Salt Tolerance of Crops in the Southern Sacramento-San Joaquin Delta (South Delta)

August 13, 2009

By

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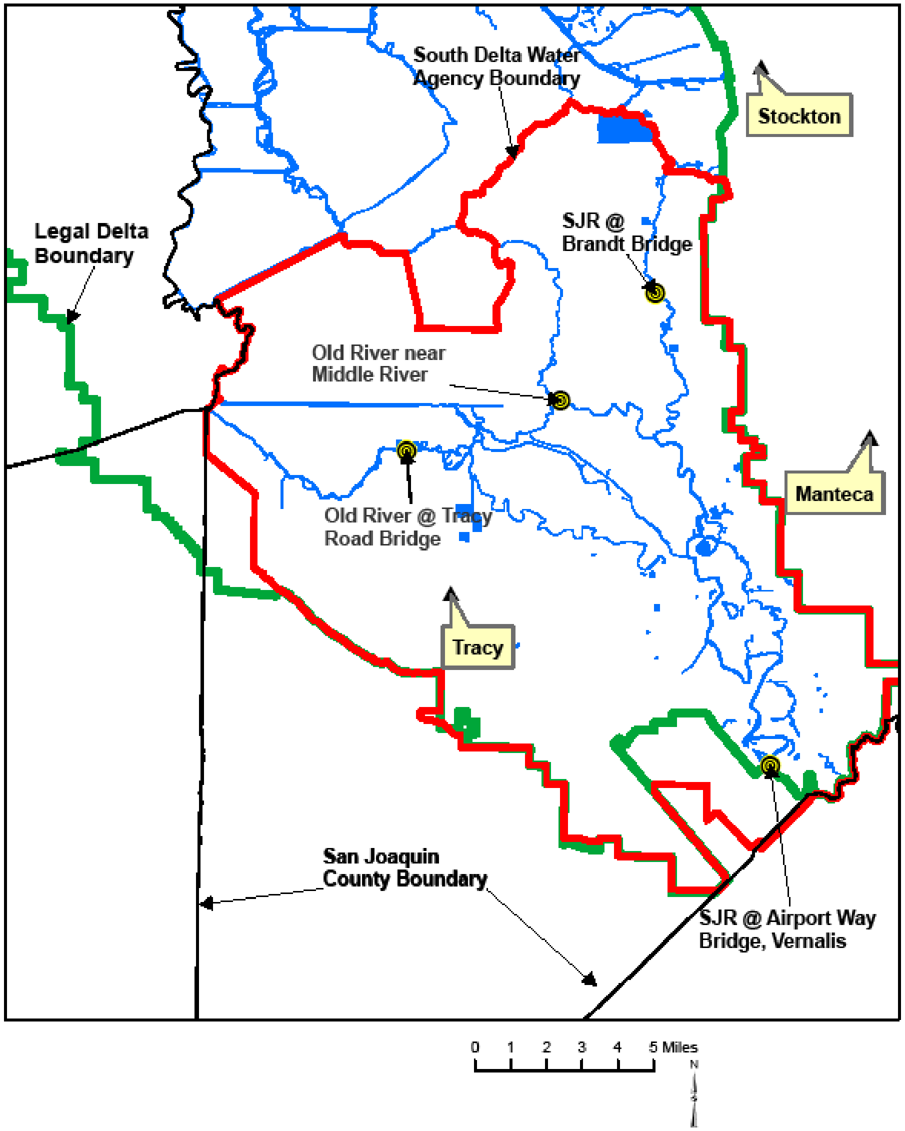
South Delta

Page 2, Figure 1.1. Location map



Objectives

- First
  - Research scientific literature
  - Prepare comprehensive list of references
  - Provide synopsis of findings
- Second
  - Review strengths and limitations of steady-state and transient models

Objectives (continued)

- Third
  - Determine and describe area and nature of saline and drainage impaired soils
  - Estimate effectiveness of rainfall
  - Compile/evaluate crop types and acreages
- Fourth
  - Identify significant gaps in literature and recommend future studies
  - Use steady-state model and South Delta data to estimate acceptable water quality for salinity control

