of the saturated soil extract) were developed by Ayers and Westcot (1985) assuming a steady-state leaching fraction. The leaching fraction is defined as the fraction (or percentage) of infiltrated water that drains below the rootzone. They developed the relationship ECe = 1.5 (ECw) as the relationship between water salinity and soil salinity using a

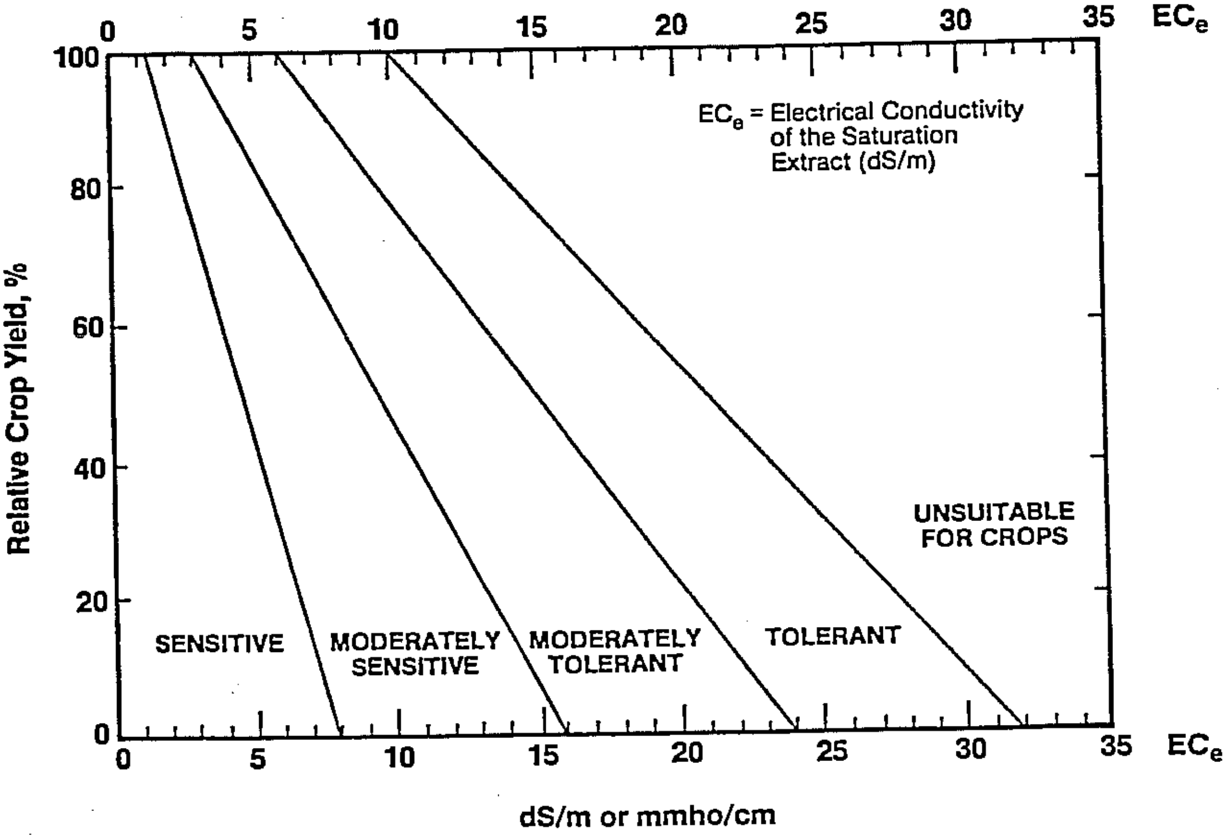


Figure 2. Relative crop yield (or yield potential) as a function of average rootzone salinity (ECe) grouped according relative tolerance or sensitivity to salinity(Adapted from Ayers and Westcot, 1985; Maas, 1990)

reasonable leaching fraction of 15-20%. This has since been adopted by the Regional Board as the standard by which water quality is assessed. When the crop salinity threshold is substituted in for the ECe value, the ECw can be calculated indicating the maximal salinity the irrigation water can be to achieve the full yield potential of a crop, given this leaching-fraction (LF). This relationship assumes continuous steay-state water flow through the system and does not account for rainfall, a higher leaching fraction or other site-specific conditons. Because of this serious limitation, we developed a transient model, described herein, that takes into account these factors.

It is important to understand that there is considerable uncertainty regarding the "yield-threshold" soil-salinity values and that such "threshold" values lack physiological justification. In fact over the past couple decades, scientists have developed non-linear expressions that fit the data better and are more scientifically justified. Some have even criticized the use of the Maas-Hoffman coefficients for expressing salt tolerance. The salinity coefficients (yield threshold and slope values) for the slope-threshold model of Maas-Hoffman are determined by non-linear least-squares statistical fitting that determines the slope and threshold values from a particular set of experimental data. Despite intense control of salinity and by holding all other important variables related to plant yield in salt tolerance studies constant, the standard errors associated with the 'threshold' values can be 50 to well over 100%. Obviously, these are very large percentages of uncertainty and suggest that actual 'threshold' values do not exist (Steppuhn et al., 2005). Rather, yields of salt-sensitive crops decrease with increased salinity in a non-linear relationship such as that proposed by van Genuchten and Gupta (1993) or by Steppuhn et al., (2004 a,b). In some cases, the response function indicates that yields may increase slightly with mild increases in salinity and then decrease at higher levels. Crops that show this type of behavior tend to be more tolerant to salinity. Therefore one has to question the scientific appropriateness or practicality of using 'threshold' values at all for determining water quality limits.

Maas and Hoffman (1977) developed these coefficients because of their potential usefulness in irrigation management. These were developed at a time when computers were not an important decision making tool on the farm as they are today. Therefore such a simplistic linear, yield-threshold expression was more attractive to growers and farm managers. Now that computers are used, there is no longer a reason to adopt such expressions.

The difficulty from a regulatory perspective is that non-linear models use an ECe_{50} value and a curve-fitting exponent to best fit the data. The EC_{50} value is the average rootzone soil salinity value that corresponds to a 50% yield potential. They do not provide "yield threshold" estimates since they do not exist. Rather, yield potentials for most crops that do not exhibit salt tolerance begin to decline as soon as the average rootzone salinity exceeds zero.

To utilize these non-linear expressions, a 100% protection limit becomes a moot point since there is no true salinity threshold. Consequently, a reasonable level of protection must then be defined. Because these non-linear expressions do fit the data better, it is likely to have less error around the 90% yield potential estimate (Steppuhn, Personal communication, 2004) even though there may be no statistical difference between yields at 100 and 90%. The average rootzone salinity of the most salt-sensitive of the dominate crops that relates to the 90 or 95% yield potential provides reasonable protection and it is a value that should be considered by the Board. We found that it made little difference determining ECe values corresponding to 90 or 95% yield potential using either the Steppuhn et al. (2004 a,b) function or the piece-wise liner function by Maas and Hoffman (1977) since these functions were based on the same data sets.

Despite the uncertainty and poor scientific justification of yield-threshold salinity values, we have considered them in the development of site-specific limits for the study area.

DESCRIPTION OF THE MODEL

The model that we developed determines, among other things, the average rootzone salinity (ECe) over the season taking into account the salinity of the irrigation water and a number of site-specific factors including crop type, soil type, climate (daily rainfall and temperature), irrigation practices, soil water movement, root water extraction, ET and leaching. In the process of developing the model, we built upon the assumptions used and described by Ayers and Westcot (1985). Our goal was to develop a dynamic model that accounts for daily changes in the crop rootzone and has obvious advantages over the current, steady-state approach. A detailed description of the model and how it operates can be found in Appendix A.

Accounting for Rainfall and Irrigation Schedules

The main goal of our model is to determine the extent by which rainfall will reduce the seasonal average rootzone salinity, allowing the use of higher salinity water that could otherwise be used if rainfall was not considered. The salt tolerance data for crops is based on this seasonal average rootzone salinity. The historical daily rainfall record over the past 53 years was used to determine the mean ECe of the growing season for each of those individual years that would be obtained under the current irrigation practices for the crops studied. The resulting simulated series of ECe values for each of the 53 years were used to establish the probability of obtaining below/above the ECe values that would protect crop yields (at 100%, >95%, or >90% yield potential) (i.e. ECe_{100}, ECe_{95} or ECe_{90}. The result is the distribution function of seasonal saturation extract salinity (ECe) based on the 53 years available.

The set of 53 mean seasonal ECe values are the main output of the model. Each year the initial water content and soil salinity in the soil water (ECsw) is taken as the final water ECsw of the previous year. If the set of 53 ECe's are ordered from minimum to maximum value, the number of years with ECe > ECe_{100} (say *n*) is the number of years in which crop yields could be affected, so the probability of having some yield loss in excess of 0, 5 or 10% under the irrigation practices analyzed will be *n*/(53+1). In the same way, if the ECe_{100} values are fixed (from the yield response to ECe curve for that crop) the probability of losing a given % of yield can be determined as the ratio of the number of years for which simulated ECe is higher than the ECe_{100} value to the total number of years plus one (54). This process is repeated for all the levels of irrigation water salinity of interest and the results (in terms of probability) depend on the ECw.

Input Data

The application of the model requires five kinds of data: (1) meteorological data for the study area location, (2) soil properties information, (3) rainfall and irrigation water quality information, (4) specific information about the crops in the study area (such as sowing and harvest dates and irrigation management practices) and (5) yearly flooding frequency in the Yolo Bypass (but only for those scenarios where this process is being considered).

The meteorological data over a 53 year-period 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). The mean annual precipitation for the period was 467 mm (18.4 inches) and the mean temperature of the year 16°C (60°F). Rainfall is concentrated in the winter and is essentially non-existent from June to September. Therefore leaching in the winter months plays an important role in the leaching of salt from the soils. The required data were daily precipitation and daily maximum and minimum temperature, from which daily estimates of ETo could be made using the Hargreaves equation (Hargreaves and Allen, 2003).

Rainfall water quality data was taken from the National Atmospheric Deposition Program database (National Atmospheric Deposition Program, 2005). The data from station CA 88 in Davis was used. The rainfall weighted mean electrical conductivity and main ions of rainwater are presented in Table 3.

Table 3. Rainfall water quality in Davis station

(CA88) reported by the National Atmospheric Deposition Program. These data are the average electrical conductivity (EC in µS/cm) and main dissolved ions in µeq/L for the period 1978-2003 (25 observations).

µS/cm	Main ionic concentrations (µeq/L)							
EC	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	NH_4^{+}	NO_3^{-}	Cl^{-}	SO_4^{2-}
7	2.9	4.6	0.7	10.2	26.4	10.5	13	8.3

The information about crop management in the area was obtained from local UC Farm advisors, Yolo Bypass growers, and a UC leaflets (e.g. Miller et al., 1980). The duration of the season for both corn and rice was taken from Goldhamer and Snyder (1989) incorporating the information by the local advisors and growers. Crop coefficients for the calculation of ET in the mid-season (Kc mid) and at the end of the season (Kc end) were also taken from Goldhamer and Snyder (1989). These Kc values were similar to those provided in Allen et al. (1998). The main crop related properties needed and the main features of the irrigation practice are presented in Table 4. The ratio of total available water to total available water (p) was taken from Allen et al. (1998).

Table 4. Main properties of the crops, irrigation practices and readily available soil water (RAW) to total available soil water (TAW) in the study area.

Corn	Rooting Depth	75 cm (2.5 feet)
	Ratio of RAW/TAW	0.55
	Number of flood irrigations in the season	6
	Crop coefficients	
	Kc mid	1.15
	Kc end	0.5
	Growing season	May 1 – September 27
Rice	Rooting Depth	7.5 – 15 cm (3" – 6")
	Ratio of RAW/TAW	0.2 of saturation (Allen et al., 1998)
	Number of irrigations in the season	Continuous flooding
	Crop coefficients	
	Kc mid	1.24 (Goldhamer and Snyder, 1986)
	Kc end	0.95 (Goldhamer and Snyder, 1986)
	Growing season	May 13 – October 6

Corn was irrigated by flood/furrow irrigation (Ron Tadlock, personal communication, 2005). The growing season began in early May and lasted until end of September. Corn received 5 to 6 irrigations with an interval decreasing from about 25 days in the beginning and end of the season to 15 days in the peak of the season (June 1 to August 28). Corn was harvested September 27th.

The growing season for rice was from May 13th to October 6th. Fields were pre-flooded and seeding took place by airplane. Rice was assumed to be continuously flood-irrigated where the height of the standing water varied between 15 and 20 cm (6 and 8 inches) after fields were flooded. Irrigation water would enter into basins (i.e checks) via weirs at the top of the field. We assumed that there were 20 basins with an average size of 0.5 ha (1.23 acres). The size and shape of the basins were typical of those found in the Yolo Bypass. Water flow rates were assumed to be 2 to 3 cfs per 100 acres, which is according to values listed in UC leaflet 21175 (Miller et al., 1980) and in agreement with a local grower (J. Dewit, personal communication, 2005). The model that we have developed for traditional crops was not appropriate for rice so we developed a separate model to account for evapoconentration as water moves among basins (see Appendix B).

YOLO BYPASS FLOODING, FREQUENCY AND QUALITY OF FLOODED WATERS

The frequency of Yolo Bypass flooding was also considered in some of our simulations. Simulations were run on soils within the Bypass considering both flooding and no flooding scenarios. To consider the flooding scenario, we added another water input to the model.

For the days when flooding occurred, a new water input was considered in the top rootzone quarter, in addition to rainfall. This new input was allowed to replenish the upper soil layer to saturation and water movement was simulated as usual after that. For everyday during flooding, the water flow downwards equals the movement of water between field capacity and saturation. The water content in any layer (rootzone quarter), a few days after flooding has begun, results between field capacity and saturation (saturation at the beginning of the day, finishing up between field capacity and saturation at the end of the day after quick drainage as water moves into the next layer).

Data on Yolo Bypass flooding over the years (1951-1999) was obtained from a report by Jones and Stokes (2000) as provided by Larry Walker and Associates. Information was also taken from Yolo Basin Foundation (2006). The series included 49 years within the series of meteorological data that have been used for this work. The last years of the series (2000 to 2003) were not available. Thus the analysis of salinity as modified by the flooding in the Yolo Bypass was performed for these 49 years.

The Yolo Bypass is not flooded all years. During the 49-yr period analyzed, there was no flooding in 17 years (data for the hydrologic years: October to September). Therefore flooding occurred roughly twice out of every three years. The number of years (frequency) with number of flooding days below a given number is presented in Figure 3.

About half of the years analyzed (24 out of 49) indicated that either no flooding occurred or that flooding was shorter than 20 days (Fig. 3). For the rest of the years, however, the mean duration of flooding was about 70 days.

The mean flooding duration in the years 1951 to 1999 lasted for 35 days, the days with a higher frequency of flooding being from January 24 to February 27 (Fig. 4). We took these dates as the mean flooding event in the Yolo Bypass to study the effect of flooding on the median precipitation years 2002 and 2003 for which there was no flooding data available.