Objectives (continued)

- Fifth
  - Present findings and recommendations to interested stakeholders

Criteria to Judge Water Quality for Crop Production

- Salinity

  Osmotic stress on plants

- Sodicity

  Loss of soil permeability

- Toxicity

  Direct toxic effect on plants

Units of Measure for Electrical Conductivity

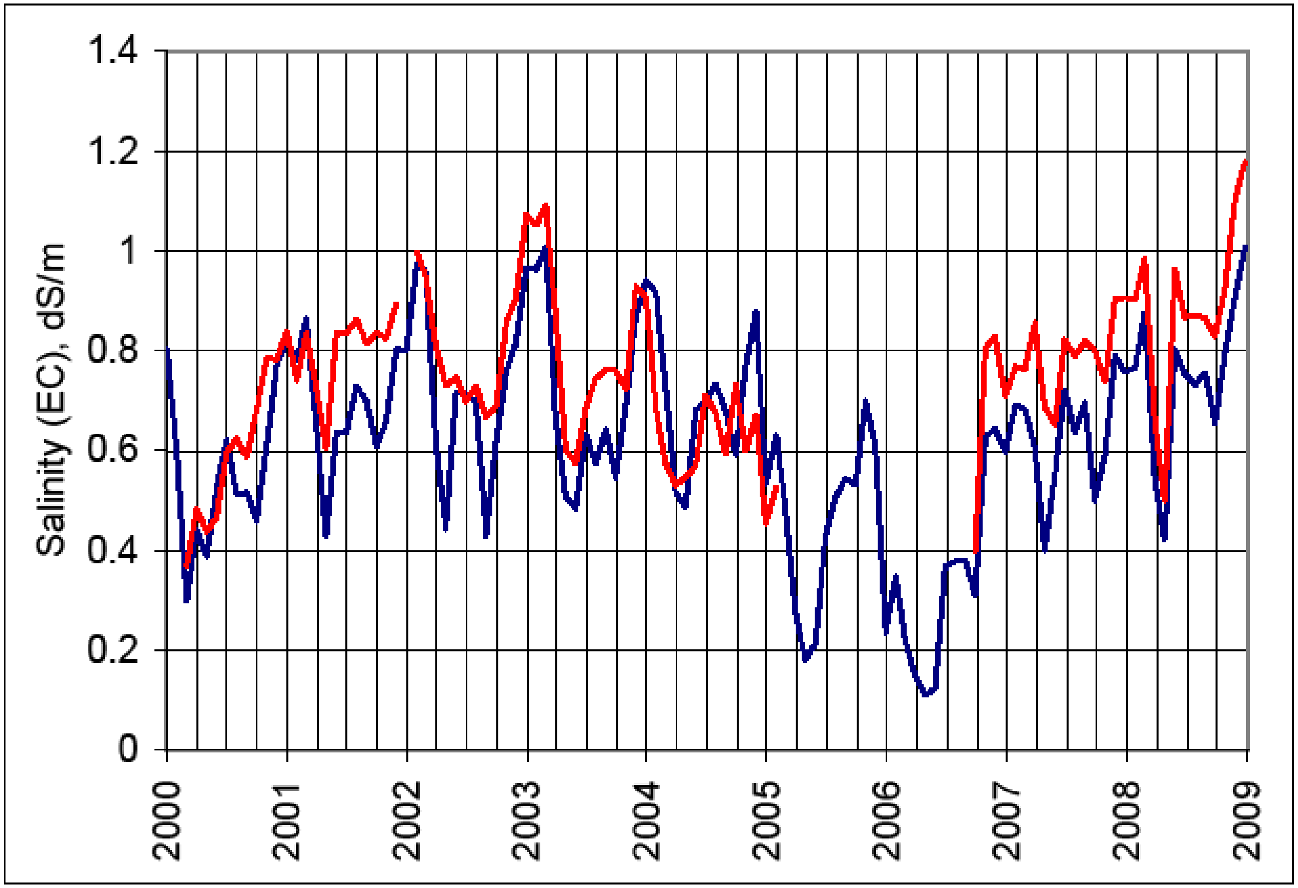
1 dS/m = 1,000 μS/cm = 1 mmho/cm

1 dS/m ≈ 640 mg/l or 640 ppm
total dissolved solids

Salinity in the South Delta

SJR @ Vernalis (blue) and Old River @ Tracy (red)