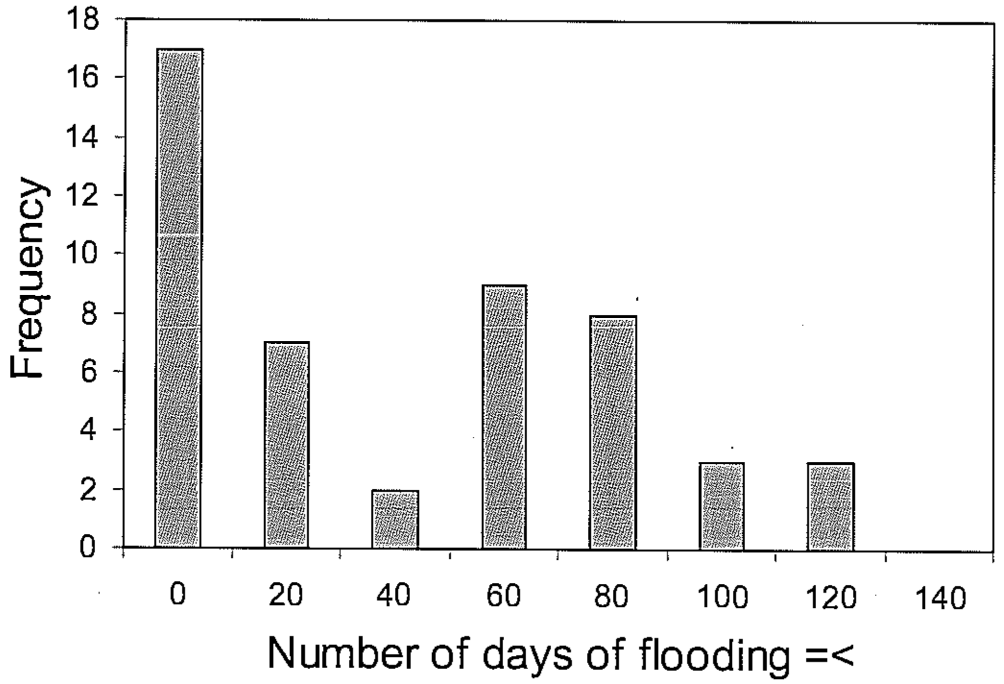


Figure 3. Frequency of flooding in the Yolo Bypass (number of days of flooding) in the hydrologic years 1950-51 to 1998-99.

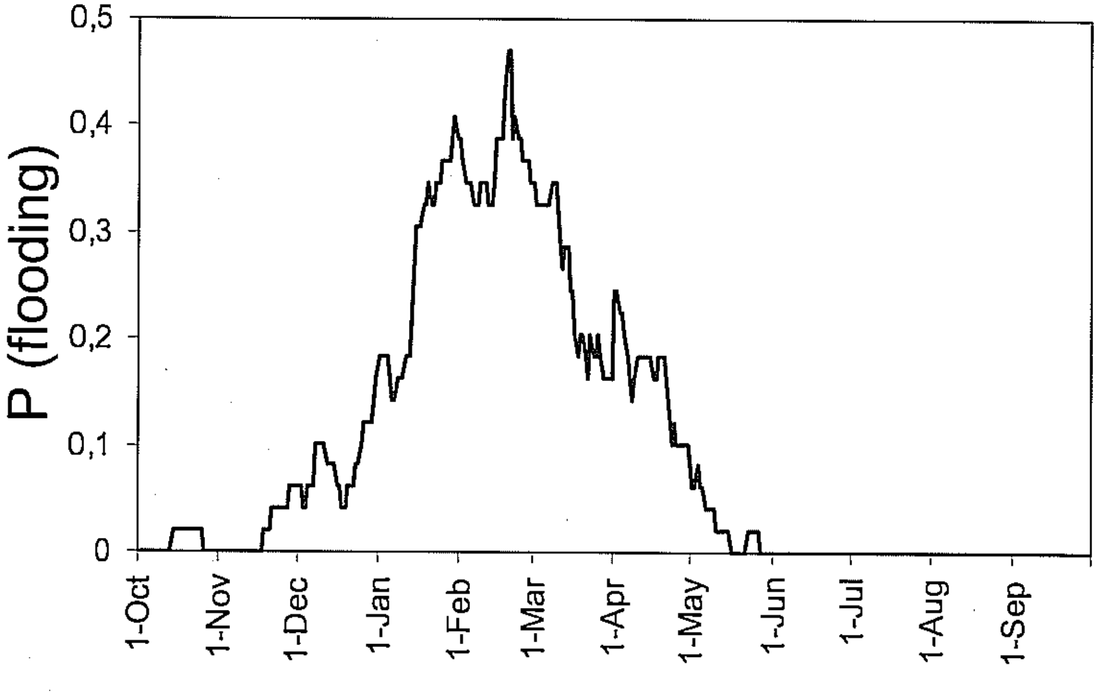


Figure 4. Probability of flooding in the Yolo Bypass in relation the hydrologic year derived as the mean frequency of flooding for that date in the period 1950-51 to 1998-99.

For the years with data available, the actual dates of flooding were considered. But in those years when flooding took place after April 29, those values were excluded so that a simulation could be run with a crop planting date of May 1.

The influence of flooding needed to be analyzed for the individual years (taking into account the actual flooding in each year) because it was found that the driest years (the worst conditions for salt leaching) coincided with those years where flooding did not occur. For those years in which flooding occurred, substantial leaching occurs such that the salinity, fluoride and boron would be reduced to considerably low levels. For example after 7 to 8 days of flooding, the ECe of he soil was less than the ECw of the flooded water. After about 24 days, the ECw more or less equaled the EC of the soil water, which is about twice the ECe. However, when flooding did not occur (or occurred for only a short duration), levels of these constituents remained fairly high.

The quality (electrical conductivity, EC) of the flooding water was found in the data of the USGS and the California DWR. The station Sacramento River at Knights Landing of the USGS presented the longest series available. As the more recent data from other stations did not differ from the data at Knights Landing (USGS, 2005) we assumed the EC of the water flooding the Yolo Bypass during the winter months to be the mean of all the data available for Knights Landing (EC = 0.19 dS/m).

RE-EVALUATION OF SPECIFIC WATER QUALITY PARAMETERS

Electric Conductivity (EC)

Electrical conductivity (EC) is the standard parameter used to characterize the salinity of the irrigation water and is the unit by which crop salt tolerance is defined (Maas and Hoffman, 1977). Units of EC reported by labs are usually in millimhos per centimeter (mmhos/cm) or decisiemens per meter (dS/m). One mmho/cm = 1 dS/m. ECw is also reported in micrommhos per centimeter (μmhos/cm). A 1000 micrommho is equal to one millimho (1 μmho = 1/1000 mmho).

Salinity affects crop production in two ways; by osmotic effects and specific-ion effects (Läuchli and Epstein, 1990). The most common whole-plant response to salt-stress is a general stunting of growth. This is generally referred to as an osmotic effect and is directly related to the salt content in the soil water. The salt-tolerance tables (Maas and Grattan, 1999) are based on crop response to osmotic effects. Specific-ion effects are those that could potentially reduce the yields beyond those described by osmotic effects alone.

Just as Ayers and Westcot (1985) used the salinity coefficients by Maas and Hoffman (1977) to determine the maximum salinity of the irrigation water that can be tolerated by a crop under steady-state conditions, we utilize the model described in Appendix A and B to determine the maximum ECw that can be used to protect corn and rice, respectively, considering transient salinity conditions. Transient salinity conditions are the best representation of actual field conditions.

Corn

Corn irrigation and yield response was simulated inside the Yolo Bypass using the three soil types as mentioned above (Cc, Cn and Sg) and outside the Bypass using the two Class one soil types (St, Sv and Sp, Sv). For those soil types inside the Yolo Bypass, corn performance was simulated considering when the Bypass was not flooded and again considering flooding during the winter.

The salinity in the crop rootzone is not static but rather changes dramatically over the season. In all years, soil salinity is lowest at the beginning of the season, due to leaching of salts from winter rains, and highest at the end of the season due to build up of salinity from irrigation and evapo-concentration in the rootzone. In some years, the initial soil salinity will be lower due to a wet season or may be higher due to a relatively dry year. In cases where flooding of the Yolo Bypass is considered, initial soil salinities are particularly low. Rootzone salinity increases as the season progresses and also cycles within an irrigation cycle (Figure 5). Note that rootzone salinity increases as roots extract soil water but then soil salinity decreases just after irrigation. However rootzone salinity does not return to the same level as it did the previous irrigation but rather continues to increase in a step-wise fashion. Since crops respond to the seasonal average rootzone salinity, those data are the ones presented in most of the graphs.

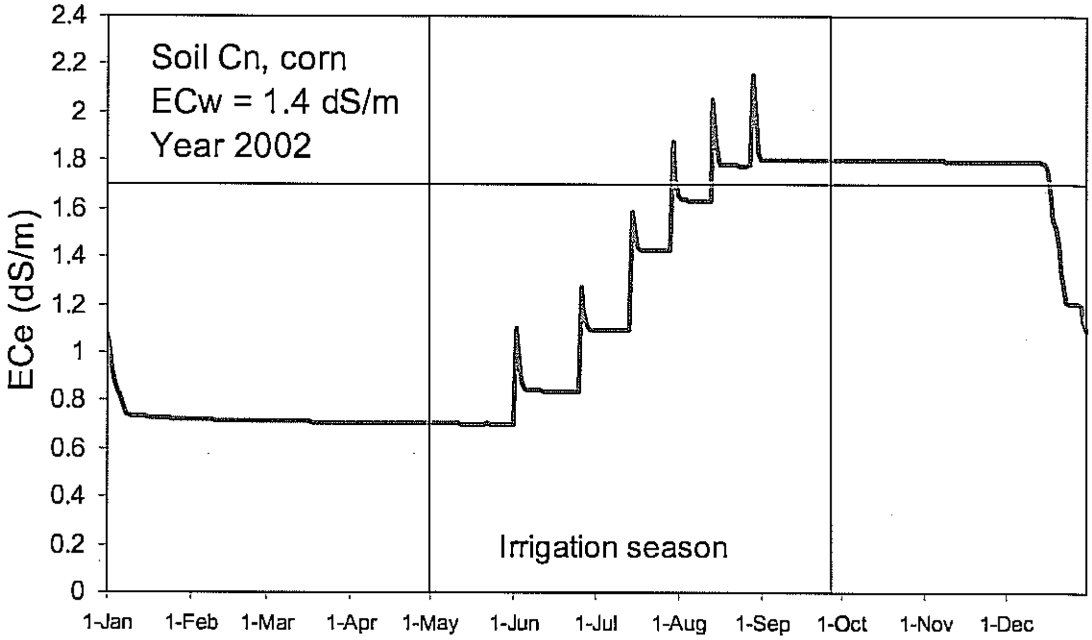


Figure 5. Changes in rootzone salinity (ECe) for corn grown during the median precipitation year (2002)

Assuming irrigation with an ECw = 1.4 dS/m) is used and that the Yolo Bypass does not flood.

Corn Inside the Bypass (No Winter Flooding)

When the simulations were run and no rainfall or flooding was considered (i.e. rainfall set to zero), the resulting seasonal average rootzone salinities varied among soil types. In the Cayay soil series (Cc), an ECw of 1.0 and 1.2 dS/m resulted in a seasonal average rootzone ECe values of 1.6 and 1.9, respectively. In the Clear Lake series (Cn), an ECw of 1.0 and 1.2 dS/m resulted in an ECe of 1.5 and 1.8 dS/m, respectively. In the Sacramento series (Sg), an ECw of 1.0 and 1.2 dS/m resulted in an ECe of 1.6 and 1.9 dS/m, respectively. For these soils using this dynamic model, the resulting average rootzone salinities were about 1.5 to 1.6 times the salinity of the irrigation water. This relationship was not much different than the steady-state approach by Ayers and Westcot (1985) where their relationship was ECe=1.5ECw based on a constant steady-state leaching fraction between 15-20%.

Not surprisingly, when actual daily rainfall was considered, seasonal rootzone salinities were substantially less than when no rain was considered. When the ECw was 1.4 dS/m, the seasonal average rootzone salinity varied among years but averaged about 1.4 dS/m, well below the yield threshold of 1.7 dS/m. The seasonal average rootzone salinity values across the 53 years ranged from about 1.0 to 1.95 dS/m, depending upon a particular year's rainfall (Figure 6). In wet years the value is generally lowest and dry years they were generally highest.

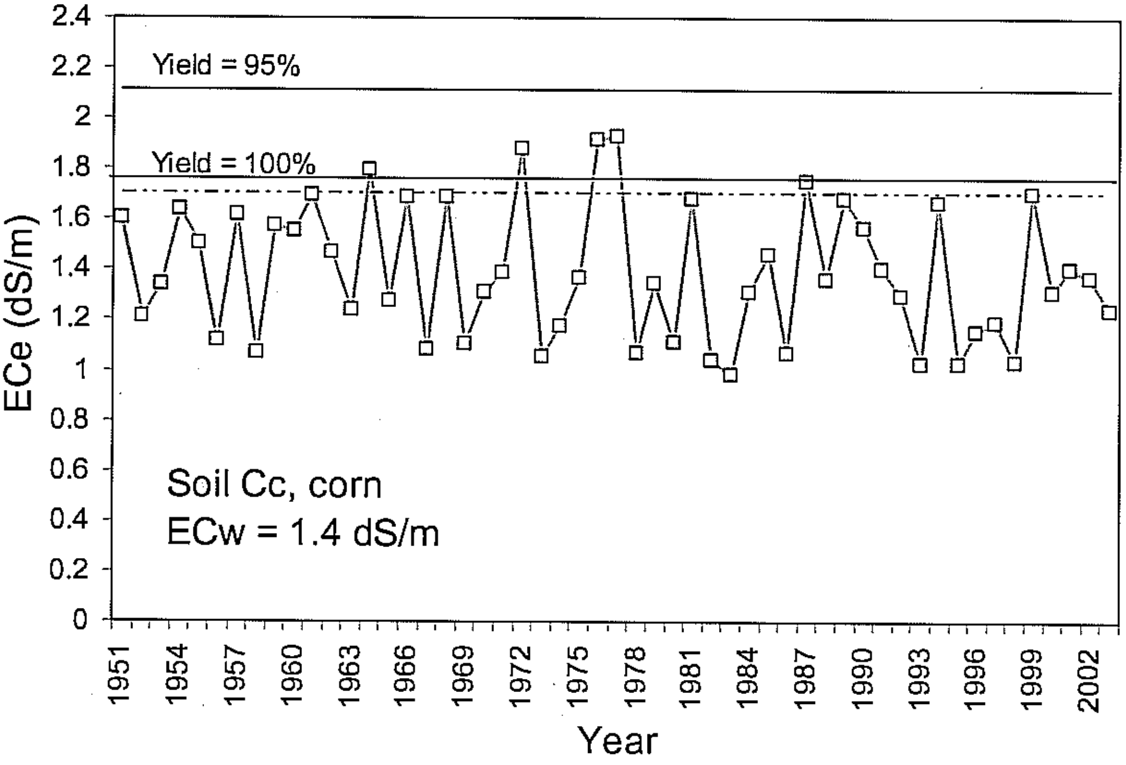


Figure 6. Electrical conductivity of the saturation paste extract (ECe) for the 53 years simulated for an irrigation water electrical conductivity (ECw) of 1.4 dS/m.

Assumes corn grown in Cc soil using an irrigation water with an ECw of 1.4 when the Yolo Bypass flooding was not considered.

Therefore for an average year, the ECw was very close to the seasonal average rootzone salinity (ECe). This suggests that irrigation water with an ECw of 1.7 dS/m can be used to keep the yield potential of corn at 100% during the average year since the resulting seasonal ECe will be 1.7 dS/m (i.e. the ECe_{100} for corn). However, in some dry years, the yield potential could fall below this 100% protection level since the ECe in those years will be above the ECe_{100} level for corn (1.7 dS/m) (refer to Table 2).

When the data are presented as a histogram (Figure 7), one can see the frequency in which certain ECe values occur when the ECw is 1.4 dS/m. This histogram is based on the Clear lake soil series, which may be described as the slightly poorest quality of the three inside the Bypass. In 90 % of the years (49 of the 53 years), the ECe will be less than 1.7 dS/m if the irrigation water is constant at 1.4 dS/m. This suggests that an ECw of about 2.2 dS/m can be used to achieve a 90% yield potential of corn, 90% of the years ($ECe<ECe_{90} = 2.5$ dS/m).

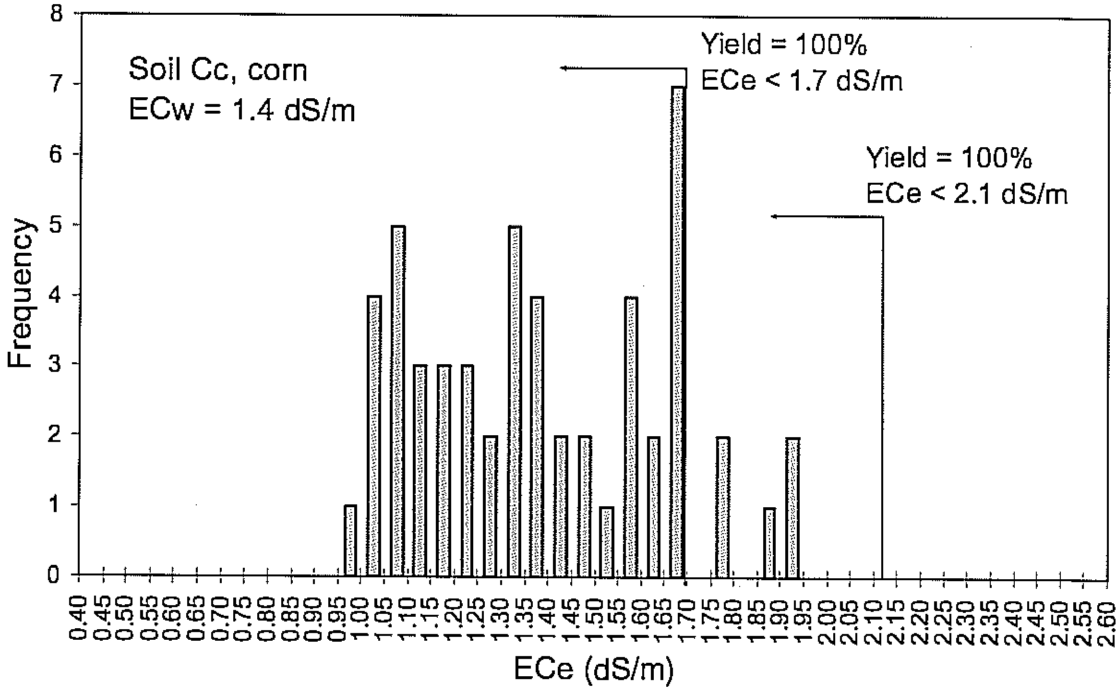


Figure 7. Histogram of the resulting seasonal electrical conductivity of the saturation paste extract (ECe) in soil Cc for the 53 years

Analyzed for electrical conductivity of the irrigation water 1.4 dS/m when Bypass flooding was not considered.

Table 5 indicates the percentage of the 53 years where yield potentials of 100, 95, and 90% are achieved given various ECw values. Based on this table, an ECw of 2.1 dS/m (by interpolation) can be used 90% of the years to achieve a >90% yield potential for corn grown on Clear lake soil (Cn). Similarly, an ECw of 1.4 dS/m can be used 89% of the years to achieve full yield potential. In those 11% of the years (dry years) where yields are less than 100%, yields are still >95%. Therefore there is an insignificant reduction in yield during the driest years.

Table 5. Percentage of years having a yield potential (Y) equal to or higher than its corresponding seasonal average rootzone salinity (ECe)

For that particular yield potential in relation to various electrical conductivities of the irrigation water (ECw). Analysis assumes corn is irrigated on Clear Lake soils (Cn) where Yolo Bypass was not flooded during the winter.

ECw (dS/m)	Y 100%	Y>95%	Y>90%
	ECe = 1.7 dS/m	ECe=2.12 dS/m	ECe=2.53 dS/m
0.8	100%	100%	100%
1	100%	100%	100%
1.2	100%	100%	100%
1.4	88.90%	100%	100%
1.6	64.00%	100%	100%
1.8	45.30%	89.90%	100%
2	29.50%	68.30%	93.80%
2.2	18.70%	60.30%	88.90%
2.4	2.40%	41.90%	67.90%
2.6	0.00%	30.40%	60.50%

Corn Inside the Bypass (Consider Yolo Bypass Flooding)

The model was re-run with the same soil series except an addition water input was included in the model where flooding of the Yolo Bypass is considered. The actual years where flooding took place are included in the model. In cases where flooding occurred (about 2/3 the years), the pre-season ECe values were all lower before irrigations commenced in the Spring. Therefore the seasonal average rootzone salinity is lower in post-flooding years (i.e those data points near 1.0 dS/m on Figure 8). In this case, using an ECw of 1.4 dS/m, the rootzone salinity averaged over all the years where flooding occurred was about 1.2 dS/m. If the ECw were elevated to 2.0 dS/m, the average rootzone salinity about equals the yield threshold for corn (about 1.65 dS/m).

When the model was run such that only flooding was considered and no rainfall, an ECw of 1.2 dS/m produced a seasonal average rootzone salinity of only 0.9 dS/m. This indicates that by considering flooding by itself (i.e. a mean flooding period of 35 days form January 24 to February 27), an ECw of 3.1dS/m water can be used and maintain the yield potential above 90% (i.e the resulting ECe would be 2.5 dS/m).

In the years when flooding of the Bypass occurred, an equal percentage of the years resulted in lower soil salinities as compared to those where no flooding was considered. Figure 9 shows a frequency distribution similar to that in Figure 7. Note that when flooding is considered on Cn soils using an ECw of 1.4 dS/m, 63% of the years corn roozones have ECe values equal to or less than 1.1 dS/m (Figure 8). This only happens 27% of the time when flooding is not considered (Figure 7). Note that there are still a few years where soil salinity can approach 1.8 to 1.9 dS/m, regardless of whether Bypass flooding is considered. This occurs in those dry years when Yolo Bypass flooding does not occur.

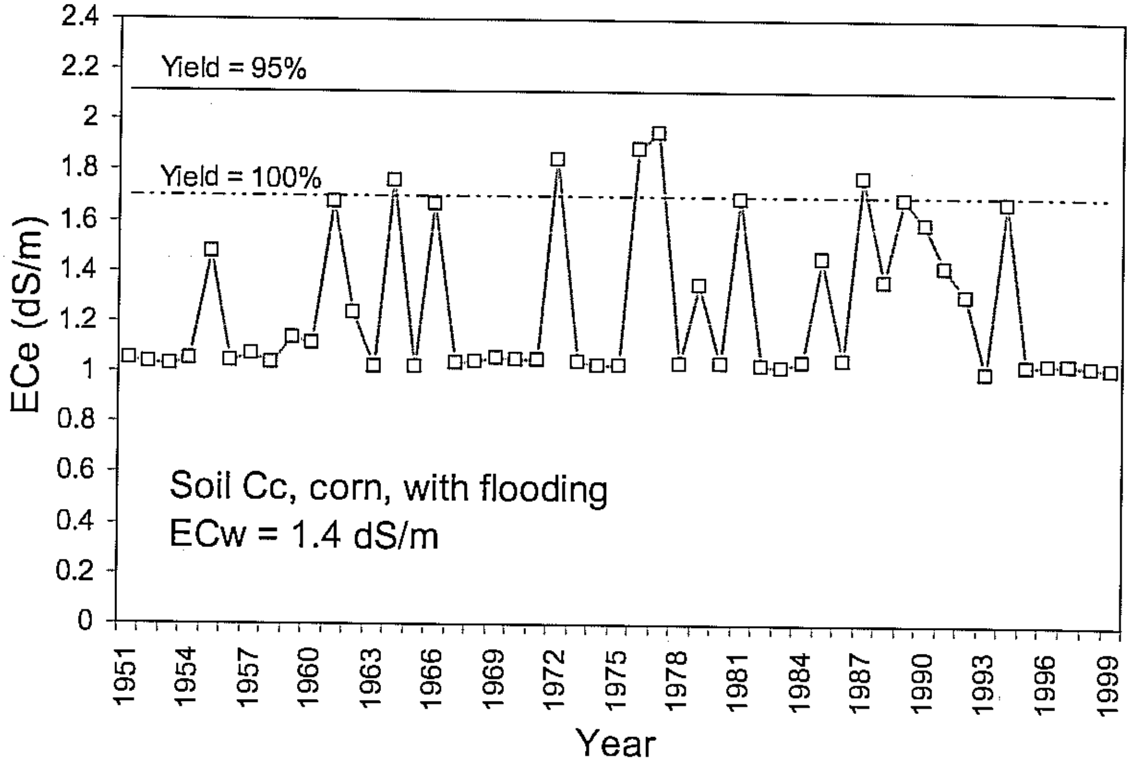


Figure 8. Electrical conductivity of the saturation paste extract (ECe) for the 53 years simulated for an irrigation water electrical conductivity (ECw) of 1.4 dS/m. Assumes corn grown in Cc soil when the Yolo Bypass flooding was considered.

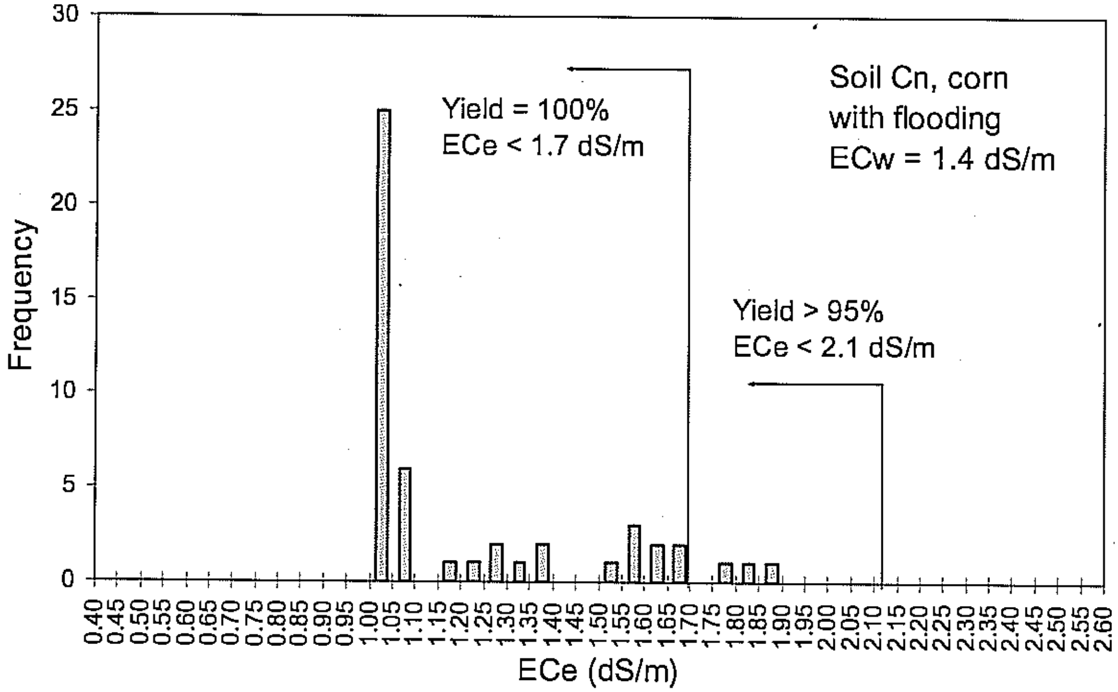


Figure 9. Histogram of the resulting seasonal electrical conductivity of the saturation paste extract (ECe) in soil Cn for the 53 years analyzed for electrical conductivity of the irrigation water 1.4 dS/m when Bypass flooding was considered.

Corn grown outside the Yolo Bypass

Simulation results were a bit different when the model is run using these Class one soils outside the Bypass. When no rainfall is considered, irrigation water with an ECw of 1.0 dS/m translates into a seasonal average rootzone salinity of 1.8 dS/m, which is higher than what occurs on the poorer soils inside the Bypass. This is also higher than what Ayers and Westcot (1985) predict using the steady-state approach.

The model was repeated using the soils outside the bypass and again using meteorological data for each of the 53 years. All other factors remained constant. Figure 10 illustrates the changes in rootzone salinity over the year when daily data from the median rainfall year (2002) was used. This relationship is similar to that using the poorer soil inside the Bypass (see Figure 5).

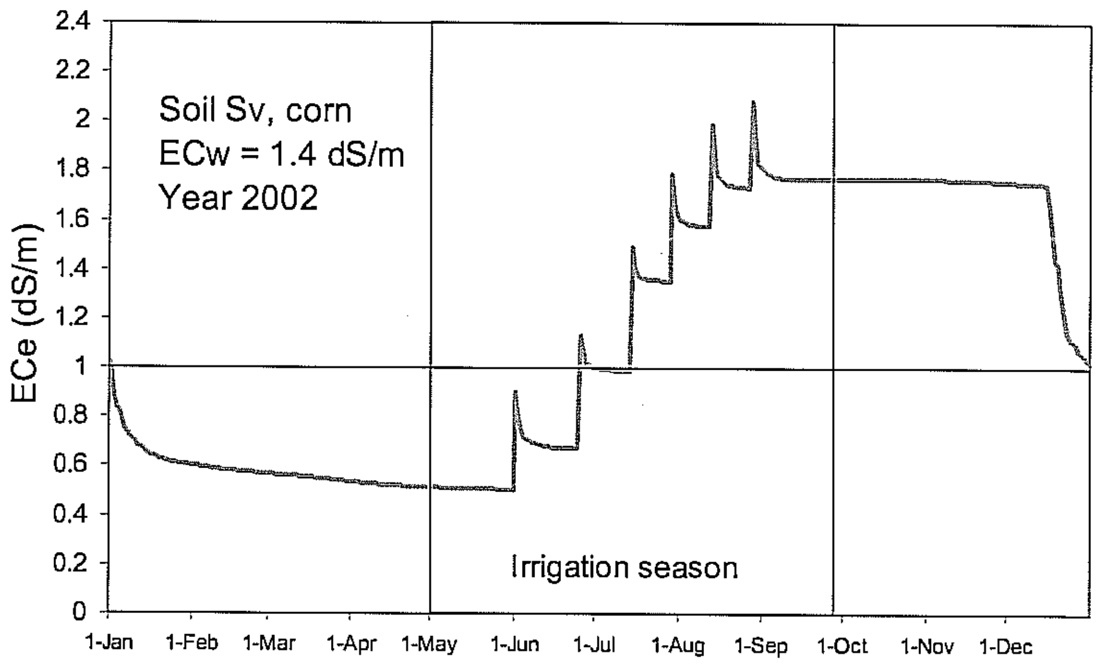


Figure 10. Changes in rootzone salinity (ECe) for corn grown in Sv soil outside the Bypass during the median precipitation year (2002). Assuming irrigation with an ECw = 1.4 dS/m).

The seasonal average rootzone salinity for all the 53 years is plotted in Figure 11. These data indicate that using irrigation water with an ECw of 2.0 dS/m, the mean ECe is 1.7 dS/m while the range varies between 1.2 and 2.2 dS/m. Those two years that result in seasonal rootzone salinities near 2.2 dS/m (EC_{90} for corn) occur under very dry years. If one excludes those years representing the driest years on record, then the maximum ECe that results in a particular year using an ECw of 2.0 dS/m is 2.0 dS/m. This value of 2.0 dS/m is very conservative and still represents one of the driest years on record.