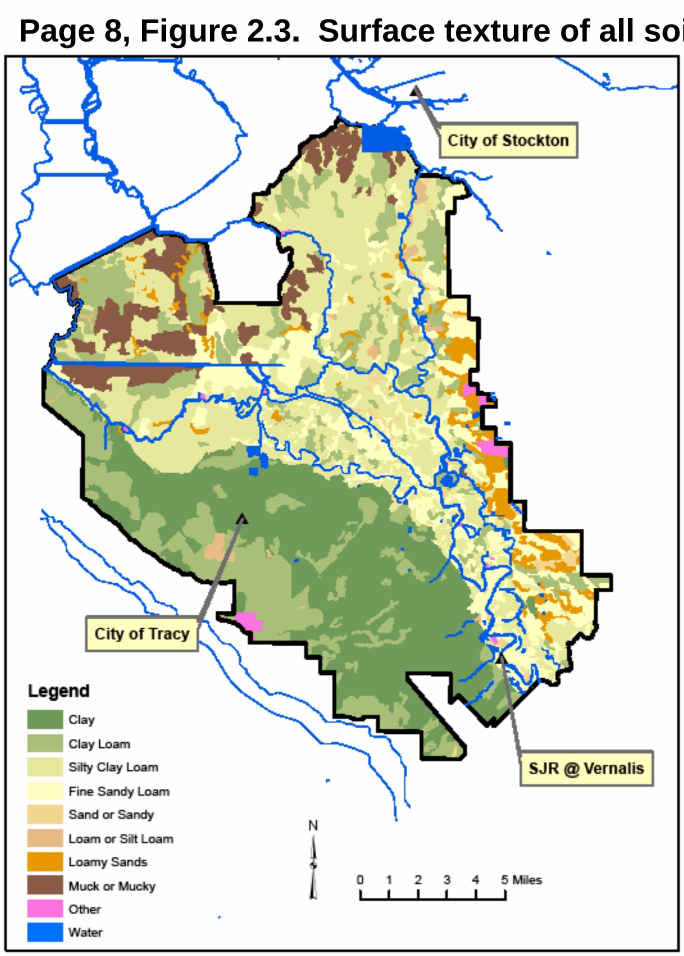
Page 6, Figure 2.1. Salinity of SJR and Old River from 2000 to 2008