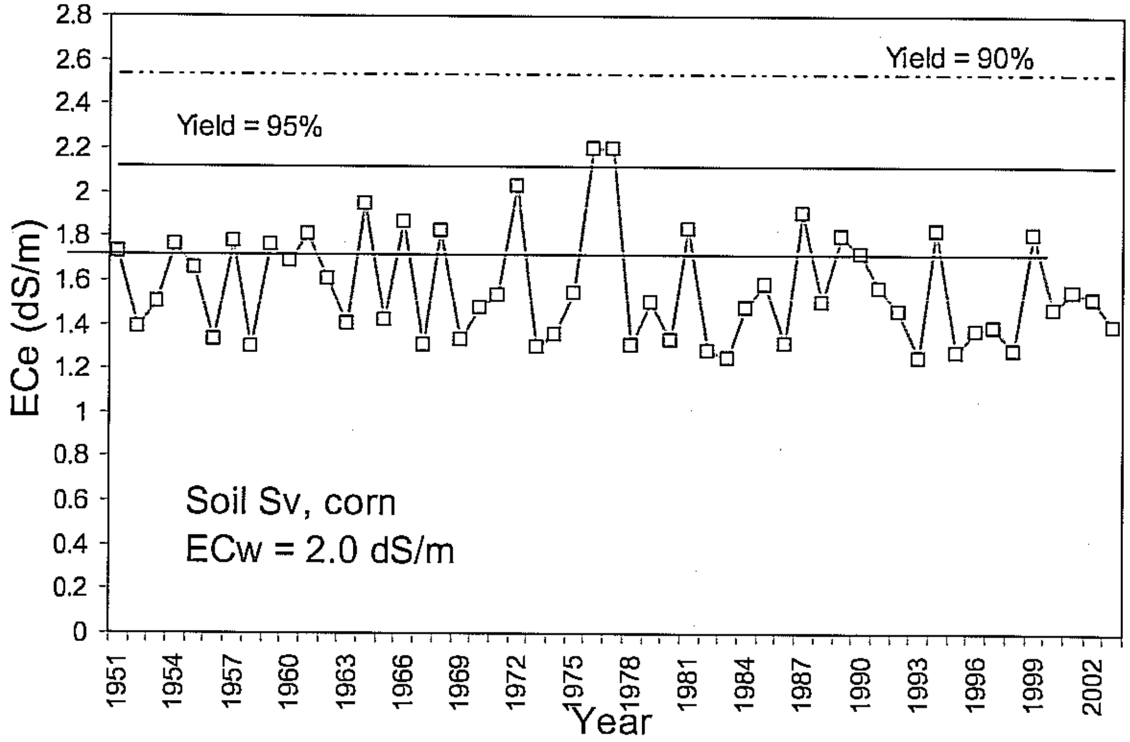


Figure 11. Electrical conductivity of the saturation paste extract (ECe) for the 53 years simulated for an irrigation water electrical conductivity (ECw) of 2.0 dS/m. Assumes corn grown in Sv soil.

The histogram in Figure 12 indicates the number of years a particular average-rootzone salinity is achieved using irrigation water with an ECw of 1.4 dS/m. For example, the highest frequency occurs at ECe of 1.05 dS/m, suggesting that using irrigation water with an ECw of 1.4 will more likely produce a salinity of 1.05 dS/m than it would an ECe of 1.3 dS/m. Nevertheless, an irrigation water with an ECw of 1.4dS/m can be used over 95% of the years and still maintain full (100%) yield potential.

The maximum ECw corn can tolerant and still achieve >90% yield potential at least 90% of the years (i.e.EC_{90} 2.5 dS/m, table 1), is 2.2 dS/m (Table 6). This value is slightly higher than the one found for irrigating corn on poorer soils inside the Bypass.

To be conservative, an ECw of 1.4 dS/m can be used over the long-term to irrigate corn grown inside and outside the Bypass. For soils outside the Bypass or those inside the Bypass and considering flooding, a higher tolerable ECw is found. Therefore setting a limit of 1.4 dS/m, will protect corn (i.e. maintain yield potential at 100%, >89% of the years) even under the worse case scenario.

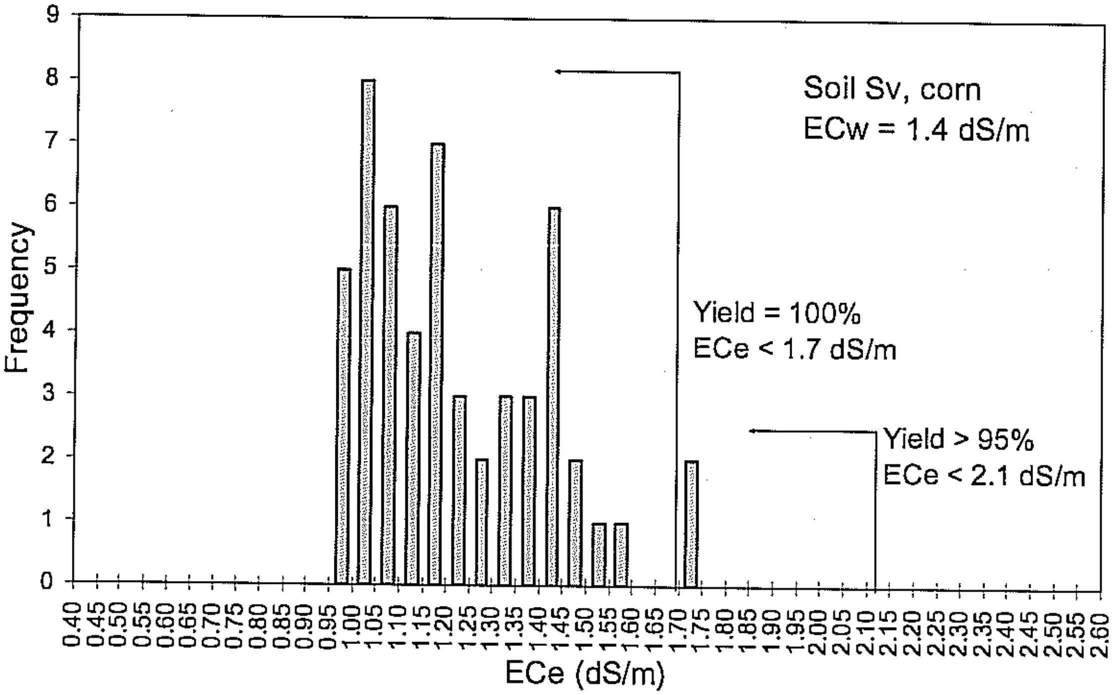


Figure 12. Histogram of the resulting seasonal electrical conductivity of the saturation paste extract (ECe) in soil Sv for the 53 years analyzed for electrical conductivity of the irrigation water 1.4 dS/m.

Table 6. Percentage of years having a yield potential (Y) equal to or higher than its corresponding seasonal average rootzone salinity (ECe)

For that particular yield potential in relation to various electrical conductivities of the irrigation water (ECw). Analysis assumes corn is irrigated on Sycamore soils (St, Sv) outside the Bypass.

ECw (dS/m)	Y 100%	Y>95%	Y>90%
	ECe = 1.7 dS/m	ECe=2.12 dS/m	ECe=2.53 dS/m
0.8	100%	100%	100%
1	100%	100%	100%
1.2	100%	100%	100%
1.4	95.20%	100%	100%
1.6	82.70%	100%	100%
1.8	63.20%	94.40%	100%
2	38.30%	80.70%	100.00%
2.2	21.90%	64.30%	93.60%
2.4	0.00%	48.20%	80.10%
2.6	0.00%	33.50%	65.30%

Rice

In the Yolo Bypass, like other places in the Sacramento valley, rice is grown in flooded basins (or checks). Irrigation water enters the top basin and flows sequentially from basin to basin through weirs where the field water evapoconcentrates as it moves along. Consequently, water in the bottom basin will have a higher salinity than that in the top basin. The model we developed for other more conventionally irrigated crops, where the net flux of water is vertically downward in the soil profile, could not be used for rice. Rather, we had to develop a different model that accounts for evapoconcentration of field water where the overwhelming movement of water in these fields, with low infiltration rates, is horizontal. The detailed description of the model is found in Appendix B. The goal in developing this model was to simulate the rice growing conditions in the Yolo Bypass in terms for field configurations, basin numbers (we selected 20 virtual basins), basin sizes and flow rates. The main output of the model was seasonal salinity of the field water (ECfw) since it is this parameter where rice salt tolerance has been developed (Grattan et al., 2002).

The mean ECfw values, considering different salinities of the irrigation water (ECw), are presented in Table 7. Along with these are other parameters that describe the maximum and minimum field water salinity among the 20 basins.

Table 7. Average salinity in the field water (ECfw mean); minimum and maximum EC (ECfw min and ECfw max) corresponding to the EC of the top and bottom basins; and mean yield loss for the whole field (YLm) for different salinities of the irrigation water (ECw).

ECw (dS/m)	ECfw mean (dS/m)	ECfw min (dS/m)	ECfw max (dS/m)	Yield Potential (%)
0.8	1.08	0.82	1.46	100
1	1.35	1.02	1.83	100
1.2	1.61	1.23	2.19	99.7
1.4	1.88	1.43	2.56	98.7
1.6	2.15	1.64	2.92	97.2
1.8	2.42	1.84	3.23	95.1
2	2.69	2.05	3.65	92.7
2.2	2.96	2.25	4.02	90.3
2.4	3.23	2.45	4.38	87.8

An ECw of 2.2 dS/m can be used such that the average field EC over the season (ECfw mean) is at the EC_{90} level (EC_{90} for rice is 3.0 dS/m, table 2). However, some of the lower basins will have ECfw values that exceed this EC_{90} value indicating that yields in all basins can not be above the 90% yield potential. When the ECw is lowered to 1.8 dS/m, the seasonal mean field-water EC (ECfw m) drops to 2.4 dS/m, equal to the EC_{95} value. This indicates that the average field-wide yield potential will be above the 95% level. However in this scenario, only the in bottom basin would yields fall to the 88% yield potential (see ECfw max).

The results of the simulations of the 53 years of data available in terms of probability of having a mean seasonal salinity (ECfw mean) higher than a given EC (i.e. the probability distribution function of the mean seasonal salinity) are presented in Figure 13 for different salinities of the irrigation water (ECw).

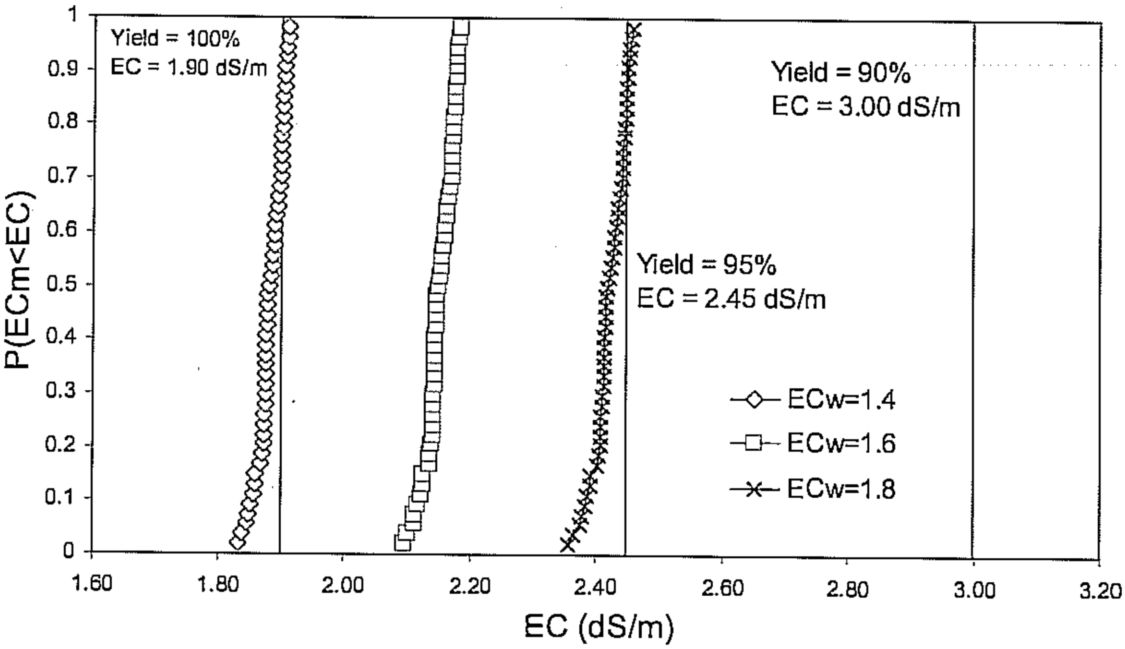


Figure 13. Probability distribution function of the mean seasonal electrical conductivity of field water, irrigated with water of different salinities (ECw).

The results in Figure 13 illustrate the mean seasonal EC (ECfw m) of the 20 virtual basins but do not show whether the ECfw in the lower basins are higher than the EC_{90} value (3.0 dS/m). Therefore, the possible yield losses in the lowest basins in the field are not reflected in this graph. However, it clearly shows that mean seasonal EC (ECfw mean) that corresponds to 95% yield potential can be maintained in essentially all 53 years using an ECw of 1.8 dS/m. This result is better illustrated in Figure 14.

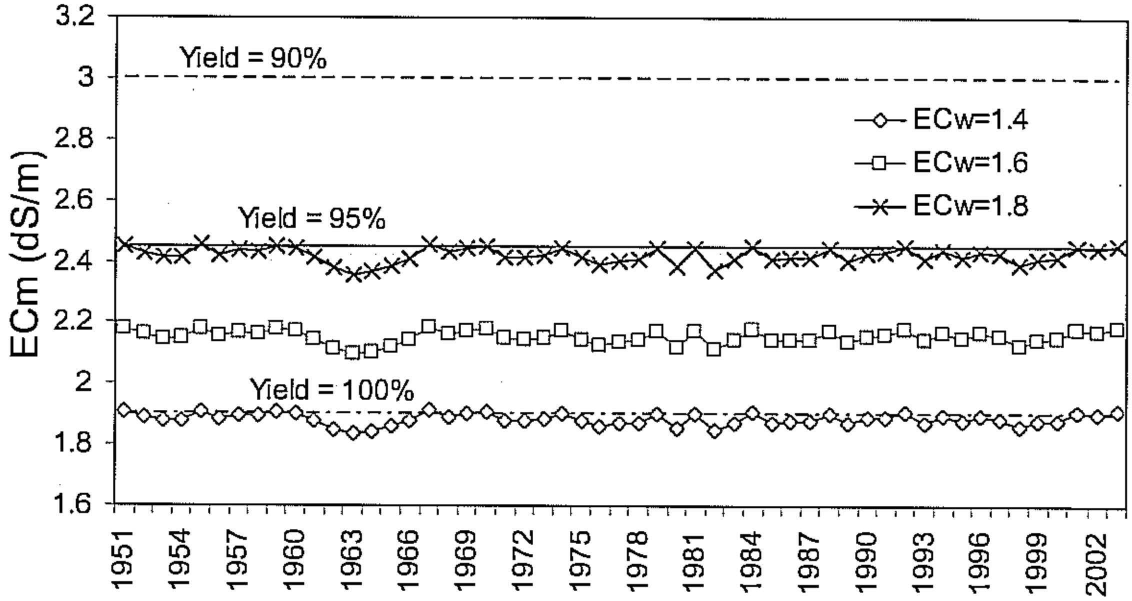


Figure 14. Mean EC in the rice plot for the 53 years simulated in relation to the limits for 100%, 95%, and 90% yield for three different ECw levels.

To be conservative, an ECw of 1.4 dS/m can be used all the years to maintain the seasonal average ECfw at or below the 1.9 dS/m, the yield threshold salinity value for rice.

Fluoride

Since World War II, industrial air pollutants have been found to be a major source of fluoride (F) that has accumulated in plant and animal tissue (Brewer, 1966). The major concern is not the adverse affect on plants, but rather the potential negative impact to livestock by eating forages with 50 mg F/kg dry wt.

The availability of fluorine in soil solutions to plants depends not so much on the total concentration in the soil, but rather it's ionic species (Stevens et al., 1998). The ionic species depends upon the soil type, pH and presence or absence of organic matter and ions that fluoride can complex with (Brewer, 1966; D. Suarez, personal communication, 2006). Fluorine is an element that can accumulate in plants but it is generally not a concern in neutral and alkaline soils where it is inactivated (Ayers and Westcot, 1985; Pratt and Suarez, 1990). The recommended maximum concentration in irrigation water for the long-term use for the protection of animals and plants was set at 1.0 mg/L, but that recommendation only implies to crops grown in areas with acid soils. In neutral and alkaline soils, fluoride complexes with magnesium and calcium so higher concentrations can be tolerated (Pratt and Suarez, 1990). In a recent study by Ruan et al (2004), they found that either adding calcium or increasing the pH, significantly reduced the F concentration in tea leaves.

Although it is extremely unlikely for F to be problematic in the Yolo Bypass or areas irrigated outside the Bypass, we ran an F speciation model using water quality data from samples collected from the City of Woodland's Waste Water Treatment facility collected in 2005.

Table 8. Water quality data based on samples from the City of Woodland's WWTP collected during the summer of 2005 and input from Stephen McCord, Larry Walker and Associates.

Constituent	Average (mg/L)	Average (meq/L)
Alkalinity (mainly HCO3)	335	5.5
Chloride	260	7.3
Sulfate	75.5	1.6
Fluoride	0.24	0.01
Calcium	67	3.4
Magnesium	60	5
Potassium	13	0.3
Sodium	180	7.8

The speciation for F was run with the MINTEQA2 program relased by the EPA (Allison et al., 1990) and cross-checked the PHREEQC model (a USGS model) yielding similar output for the free F- (D.Suarez, personal communication, 2006). Using the table of the constituents above, modified only by adding 2 meq/L of Cl to get charge balance, at pH 7.5 and F at 0.01mM (corresponding to 0.19mg F/L), results indicate that 89.3% of F exists as uncomplexed F- , with 1% as CaF+, 9% as MgF+, and 0.5% NaF . Increasing the F concentration to 1.9mg/L did not change the speciation distribution (i.e. same % complexation).

In a study to better understand the biogeochemistry of fluoride in plant-solution systems, Mackowiak et al. (2003) found that F was preferentially taken up in rice as the neutral HF^o complex and that F- uptake was likely restricted. This has important implications since pH has a large influence on both the F- and HF^o species. As the pH increases, the HF^o activity decreases dramatically suggesting that plants grown in neutral to alkaline soils would tolerate higher F concentrations because F would be present primarily as F-, not HF^o, thereby reducing plant uptake.

The pKa for HF is around 3.45, indicating that at pH 3.45, HF^o and F- have equal activities. At pH 6.45, HF^o is only 0.1% of the F- activity. At a pH of 7.45, the activity of HF^o will be 1/10,000 that of F-.

It has been known for half a century that soil management practices can readily be adopted to decrease the potential for fluoride toxicity. Liming soils to a pH above 6.5 will assure almost compete fixation of soluble fluoride in or added to the soil (Brewer, 1966). While the total fluoride concentration in the City of Woodland WWTP of 0.24 mg/L is far below the 1.0 mg/L upper limit for long-term irrigation on acid soils, the available concentration will be far less when taking into account site-specific soil conditions since soils in the Yolo bypass have a pH between 6.1 to 8.4. It is uncertain to what extent the F limit should be raised above the 1.0 limit based on the F chemistry in the soil solution until further research is conducted. It is important to understand that soils with neutral pH such as these, control the HFo concentrations to low levels protecting the crops from F uptake and damage. Taking into account Bypass flooding and rainfall will also increase allowable F concentrations in the irrigation water. Regardless, irrigation of crops with undiluted WWTP effluent from the City of Woodland will not pose a potential fluoride concern with respect to irrigated agriculture both inside and outside the Yolo bypass.

Boron

Boron (B) is an essential element for crops but has a small concentration difference between that considered deficient and that considered toxic. Certain crops, particularly trees and vines, are sensitive to B in the irrigation water and can develop injury to leaves or young stems if concentrations exceed 1 mg/L. Boron injury, if severe enough, will likely reduce yields beyond that predicted by EC alone but few data are available to predict such a yield loss (see Table 9).

The characteristics of boron injury are crop specific and are related to plant's ability to mobilize this element (Brown and Shelp, 1997). In certain species (e.g. alfalfa, bean, corn, tomato and wheat) boron is immobile within the plant and consequently it does not move out of the leaves once it has accumulated there. As such, B injury is characteristic of necrosis (burn) along the margins and tips of older leaves. Injury can occur when the leaf concentrations exceed 250-300 mg/Kg dry wt. In other species (e.g. almond, carrot, celery, grape, and stone fruits), boron is mobile within the tree and injury does not appear on leaves but rather in young stems as tip die back or in fruits as a gum discharge. For these crops, leaf analysis is not a viable method of assessing toxicity.

Threshold levels in the irrigation water that produce such injury are reported in FAO 29 (Ayers and Westcot, 1985). Most of the data where crops are classified as "sensitive" (threshold B < or equal to 1.0 mg/L in the soil water), were based on the work by Eaton (1944) or others from the 1920s-1960s. The B tolerance guidelines (Ayers and Westcot, 1985) are not all based on yield but are based on the maximum concentration above which plant injury is likely to occur.

Since publication of FAO 29 (Ayers and Westcot, 1985), there was a considerable about of boron research conducted in Riverside by L. Francois and F. Bingham. They conducted boron tolerance studies in sand tanks with the purpose of developing yield reduction functions with increases in boron in the soil water similar to what has been done with salinity. These investigators applied the same "threshold-slope" coefficient approach by Maas-Hoffman to express yield potential of certain crops. These values are presented in a book chapter by Maas and Grattan (1999).

Of the 17 crops where such coefficients are provided, nearly all sbow a relatively low reduction in yield with increases in soil boron (Table 9). This is quite different than crops behavior to increases in soil salinity. For example wheat and broccoli, crops with a reported boron tolerance threshold of 1.0 mg/L in the soil water, can tolerate 4.0 and 6.5 mg/L in the soil water, respectively, and still maintain 90% yield potential. By far, the most sensitive of the crops listed was bean. This crop could only tolerate 1.8 mg/L boron and maintain yield potential at 90% (i.e. B_{90}). Of those in Table 9 that are grain crops, B_{90} values varied between 4.0 to 9.5 mg/L.

Table 9. Maximum concentrations of boron in the soil water various crops can tolerate to maintain yield potential about 80, 90 and 95% yield potential (Source; Maas and Grattan, 1999).

Crop	Tolerance based on:	Boron concentration at 100% yield potential	Boron concentration at 95% yield potential	Boron concentration at 90% yield potential
Barley	Grain yield	3.4	4.5	5.7
Bean, snap	Pod yield	1	1.4	1.8
Broccoli	Head fresh wt	1	3.8	6.6
Cauliflower	Curd fresh wt	4	6.6	9.2
Celery	Petiole fresh wt	9.8	11.4	12.9
Cowpea	Seed yield	2.5	2.9	3.3
Garlic	Bulb yield	4.3	6.2	8
Lettuce	Head fresh wt	1.3	4.2	7.2
Onion	Bulb yield	8.9	11.5	14.1
Radish	Root fresh wt	1	4.6	8.1
Sorghum	Grain yield	7.4	8.5	9.5
Squash, scallop	Fruit yield	4.9	5.4	5.9
Squash, winter	Fruit yield	1	2.2	3.3
Squash, zucchini	Fruit yield	2.7	3.7	4.6
Sugar beet	Storage root fresh wt	4.9	6.1	7.3
Tomato	Fruit yield	5.7	7.2	8.6
Wheat	Grain yield	1	2.5	4

Boron has a higher affinity to the soil than common salts requiring much more water to reclaim soil B to pre-existing levels than it does to reduce the salinity to pre-salinization levels. For this reason, we consulted with experts at the US Salinity laboratory who have considerable expertise with boron soil chemistry. Boron's affinity for the soil is dependent upon many characteristics including among others clay content, organic carbon, pH, and soil surface area (D. Suarez and S. Goldberg, 2005, personal communication). These scientists are developing models to predict soil solution boron concentrations in relation to soil type, soil chemistry, ET and applied water. One of their models indicates that over the short term, much higher boron concentrations can be used than the guidelines indicate but over the long term, soils may eventually become saturated with boron (Suarez, 2002). Our model is not appropriate to predict soil boron behavior nor could it be readily adapted to account for complex soil boron chemistry. This is not to imply that this can not be done but rather it would take a more substantial undertaking to incorporate soil chemistry component into our model.

On the other hand, there are soil boron reclamation formula that can be used to estimate the percent reduction of B in soils from Yolo Bypass flooding. Hoffman (1980) developed a formula for boron reclamation where;

$$\%\ \text{Soil Boron Reduction} = (1 - 0.6\ Ds/Dw)\ 100$$

Ds and Dw refer to the depth of rootzone and infiltrated water, respectively. Based on this information and using the soil with the least infiltrated water (Sg), we could predict the % reduction in soil boron. The average depth of water infiltrated is 1884 mm considering only those years where flooding occurs more than 20 days. If rice were to be planted following the flooding period (a crop with a maximum rootzone of 6 inches or 152 mm), then over 95% of the soil boron will be removed during the flooding period. Therefore if boron in the soil accumulated to 5 mg/L the previous year (an extremely high and unlikely value), the soil boron would drop to 0.3 mg/L. Of the years where flooding occurred more than 20 days, the maximum boron removal by flooding was 98% and the minimum was 86%. In the worse case flooding scenario, a soil with a post season concentration of boron of 5 mg/L would drop to 0.7 mg/L boron. Considering that Yolo Bypass flooding occurs more years than not, this provides assurance that whatever boron has accumulated in the soils, the bulk of it is removed after a winter of Bypass flooding to levels fully protective of all crops.

There are only two crops listed in Table 9 that are dominant crops in the study area, sorghum and tomato. Although there is boron sensitivity information on other dominant crops in the area, such as corn and melon (Table 2), there is no information on yield losses with increases in soil boron concentration. Therefore one must be conservative in setting limits so as to assure protection of all dominant crops in the area even though data are not available for all the crops in the study area.

For these reasons, and consulting table 9, it is recommended that an interim limit be set at 1.5 mg/L. This is not to say that maximum yields can not be obtained should concentrations exceed this value, but more research is needed to determine specific tolerances of all the dominant crops in the Bypass. This 1.5 value is very conservative given the slow rate of yield reductions with increases in soil boron and if Yolo Bypass flooding is considered. In addition, a model, such as the one presented by Suarez (2002), might be able to be modified to determine long-term boron concentrations in the rootzone when using irrigation waters of variable B concentrations under historical rainfall conditions in the area.

Sodium Adsorption Ratio (SAR)

The sodium adsorption ratio (SAR) is an important water quality parameter that when used with the ECw, can assess the infiltration hazard of the water. The SAR is defined as

$$\text{SAR} = \text{Na}/[(\text{Ca} + \text{Mg})/2]^{1/2}$$

Where Na, Ca and Mg are the concentrations of sodium, calcium and magnesium in meq/L. Water that is very low salinity and those high in sodium relative to calcium and magnesium (i.e. high SAR) can pose problems for water infiltrating the soil. Both water quality conditions favor dispersion of clays, thereby reducing the fraction of large pores in the soil and thus water infiltration into the soil. Conversely, when salinity is high and the SAR is low, the water infiltration hazard is low.

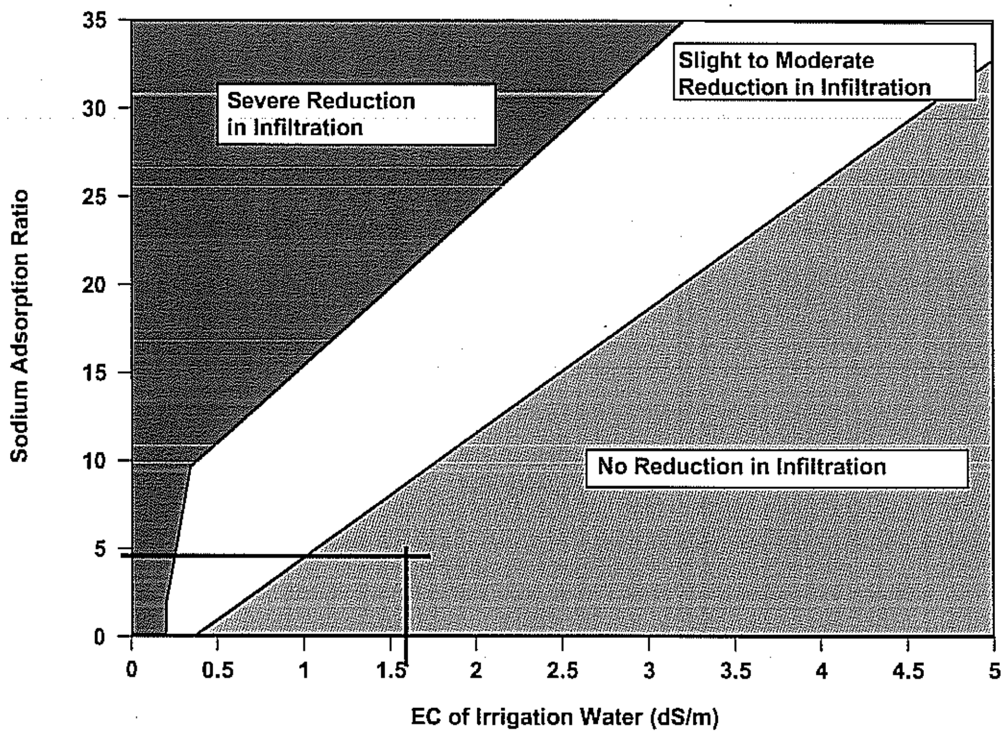


Figure 15. The relationship between ECw and SAR and the likeliness of the water causing a reduction in the infiltration.

Figure 15 shows the relationship between EC and SAR indicating the zones (combinations of ECw and SAR) where water infiltration is likely problematic and where it is not.

Based on the water composition of the water from the Woodland Waste Water Treatment plant, the SAR of the water is 3.8. When precipitation of calcite is considered, the SAR adj can be calculated (Ayers and Westcot, 1985) and the adjusted value is 4.3. When these values are considered along with the ECw, the water infiltration hazard can be assessed. Table 8 does not have a reported ECw value, but this value that can be closely estimated based on the relationship that EC (dS/) = (sum of the cations or anions in meq/l)/10. Based on this approach, the EC is about 1.65 dS/m.

The lines closely representing the EC 1.65 dS/m line and the SAR 4.3 line are drawn on Figure 15 intersecting in the blue (no water infiltration hazard zone). This indicates that the Woodland WWTP effluent water would not likely pose a water infiltration problem.

More importantly, unlike the other water quality parameters discussed above, SAR is a ratio that can readily be changed. Addition of gypsum ($CaSO_4$) to the water or soil will reduce the SAR should it become problematic in the future. The NRCS soils survey report indicates soils in the study area have low SAR values. Those outside the Bypass have an SAR of 0 while those dominant soils inside the Bypass have an SAR of 0-5. Should these soil SAR values still hold true, gypsum applications would probably not be beneficial.

Acknowledgements: We would like to extend thanks to Drs. D. Suarez and S. Goldberg at the USDA/ARS Salinity laboratory for their insightful discussions regarding soil boron and for D. Suarez in particular who ran the fluoride speciation analyses. We would like to extend our appreciation to Yolo Bypass growers Rogina Cherovsky; Jack Dewit and Ron Tadlock, who helped us identify dominant crops in the area and understand management practices in the study area.

APPENDIX A

DESCRIPTION AND DETAILS OF THE MODEL

Water Balance

The proposed model performs a water balance in the root zone. A salt balance is performed along with the water balance and, similar to the assumptions of Ayers and Westcot (1985), assumes that the solutes move freely with the soil water. This is not a bad assumption considering the composition of the water from the treatment plant and long-term nature of the simulation. The model also uses the approach by Ayers and Westcot (1985) by dividing the rootzone into four quarters (layers) of equal depth. The water inputs and outputs in each layer are calculated on a daily basis and the salt concentrations of each flow component are estimated assuming complete mixing and no chemical dissolution or precipitation.