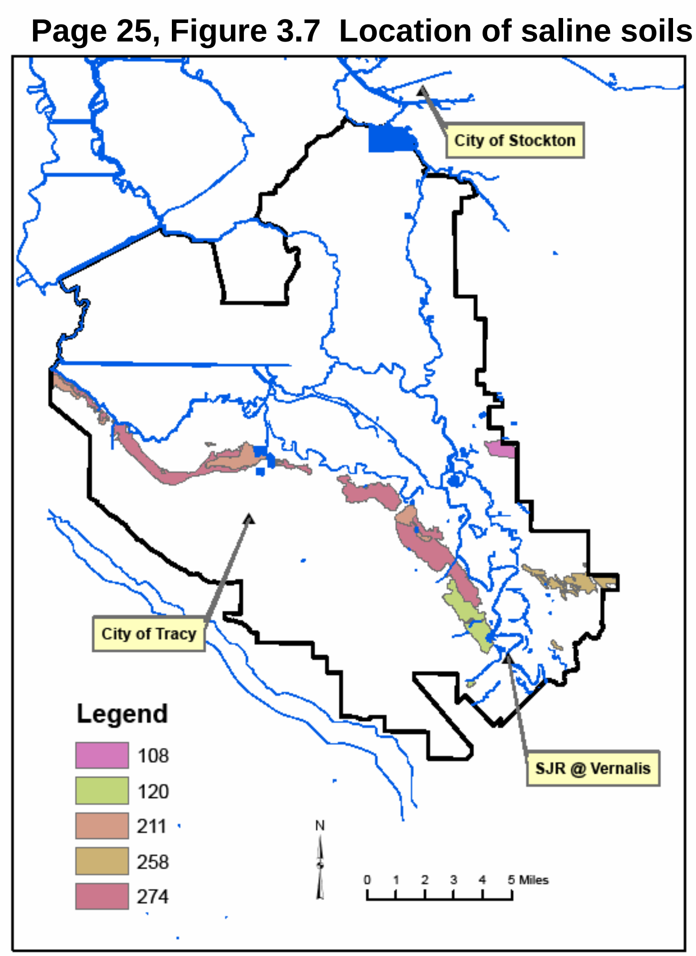


Sodicity and Toxicity

- No information found to indicate any problem

Soils in the South Delta





Crops in the South Delta

Excerpt from Page 11, Table 2.2. Summary of Crop Acreages

Crop	Salt Tolerance	DWR Acreage	SJ County Ag Commissioner Acreage
Alfalfa	MS	31,356	33,021
Almond	S	3,087	2,860
Asparagus	T	3,651	4,137
Dry bean	S	3,855	2,998
Corn	MS	11,638	14,242
Grape	MS	2,903	2,940
Oats	T	---	4,616
Saflower	MT	1,803	2,768
Tomato	MS	16,263	18,635
Walnut	S	2,043	1,699
Wheat	MT	---	5,806

Factors Affecting Salinity Objective for Irrigated Agriculture

- Season-long crop salt tolerance
- Crop salt tolerance at various growth stages
- Preferential (bypass) flow of applied water
- Effective rainfall
- Irrigation method
- Crop water uptake distribution
- Climate
- Salt precipitation / dissolution
- Shallow groundwater
- Leaching fraction