The balance is performed on a daily basis because the available data (rainfall and temperature records for ET calculation) are given daily. The inputs for the first (top) layer are the applied irrigation (I) and rainfall (P), and the outputs are the drainage above field capacity (D, from layer 1 to layer 2), 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, flow below field capacity (U) is considered between layers and is calculated in daily steps. It is related to the difference in the water content (more precisely in 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.

ET is calculated in each layer using appropriate Kc values (Goldhamer and Snyder, 1989), ETo data calculated by the Hargreaves formula (Hargreaves and Allen, 2003) and a stress factor that takes into account the soil water content that limits water uptake when water in the soil drops below the RAW.

The daily ETo was calculated from the daily maximum (T_{max}) and minimum (T_{min}) temperatures and the extraterrestrial radiation (R_a) by the Hargreaves formula:

$ETo(mm/d) = 0.0029 \cdot R_a \cdot (T_m) \cdot (T_{max} - T_{min})^{0.4}$ where T_m is the mean daily temperature $\left(T_m = \frac{T_{max} + T_{min}}{2}\right)$ and R_a is calculated in MJ m^{-2} d^{-1} from the latitude and the day of the year and converted to mm/d dividing by the latent heat of evaporation (Allen et al., 1998). We used the latent heat of evaporation calculated at temperature $T_{\min} + \frac{3 \cdot (T_{\max} - T_{\min})}{4}$, approximately the mean temperature during the day hours, when extraterrestrial radiation takes place.

These monthly ETo estimates using the Hargreaves formula were slightly higher than the monthly values presented by Goldhamer and Snyder (1989), the ETo estimates we regarded as the most reliable site-specific information. The regression relating the mean monthly values of ET calculated for the period 1951-2004 by the Hargreaves formula ($ET_{Har\,mo}$) to the mean monthly estimates of Goldhamer and Snyder (1989) —ET_{om}— was $ET_{om} = 1.04 \cdot ET_{Har\,mo} + 22.53, \quad R^2 = 0.996$. Thus, daily estimates of ETo by the Hargreaves formula (ET_{Har}) were transformed by the formula $ETo = 1.04 \cdot ET_{Har} - \frac{22.53}{30}$ when ETo was greater than 0. The original ET_{Har} was used whenever ETo resulted < 0.

The achievable, non-stressed crop ET is calculated as ETc = Kc ETo. Between cropping seasons, all ET [or evaporation (E) since there is no crop] is assumed to take place from the upper layer. Kc is calculated taking into account the interval between precipitation events of each month and the ETo (Cuenca, 1989). ET for the initial development stage (Stage 1) was also calculated in this way considering irrigations to establish the interval between wetting events following the method proposed by Allen et al. (1998).

The crop coefficients for the full development stage (Kc mid, Stage 3) and for the end of the growing season (Kc end) were taken from Goldhamer and Snyder (1989). For the crop development stage (Stage 2), Kc was interpolated linearly between Kc of the last day of the initial stage and Kc mid. The Kc is also interpolated linearly between Kc mid and Kc end for the late season period (Stage 3).

Similar to the assumptions by Ayers and Westcot (1985), during the growing season the extraction pattern for each descending quarter-layer of the rootzone is 40%-30%-20%-10% for flood irrigation and 60%-30%-7%-3% for drip irrigation. Therefore the achievable crop ET from layer "j" is ETc(j) = C_j ETc where $C_1 = 0.4$, $C_2 = 0.3$, $C_3 = 0.2$, and $C_4 = 0.1$ for flood irrigation and $C_1 = 0.6$, $C_2 = 0.3$, $C_3 = 0.07$, and $C_4 = 0.03$ for drip irrigation.

There are two crop-dependent parameters: the effective rooting depth (RD, mm) and the ratio of readily available soil water (RAW) to TAW (p = RAW/TAW) (Allen et al., 1998). The importance of this parameter is that not all of the TAW is equally available to the plant and that crops extract soil water much more readily near the FC limit than they do near the WP limit. When the soil water content [W(j)] in a layer falls below We(j) = WP + (1-p) TAW, the ET from that layer [ETr(j)] drops below the ETc(j). The actual ET of the layer is taken as ETr(j) = Ks·ETc(j), where Ks is a stress coefficient calculated following Allen et al. (1998):

$$Ks = \begin{cases} 1\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & if \quad W(j) > We(j) \\ \dfrac{W(j) - We(j)}{We(j) - WP(j)} & if \quad WP(j) < W(j) < We(j) \\ 0\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & if \quad W(j) < WP(j) \end{cases} \quad \text{[Eq. 1]}$$

where WP(j) is the permanent wilting point for layer "j". Surface runoff (SR) was considered out of the growing season when rainfall occurs so that the model will not overestimate the infiltrated rainwater. This, along with the out of the season evaporative component, determines "effective rainfall" rather than considering the total rainfall.
Surface runoff was calculated following the curve number methodology of the former Soil Conservation Service (Chow, 1988). The curve umber (CN) is estimated from the hydrologic properties of the soil for infiltration and the properties of the soil cover. Usually the rainfall in the previous 5 days is considered, but since we were performing a soil-water balance, our modification was done according to the water content of the surface layer (W) as follows:

$$CN = \begin{cases} CN(I) = \dfrac{4.2 \cdot CN(II)}{10 - 0.058 \cdot CN(II)} & if \quad W \le \dfrac{WP + FC}{2} \\ CN(II) \quad \cdots \quad \cdots \quad \cdots \quad \cdots & if \quad \dfrac{WP + FC}{2} < W < \dfrac{FC + S}{2} \\ CN(III) = \dfrac{23 \cdot CN(II)}{10 + 0.13 \cdot CN(II)} & if \quad W \ge \dfrac{FC + S}{2} \end{cases} \quad \text{[Eq. 2]}$$

The curve number determines the maximum potential retention (S, related to the amount of rainfall needed to cause runoff): $S = 254\left(\dfrac{100}{CN} - 1\right) mm$. Then runoff is calculated as

$$SR(mm) = \begin{cases} \dfrac{P'(mm) - 0.2 \cdot S^2}{P'(mm) + 0.8 \cdot S} & if \ P' > 0.2 \cdot S \\ 0\ldots \ \ldots \ \ldots \ \ldots & if \ P' \le 0.2 \cdot S \end{cases} \quad \text{[Eq. 3]}$$

where P' is the rain of a single precipitation event, since the curve number method is applied to single rainfall events. Since we had no data for precipitation events, only daily rainfall totals, we assumed that the total rainfall in 24 hours took place in a single event and calculated the runoff that it produced. This was a conservative approach that probably leads to an excess runoff and a slight underestimation of infiltrated rain-water than would otherwise occur.

Drainage from upper to lower layers is calculated with use of two terms. We considered that when the soil water content [W(j)] was above FC(j), the excess water drained to the lower layer over a two-day period. An empirical term D is defined for the drainage above FC, so that W drops to FC in two days (or one) and that the flow is higher in the first day than the second. The fraction of the excess water (Ex = W-FC) that is drained the first day (α, $0 < \alpha < 1$) is calculated through an empirical relation obtained to match the results presented by Hillel and van Bavel (1976) for three soil types considered in this report. For that purpose, two arbitrary water contents in excess of FC, Wa and Wb, are defined from the FC and saturation (S) of the soil layer and the fraction α: $Wa = FC + (1-\alpha)\cdot(S - FC) < Wb = FC + \frac{1-\alpha}{\alpha}(S - FC)$ and D is calculated as:

$$D = \begin{cases} \alpha \cdot (W - FC) \ldots\ldots\ldots\ldots \text{if} \quad W > Wb \\ (1-\alpha)\cdot(S - FC) \ldots\ldots \text{if} \quad Wa < W < Wb \\ W - FC \ldots\ldots\ldots\ldots\ldots\ldots \text{if} \quad W < Wa \end{cases} \qquad \text{[Eq. 4]}$$

Additionally, there is a slow drainage term that follows the matric potential between soil layers. This term is only considered when W < FC+0.5·(Wa-FC), indicating that when W is well above FC, water movement depends mainly on the water content of the soil. However when W is considerably lower, water movement depends more on the water content of adjacent layers and their soil properties. This term allows for the redistribution of water in the profile, such as the wetting of the upper layer from lower layers when soil water is depleted by ET.
The soil matric potential in each layer is calculated by means of the equation

$$\psi = \psi_S \cdot \left(\theta / \theta_S \right)^{-b} \qquad \text{[Eq. 5]}$$

where θ is the volumetric water content, θ_S is the volumetric water content at saturation, ψ_S is the water entry potential or "saturation" water potential, and *b* is the slope of the water retention curve on a logarithmic plot (Clapp and Hornberger, 1978). For each soil type, we calculated *b* and ψ_S from the volumetric water content at field capacity and wilting point (θ_{FC} and θ_{WP}) and their respective potentials assumed to be: $\psi_{FC} = 316$ cm and $\psi_{WP} = 15849$ cm [so that pF(FC) = 2.5 and pF(WP) = 4.2]. Taking logarithms in the expression of the potentials for FC and WP become linear equations

$$\log(\psi_{FC}) = 2.5 = \log\psi_S - b \cdot \log(\theta_{FC} / \theta_S)$$
$$\log(\psi_{WP}) = 4.2 = \log\psi_S - b \cdot \log(\theta_{WP} / \theta_S)$$

from which we obtain *b* and θ_S for that soil layer.
The unsaturated hydraulic conductivity for a given volumetric water content, K, is

$$K = K_S (\theta / \theta_S)^{2b+3} \qquad \text{[Eq. 6]}$$

where K_S the saturated hydraulic conductivity. In a given day, we used for unsaturated conductivity between two layers (K_{1-2} between layers 1 and 2, e.g.) the harmonic mean of the conductivities of both layers:

$$K_{1-2} = \left(\frac{K_1^{-1} + K_2^{-1}}{2} \right)^{-1} \qquad \text{[Eq. 7]}$$

Thus, the flow between layers 1 and 2 (U_{1-2}) is calculated as

$$U_{1-2} = K_{1-2} \cdot \left(1 + \frac{\psi_2 - \psi_1}{\Delta Z}\right) \quad \text{[Eq. 8]}$$

where ΔZ is the distance between layers, ¼ of the rooting depth. For the flow from layer 4 to below we assumed that water flowed down by gravitational potential only, indicating that there is no restrictive layer, and the soil properties are similar at least in the layer above and below layer 4, as is the case in all the soils studied. The unsaturated hydraulic conductivity is taken as that of the fourth layer, that is: $U_{4\rightarrow} = K_S\left(\theta / \theta_S\right)^{2b+3}$ where the parameters K_S, θ_S and b correspond to layer 4 and θ is the volumetric content in layer 4.

The terms of the water balance are incorporated into the balance as follows. For layer 1 with an initial water content W_0 in day 0 the irrigation and precipitation (I_1 and P_1) of day 1 are added, and the surface runoff for day 1 (SR_1) [calculated with Eq. 3 based on P_1 and W_0 (which is used to establish the moisture conditions for the calculation of CN, Eq. 2)] is subtracted. The new water content of the layer is $W_1^a = W_0+P_1+I_1-SR_1$. Next, this water content after irrigation, precipitation and surface runoff (W_1^a) is used to determine the drainage above field capacity or rapid drainage (D_1) by use of Eq. 4. Third, the ETr is calculated using the water content after D, $W_1^b = W_0+P_1+I_1-SR_1-D_1$ to determine the stress coefficient Ks (Eq. 1). The same calculations are performed for layers 2, 3 and 4 where the inputs are the fast drainage D from the upper layer instead of I and P and obviously without considering SR. In layer 2, for example, the process is: $W_1^a(2) = W_0(2)+D_1(1)$; $W_1^b(2) = W_1^a(2)-D_1(2)$; $W_1^c(2) = W_1^b(2)-ETr_1(2)$, with the terms in brackets indicating the layer and sub-indexes indicating the day.

Finally, the water content after D and ETr ($W_1^c = W_0+P_1+I_1-SR_1-D_1-ETr_1$) is used to establish the redistribution of water in the profile, U. For example, for layers 1 and 2 the water contents in day 1 after the other terms of the balance have been considered are $W_1^c(1) = W_0(1)+P_1+I_1-D_1(1)-SR_1-ETr_1(1)$ and $W_1^c(2) = W_0(2)+D_1(1)-D_1(2)+ETr_1(2)$, where the terms in parentheses specify the layer and the sub-indexes stand for the day. The volumetric water contents used to calculate $U_1(1)$ (redistribution flow from layer 1 to 2 if positive, or from layer 2 to 1 if negative) are $\theta_1 = W_1^c/\Delta Z$ and $\theta_2 = W_2^c/\Delta Z$ (ΔZ is the depth of the layer, ¼ of the rooting depth). The matric potentials ψ_1 and ψ_2 (Eq. 5) as well as K_1 and K_2 (Eq. 6) are calculated from these θ_1 and θ_2 values and the unsaturated conductivity between layers 1 and 2 is given by Eq. 7. All these terms determine the flow $U_1(1)$ (Eq. 8).

Results of the water balance for an almond orchard in Fresno considering the median rainfall year (1981) for a uniform soil type where all four layers have the same soil characteristics of S, FC and WP, are shown in Figure 1. The increase in the soil water content in each of the 4 layers (W(1)- W(4)) after irrigation or rainfall events and their subsequent depletion in the days that follow can readily be seen. It is also clear that the upper layers deplete to lower water contents between irrigations or rainfall events than do lower layers.

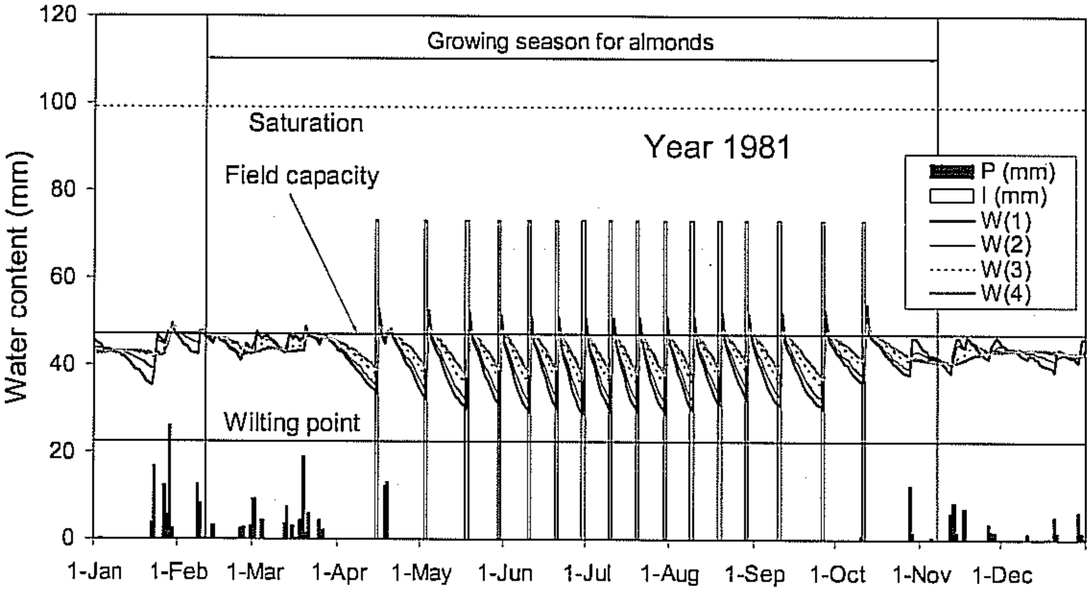


Figure 1. Changes in soil water coutent in the four soil layers over the course of the median rainfall year (1981) in almonds grown in a soil in the Fresno area. Precipitation (P) and the irrigation events (I) for flood irrigation are also illustrated.