Season-Long Crop Salt Tolerance

$$Y_r = 100 - b\,(EC_e - a)$$

Excerpt from Page 16, Table 3.1. Crop salt tolerance coefficients

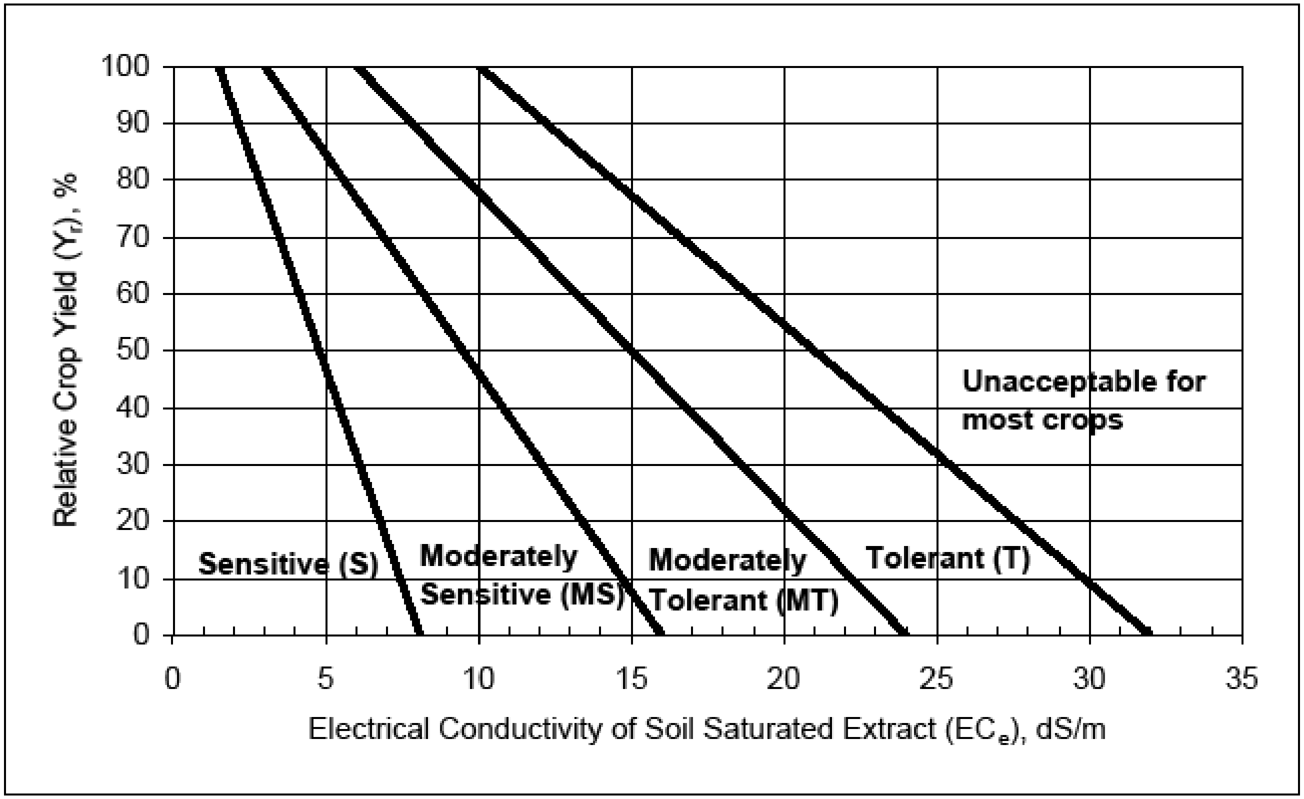
Common Name	Botanical Name	Tolerance based on	Threshold* ECe, dS/m	Slope* % per dS/m	Relative Tolerance **
Alfalfa	Medicago sativa	Shoot DW	2.0	7.3	MS
Almond	Prunus duclis	Shoot growth	1.5	19	S
Asparagus	Asparagus officinalis	Spear yield	4.1	2.0	T
Bean	Phaseolus vulgaris	Seed yield	1.0	19	S
Corn	Zea mays	Ear FW Shoot DW	1.7 1.8	12 7.4	MS MS
Grape	Vitus vinifera	Shoot growth	1.5	9.6	MS
Oat	Avena sativa	Grain yield Straw DW	--- ---	--- ---	T T
Safflower	Carthamus tinctorius	Seed yield	---	---	MT
Tomato	Lycopersicon lycopersicum	Fruit yield	2.5	9.9	MS
Walnut	Juglans	foliar injury	---	---	S
Wheat	Triticum aestivum	Grain yield Shoot DW	6.0 4.5	7.1 2.6	MT MT