ET takes place only from the upper layer at times outside the growing season, and from all four layers during the growing season, as shown in Figure 2. Occasionally the total ET from the soil (sum of the 4 ETr) does not match the achievable ETc, suggesting that some water stress occurs to the crop (Fig. 2). The high frequency of irrigations in the study area for both crops, leads to a very good use of the water by the crops, and ETr is just a little under ETc during the growing season in most of the years.

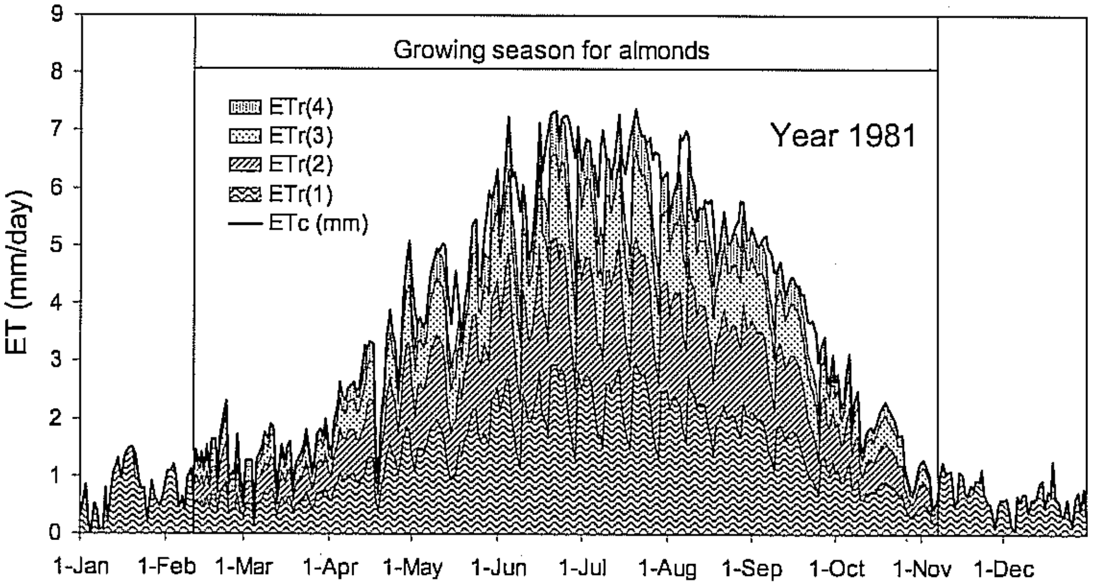


Figure 2. ET from the each soil layer [ETr(1), ETr(2), ETr(3), and ETr(4)] and maximum achievable crop ET (ETc) in almonds irrigated by flooding on Fresno soil (Hst) during the median year (1981).

Salt Balance

The salt balance is performed along with the water balance assuming that there is a complete mixing of the incoming flows with the water in each layer. It is assumed that the EC and TDS of the soil solution behave like conservative solutes such as Cl. These processes are identical for most solutes but data are presented only for the EC.

Salinity of the irrigation water (ECw) is used as a variable input where several values are selected in the range of interest. The salinity of the rainfall (ECp) is very low and actual values were taken from available data. These inputs mix with the water present in the first layer the previous day (W_0 with soil solution salinity $ECsw_0$).

Salts removed by surface runoff were also considered. Surface runoff is mixed completely with the upper 1 cm layer of the soil, such that the resulting EC of SR is derived from the equation

$$ECw \cdot I_1 + ECp \cdot P_1 + ECsw_0 \cdot W_0 \cdot \frac{Zml}{\Delta Z} = ECsr \cdot \left(I_1 + P_1 + W_0 \frac{Zml}{\Delta Z} \right) \qquad \text{[Eq. 9]}$$

where *Zml* is the depth of the mixing layer for SR (1 cm) and soil salinity for day 1 in layer 1 is obtained as

$$ECsw_1{}^a = \frac{W_0 \cdot ECsw_0 + I_1 \cdot ECw + P_1 \cdot ECp - SR_1 \cdot ECsr_1}{W_1{}^a} \qquad \text{[Eq. 10]}$$

The salt remaining in the layer ($ECsw_1^a \cdot W_1^a$) is concentrated by ET from that layer

$$ECsw_1^c \cdot \left(W_1^a - ETr_1\right) = ECsw_1^c \cdot \left(D_1 + W_1^c\right) = ECsw_1^a \cdot W_1^a \quad \text{[Eq. 11]}$$

and the salinity of both the water remaining in the layer (W_1^c) and drainage to layer 2 (D_1) is given by $ECsw_1^c$. The same procedure is applied to the other layers taking D from the upper layers as inputs and D to lower layers as outputs. Finally, the redistribution flow (U) is considered and the salinity resulting for the layer in the next day is given by (layer 1)

$$ECsw_2(1) = \begin{cases} \dfrac{ECsw_1^c \cdot W_1^c - U_1 \cdot ECsw_1^c(1)}{W_2} & \text{if } U_1 \geq 0 \\ \dfrac{ECsw_1^c \cdot W_1^c + U_1 \cdot ECsw_1^c(2)}{W_2} & \text{if } U_1 < 0 \end{cases} \quad \text{[Eq. 12]}$$

Once the soil water salinity ECsw has been calculated, the corresponding salinity of the saturation extract is calculated taking into account the water content of the soils. For layer *k* and day *j* the EC of the saturation extract [$ECe_j(k)$] is calculated from the EC of the soil solution of that day [$ECsw_j(k)$] as

$$ECe_j(k) = ECsw_j(k) \cdot \frac{W_j(k)}{S(k)} \quad \text{[Eq. 13]}$$

where $W_j(k)$ is the water content of the layer and S(k) the saturation water content of that layer. The daily ECe's are averaged for the 4 layers resulting in the mean daily ECe of the root zone in day *j*:

$$ECe_j = \frac{1}{4}\sum_{k=1}^{4} ECe_j(k) \quad \text{[Eq. 14]}$$

Generally crops respond to the mean salinity of the root zone over the entire growing season (Ayers and Westcot, 1985). Therefore the daily values of ECe_j are averaged over the entire growing season

$$ECe = \frac{\sum_{Growing\ Season} ECe_j}{Number\ of\ days\ in\ the\ growing\ season} \quad \text{[Eq. 15]}$$

which gives the seasonal-average rootzone ECe. It is this value that is compared with the crop salt tolerance ECe values. Historically, the goal in salinity management is to manage the water such that the soil salinity 'threshold' value (ECe) for the given crop (ECth) is not exceeded. For example, if ECe < ECth there is no yield loss during that year, but if ECe > ECth the yield loss depends on the slope of the yield-ECe curve for the given crop. However in light of the discussion in the report about the uncertainty of 'threshold' values and their appropriate use, other ECe values can be used for a particular level of protection.

The mean daily ECe values for a particular year, assuming that the irrigation water ECw is 1.2 dS/m, are illustrated in Figure 3. Each irrigation event adds some salts that are leached as drainage following the irrigation, causing the spikes in the growing season. The reduction in salinity in the winter and early spring is due to leaching by rainfall.

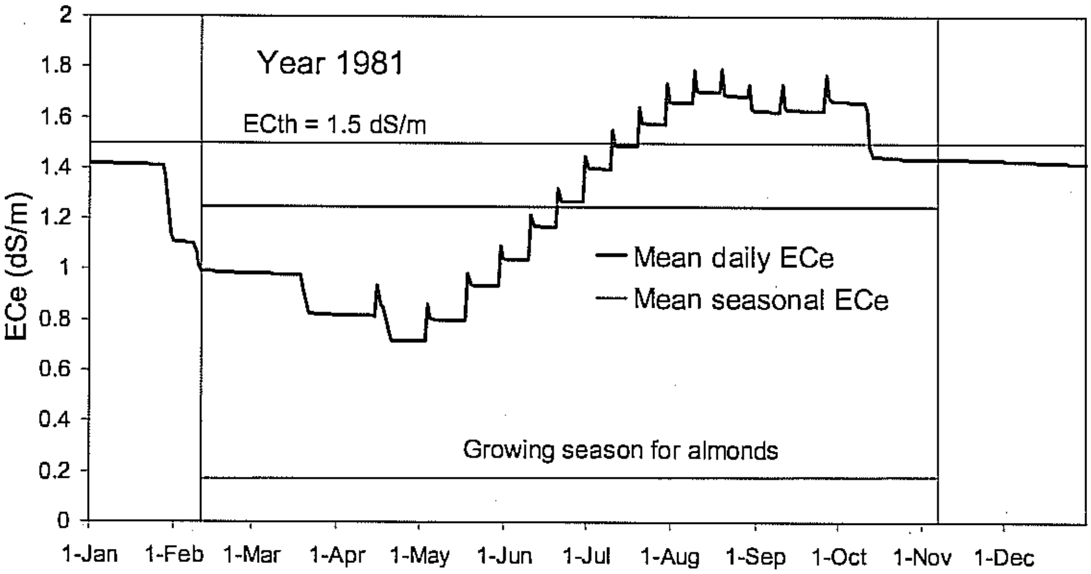


Figure 3. Mean daily electrical conductivity of the saturation extract (ECe) and mean seasonal weighted ECe for almonds grown on soil Hst by flood irrigation (ECw = 1.2 dS/m) in the median rainfall year 1981. The illustrative purposes, the threshold ECe during the growing season for yield reduction in almonds is also shown (ECth = 1.5 dS/m).

Under drip irrigation, the water uptake pattern is different (0.6-0.3-0.07-0.03) and the crops more closely respond to the average soil salinity, weighted by water uptake in each layer (Ayers and Westcot, 1985). Therefore under drip irrigation, the ECe of the layers averaged by the water extraction from each layer was used to characterize the resulting daily ECe of the soil, i.e., for a given day:

$$ECe = \frac{ECe(1)\cdot ETr(1) + ECe(2)\cdot ETr(2) + ECe(3)\cdot ETr(3) + ECe(4)\cdot ETr(4)}{ETr(1) + ETr(2) + ETr(3) + ETr(4)} \qquad \text{[Eq. 16]}$$

rather than Eq. 14.

Drip irrigation, where irrigations are more frequent using smaller volumes of water each irrigation, gives rise to a slightly different soil salinity patterns over the year. The spikes are not so evident and the mean salinity is usually higher than under surface irrigation (Fig. 4).

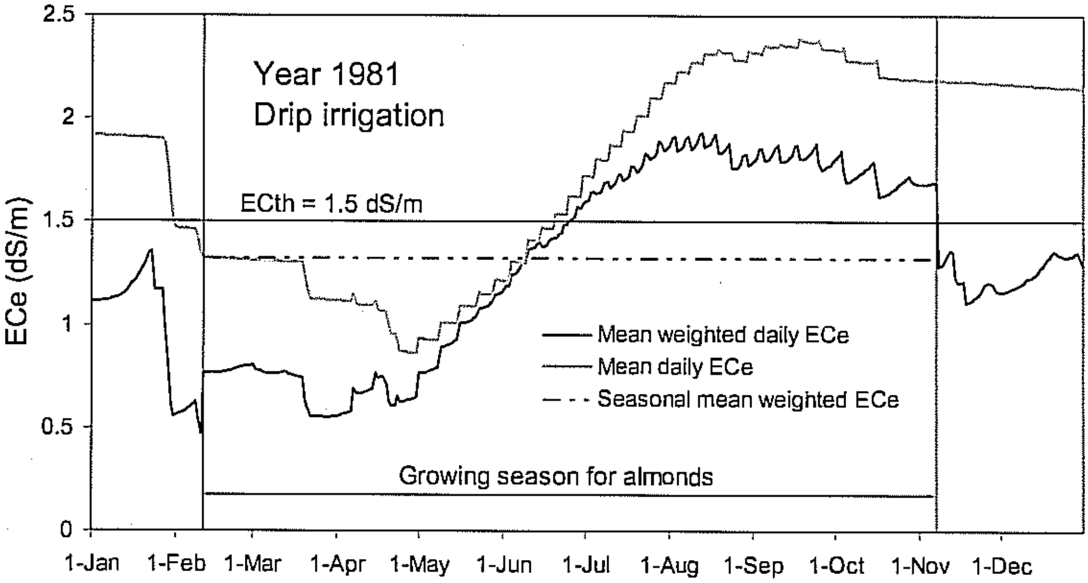


Figure 4. Mean daily ECe of the crop rootzone and mean water-uptake weighted daily ECe for almonds grown on a Fresno soil (Hst) with drip in the median rainfall year 1981. The ECw was 1.2 dS/m and seasonal mean water-uptake weighted ECe was about 1.3 dS/m, well below the yield threshold ECe of 1.5 dS/m.

APPENDIX B

MODEL TO SIMULATE THE SALINITY (EC) OF THE STANDING WATER IN RICE FIELDS

The salt tolerance of rice has been assessed based on yield response to the salinity (the electrical conductivity, ECfw) of the field water (Grattan et al., 2002). The threshold ECfw for rice (that is, the ECfw for which there is no yield loss) that provided the best "least squares" fit was 1.9 dS/m, and the slope of the yield decline above that threshold EC was 9.1 %/(dS/m). Therefore that ECfw value that represents 90% yield potential is 3.0 dS/m.

Our approach consisted of dividing the rice field into a number of virtual basins (20) and we modeled the electrical conductivity of the standing water (ECfw) in each of the basins as it sequentially moved and evapoconcentrated (combined transpiration of the crop and evaporation from the field water) across the field from basin to basin. We assumed that irrigation water is delivered to the field through a single inlet and moves across the first basin, then onto the second basin and so on. Water moves to the next basin only after it has flowed over the entire length of the previous basin. This is a conservative method and results in the highest possible ET (thus the worst possible case for salinity increases). If water flowed from one basin to the next through other paths, without traveling along the whole check, the resulting salinity would be lower. Therefore this represents the worst-case scenario for evapoconcentration.

The movement of water in a basin is based on the features of rice irrigation systems in the Sacramento Valley, and the parameters chosen for the model resemble normal irrigation practices in this area.

The simulation was made on a unit area basis. The volumes of water (applied or lost to evapotranspiration (ET) or deep percolation) are given in mm, as volume per unit area. The first basin receives the total irrigation amount normal for the area. ET for a particular day in a particular basin is taken as 1/20 of the daily ET for the entire area but percolation is calculated differently for each basin, depending on the amount of water that has already infiltrated into the soil. Water inputs by rainfall were neglected, again representing a worst- case scenario. The model was then applied to the 53 years with meteorological information available to obtain the probability distribution of the resulting ECfw, and its influence on the yields.

Evapotranspiration

Daily reference ET (ETo) was calculated by the Hargreaves method, based on the daily maximum and minimum temperature and solar radiation. The growing period for rice was taken from May 13 to October 6 every year; a 146-day growing season (Goldhammer and Snyder, 1989). Crop coefficients were taken from Goldhammer and Snyder (1989): Kc initial = 0.95, Kc mid = 1.24 and Kc end = 1.00; as well as the length of the seasons. The crop coefficients for each day were determined from these following the FAO procedure to Allen et al. (1998).