* Values of threshold = (a) and slope = (b) in above equation

** Relative salt tolerance ratings: (S) sensitive, (MS) moderately sensitive, (MT) moderately tolerant, and (T) tolerant

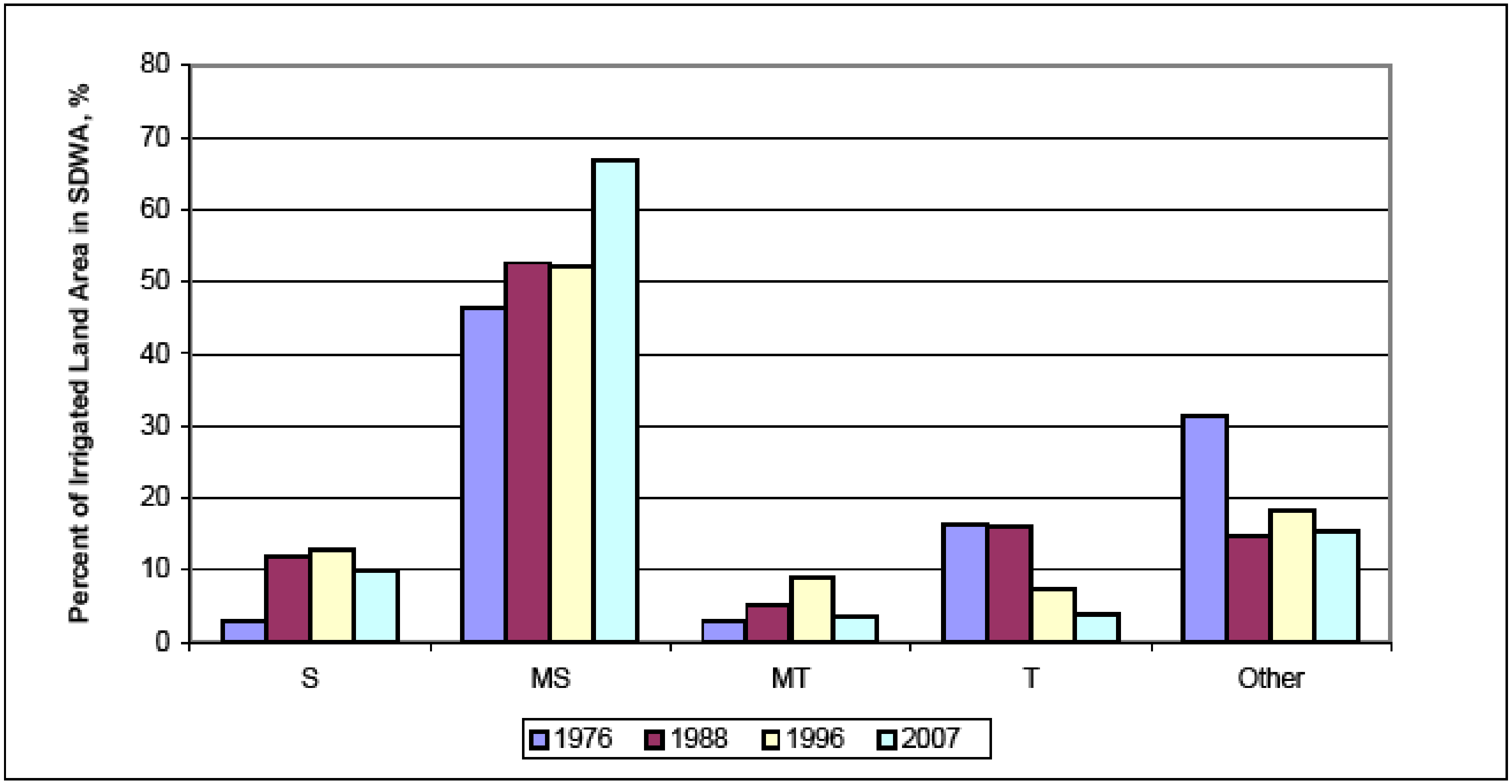
Season-Long Crop Salt Tolerance

Page 17, Figure 3.2. Classification of crop salt tolerance based on relative crop yield



Season-Long Crop Salt Tolerance

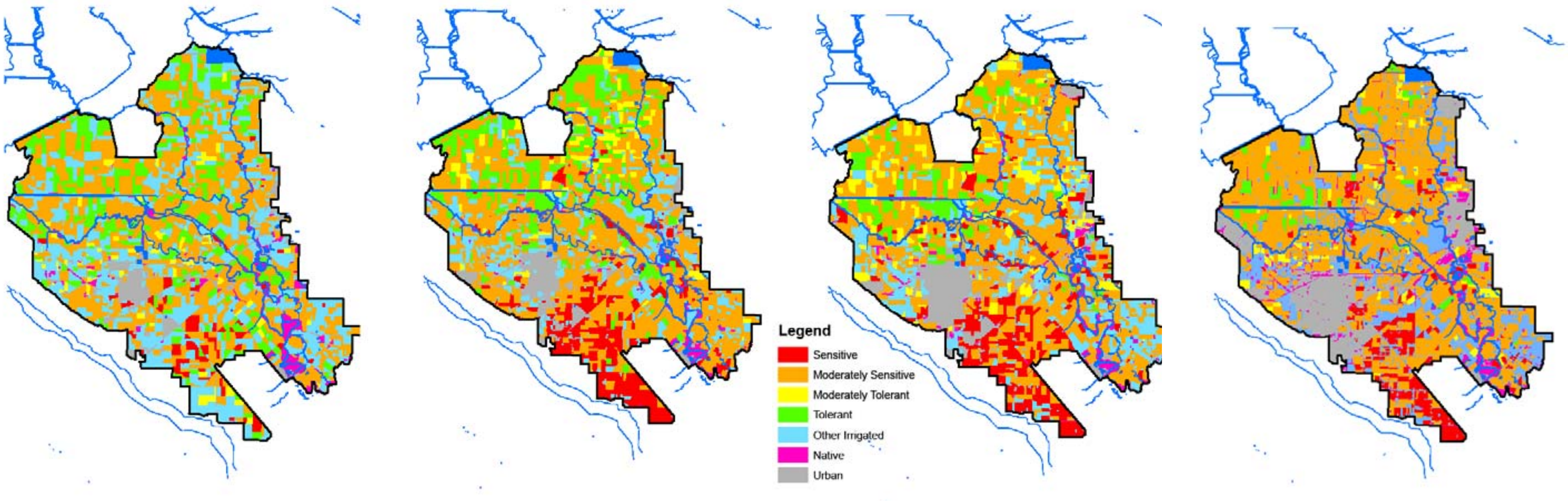
Page 17, Figure 3.3. Distribution (as a percent) of crops in the South Delta based on salt tolerance