Percolation

According to a University of California leaflet (1980), in the first days of the irrigation period, 12 to 16 cfs per 100 acres (from 72 to 96 mm/day) are applied to rice fields to provide about 12" (150 mm) of water to the soil and create a depth of about 6" (75 mm). The fields have to be flooded in about 4 days, and then the volume of water applied is reduced to 2-3 cfs/100 acres in the rest of the season. After that, the usual percolation is about 1' to 4' for the whole season (that is 0.2 to 0.8 mm/day). Based on these reference values, we took a storage capacity for the soil of 180 mm. Percolation in each basin is taken as half the water left to replenish a storage of 9 mm (one twentieth of the total 180 mm storage per unit area) until the storage is filled, and then as 0.8 mm/day thereafter. That is, percolation is a function of the water stored in the soil. This condition applies only until the soil is replenished to 180 mm (a few days after the flooding begins). After that, percolation drops to a constant value of 0.8 mm/day. Again we assumed the higher possible percolation (in the range given by Division of Agricultural Sciences University of California, 1980) because it is the most restrictive case for salinity. Thus percolation for day 1 in basin "*j*" ($p_1{}^j$) was calculated as:

$p_1^j = \max\begin{Bmatrix} k\cdot\left(S_{\max}^j - S_0^j\right) \\ p_{\min} \end{Bmatrix}$ with $S_0{}^j$ the water storage in the check the previous day (day 0), $S_{max}{}^j = 180$ mm (the same S_{max} for all basins, that is, for all "*j*"), $p_{min} =$ 0.8 mm/day and $k = 0.5$. The values of k and S_{max} were chosen so that the after irrigation begins the field was flooded in about 4 days, which is the usual for rice fields in Sacramento Valley (Hill et al., 1991).

This approach to calculate percolation only required 3 soil related parameters (p_{min}, k, and S_{max}) that were chosen from known features of rice irrigation systems in the Sacramento Valley, and are thus independent from the particular soils irrigated.

Water Balance

The water balance was performed in daily time steps. That is, water inputs and outputs into and from each virtual basin were calculated in daily steps. The height of the field water was taken as 180 mm for the whole season since the beginning of the irrigation, that means that the height for each virtual check is 1/20 of 180 mm, i.e., 9 mm. As water flowed into the first basin, ET and P were calculated and deducted from the input, from the remaining water, 9 mm are kept in the basin and the rest is taken as the inflow into the next basin. In this way, for a given daily input, water advanced into a certain number of basins and with the parameters chosen, water reached and flooded the last basin after 4 days. The water sheet in a basin may be different form 9 mm in the beginning of the season (if the input minus the output for that day is not greater than 9 mm), but after the check is completely flooded (sheet reaches 9 mm) it remains like that until the end of the season. Therefore water sheet in the "*j*" sheet in day 1 ($Z_1{}^j$) and outflow form check "*j*" into basin "*j+1*" ($O_1{}^j$) were calculated as:

$$Z_1^j = Z_0^j + I_1^j - ET_1^j - P_1^j - O_1^j$$

$$O_1^j = \begin{cases} 0 & if\ Z_1^j < 9mm \\ Z_1^j - 9 & if\ Z_1^j < 9\ mm \end{cases}$$

The same criteria applies to the next basins, taking the inflow into basin "*j+1*" as the outflow from basin "*j*": $I_1^{j+1} = O_1^j$. Of course, water sheet in each basin is assumed to be zero at the beginning of the irrigation $Z_0^j = 0 \quad \mathit{for\ all}\ j$ and remains like that until it receives an inflow greater than the ET and P corresponding to that basin in that day.

Input into the first basin in day "*h*" is the total irrigation water of the day ($I_1^h = I_1$). Irrigation volume was taken as 80 mm/day during 6 days (4 days before sowing and the next 2 days), then it was reduced to 12 mm/day and during the peak ET period it was increased to 18 mm/day. These values are in the range given by Division of Agricultural Sciences University of California (1980): 12 to 16 cfs per 100 acres (from 72 to 96 mm/day) in the first days and 2-3 cfs/100 acres (12 to 18 mm/day) in the rest of the season. The water balance is performed in daily time steps. Again, the duration for the periods with these irrigation volumes and the time in which they take place can be changed to match true irrigation practices. The total amount of water supplied with this irrigation schedule was 2682 mm, which is found in the normal range for rice irrigation in the area [i.e. from 5 to 9 feet (1524 to 2743 mm) according to Division of Agricultural Sciences University of California (1980)].

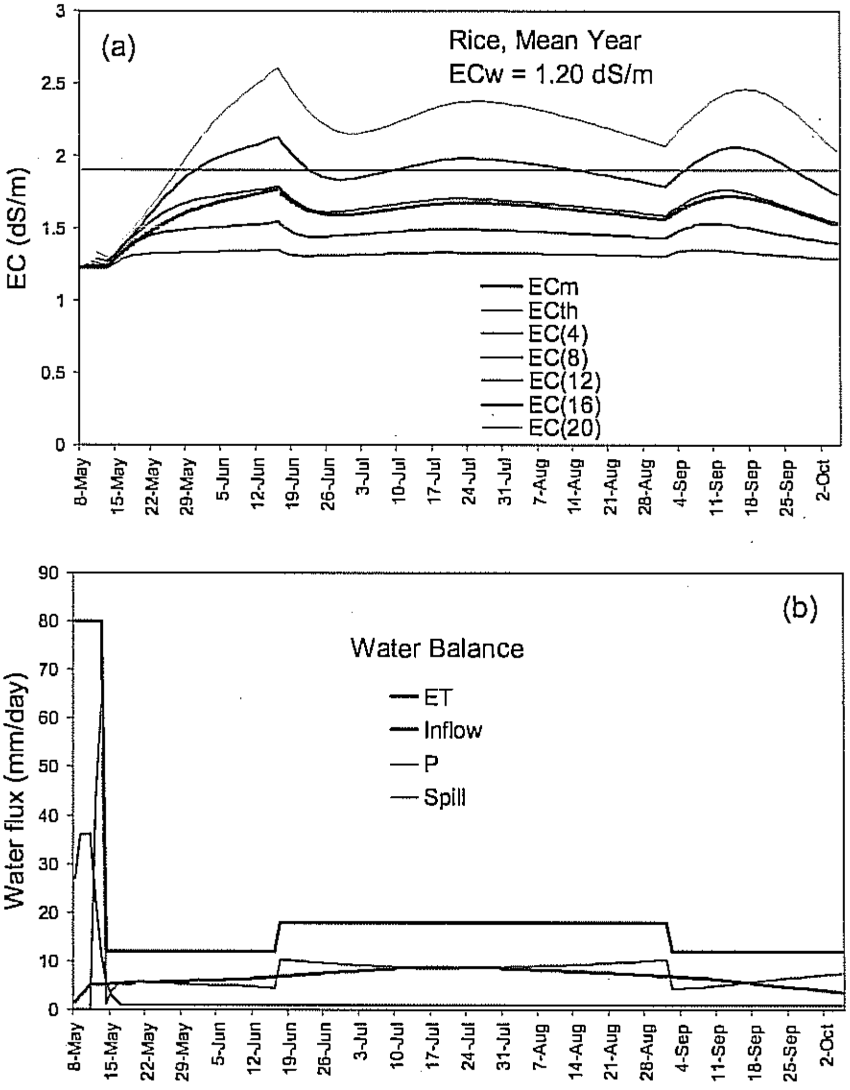
Finally, the spill from the irrigated field in any day "*t*" (S_t) was taken as the outflow from the last (20th) check: $S_t = O_t^{20}$.

Salt Balance

The salt balance was performed assuming there was a complete mixing of the inflow with the water in the checks, and that the outflows (percolation and outflow to the next basin) had the same concentration as the resulting water in the basin. Salinity is characterized by EC. The salt balance equation for check "*j*" in day "*t*" is given by $Z_{t-1}^j \cdot EC_{t-1}^j + I_t^j \cdot EC_t^{j-1} = \left(Z_t^j + P_t^j + O_t^j\right) \cdot EC_t^j$ where the sub-index *t-1* refers to the previous day and the super-index *j-1* refers to the preceding check. The EC in a given check and day (EC_t^j), that is also the EC of the outflow from the basin and inflow into the next basin, was calculated with this formula. For the first basin, the EC of the inflow is that of the irrigation water (ECw).

The mean EC for each basin was averaged for the whole irrigation season and these mean ECfw for each basin were compared to the ECfw for rice that relates to the 90% year potential (3.0 dS/m). As a result, salinity increases from top to bottom basins. Depending upon the ECw of the inlet water to the top basin, salinity could reach damaging levels by the time the water reaches the lower basins.

Figure 1 presents the results of the simulation for the mean year with ECw = 1.2 dS/m. Results indicate that salinity steadily increases as water moves to lower basins (i.e. those basins with higher numbers) but in all basins, salinity remains below the EC_{90} level (Fig. 1(a)). Also in the lower basins, absolute changes in basin ECfw is higher across the year than in the upper basins. Fig. 1(b) shows that percolation is very high in the beginning of the season (until the soil storage is filled) and remains constant thereafter. The spill also shows a spike in the beginning of the season but is fairly constant for the rest of the season, varying only slightly as ETc and irrigation change along the season. Finally, the mean seasonal EC in each basin (ECfw) increases downstream, Fig. 1(c).



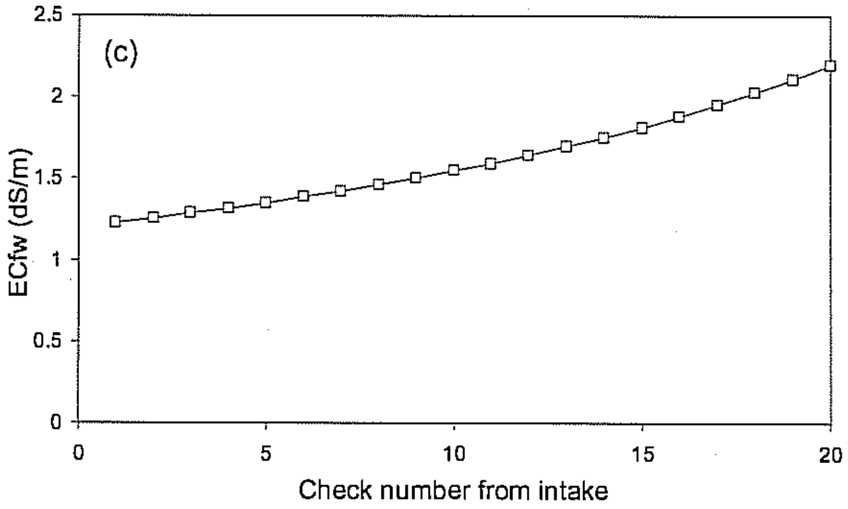


Figure 1. Results for a rice field irrigated with a water of electrical conductivity ECw = 1.2 dS/m: (a) EC of the field water in the 4th, 8th, 12th, 16th, and 20th basins (checks) from the inlet along the season; (b) Water balance in the field along the season: Inflow (irrigation), evapotranspiration (ET), percolation (P), and Spill; and (c) Mean EC of the field water (ECfw) for the whole season in each basin.

Statistical application of the model

This procedure was used with several values of ECw (ECw = 0.8-1.0-1.2-1.4-and 1.6 dS/m) for the 53 years with data available. The probability distribution function of the resulting mean seasonal EC in each basin can be obtained this way. Rather than using so many figures, we elaborated the mean seasonal EC for the whole field (mean of the 20 seasonal means of the 20 basins). We also obtained the probability distribution function of the fraction of field that has a mean salinity higher than the EC90 value that is the fraction of the field where there is some potential yield loss greater than 10% due to salinity. The yield loss for a field is obtained as the mean of the yield loss in each of the 20 basins.

APPENDIX C

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APPENDIX D

STAKEHOLDER REVIEW PROCESS

As part of the Electrical Conductivity, Boron and Fluoride Study, the City of Woodland convened an advisory group of local agricultural interests to gain input on the salinity model assumptions and the report conclusions. Some of the key issues discussed with the agricultural participants included what types of crops are grown and could possibly be grown in the area, what are the irrigation practices, what is an appropriate level of crop protection and what the general sentiments regarding salt tolerances for the crops in the area. During the course of the study, there were three in-person meetings with agricultural interests and several phone interviews regarding the issues identified above. The meetings and discussions at the meetings are summarized below. We have also provided a partial list of agricultural interests that were consulted throughout this process.

July 5, 2005 – Yolo County Farm Bureau Executive Committee

On July 5, 2005, Tess Dunham of Larry Walker Associates met with the executive committee of the Yolo County Farm Bureau to present the scope of the study underway and to obtain feedback regarding the study and others that should be consulted. Based on the input from the meeting, LWA was directed to consult with farmers that farm on the Conaway Ranch and was directed to contact individual farmers such as Jack DeWit and Ron Tadlock, who both farm in the general area. In addition, the Farm Bureau requested that Denise Sagara remain involved in providing input from the Farm Bureau.

August 9, 2005 – Regina Cherovsky, Operations Manager for the Conaway Preservation Group, LLC

Based on the input from the Farm Bureau Executive Committee, Tess Dunham and the Study authors, Drs. Stephen Grattan and Daniel Isidoro-Ramirez, met with Regina Cherovsky at the Conaway Ranch to discuss farming operations on the ranch. Ms. Cherovsky provided valuable information regarding crops on the ranch and within the area, as well as the use of Tule Canal water on the ranch. According to Ms. Cherovsky, little if any Tule Canal water is used on the Conaway Ranch to irrigate crops. Most of the water used on the Conaway Ranch is directly from the Sacramento River. Additional supplemental irrigation water is pumped groundwater. According to Ms. Cherovsky, the predominate crops in the area are rice, wild rice, alfalfa (directly outside the bypass), tomatoes and wildlife habitat.

April 19, 2006 – E.C. Study Review, Agricultural Interests

On April 19, 2006, the City of Woodland convened a meeting of various agricultural interests to discuss the draft study as prepared by Drs. Stephen Grattan and Daniel Isidoro-Ramirez (an agenda for the meeting and the participant sign-up sheet are attached). At this meeting, the City outlined the purpose of the study, the assumptions made within the study and the draft results of the study. As part of the discussion, the types of crops grown within the area were discussed. Also discussed was the appropriate level of yield protection to consider when establishing a criterion for electrical conductivity.

A couple of the group participants conveyed a general sentiment that wild rice was more sensitive to salt than conventional rice and therefore the estimates used for rice might not be protective for wild rice.

In addition, the group participants expressed reservations regarding the selection of a criterion based only on a 95% yield protection level. Rather, they seemed more comfortable with 100% yield protection, understanding that there it is difficult to ascertain what is 100% protection. The group understands that rainfall amounts and distribution vary from year to year but were comfortable with selecting a criterion based on protection for 95% of the years as long as 100% crop protection levels were used. In fact, one farmer expressed that in the critical dry years there was a tendency to obtain higher crop yields despite a slight increase of salinity because of the better farming conditions associated with dryer soils.

With regard to fluoride, none of the participants had ever heard about a problem associated with fluoride. However, all of the participants expressed concerns regarding boron levels. Boron is a major water quality issue throughout the County, especially areas that rely heavily on groundwater for irrigation purposes. Also, it was expressed that sunflowers are a growing industry in the area and that they might be sensitive to boron. However, there is little information regarding sensitivity levels for sunflower to boron in irrigation water and there is no information that the group is aware of regarding boron tolerance in rice.

At the close of the meeting, several unknowns were identified. They included salt sensitivity issues related to wild rice for EC, and sunflowers and rice for boron. Based on the discussion at this meeting, the City's report was revised to reflect 100% yield protection and additional research was done with regards to the salt sensitivity for wild rice.

Agenda

City of Woodland E.C. Study Review

April 19, 2006

9:00 – 11:00 a.m.

Larry Walker Associates, Inc.
707 4th Street, Suite 200
Davis, California 95616
(530) 753-6400

I. Introductions

II. Purpose of the Study..Tess Dunham

III. Results of the Study..Dr. Steve Grattan

IV. Discussion Regarding Assumptions..Group

V. Recommendations from Ag Participants.....................................Group

VI. Next Steps..All

City of Woodland EC Study Review
Sign Up Sheet 4/19/06

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Regina Cherovsky	Conaway Ranch	530 662-1484
TINA Lunt	NCWA	916-442-8333