S = **Sensitive; MS** = **Moderately Sensitive; MT** = **Moderately Tolerant; T** = **Tolerant; Other** = **crops not identified**

Season-Long Crop Salt Tolerance

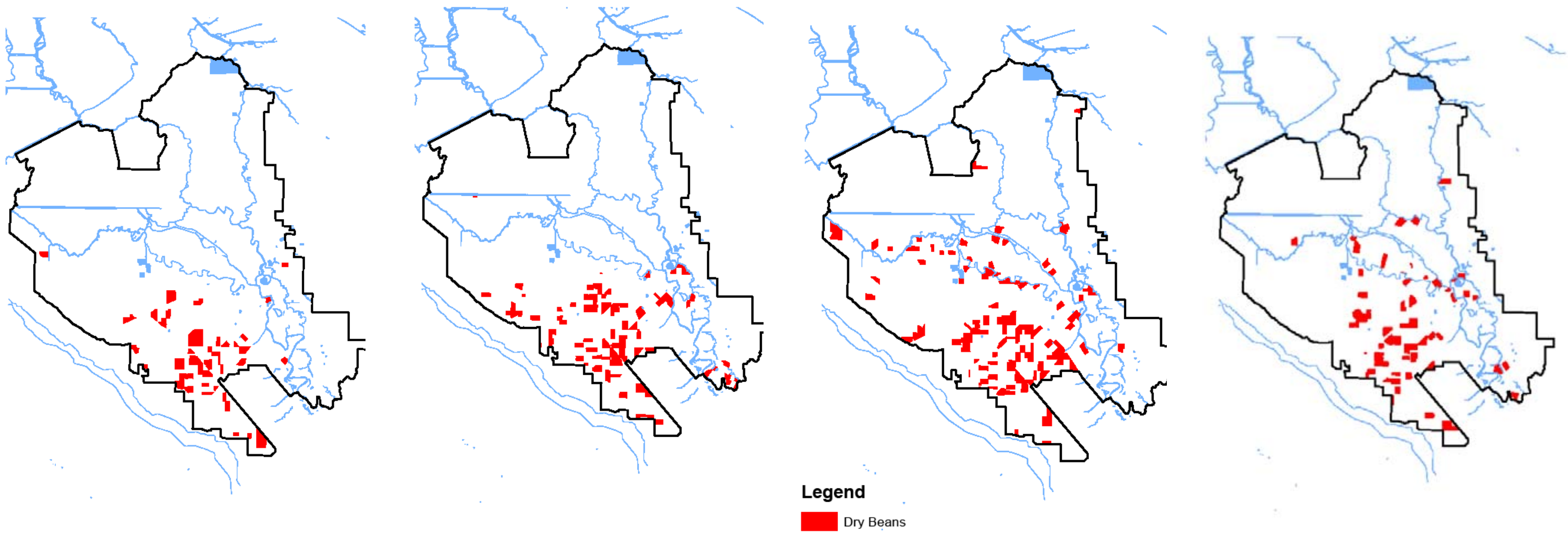
Page 18, Figure 3.4. Distribution of crops grown in the South Delta



1976 1988 1996 2007

Season-Long Crop Salt Tolerance

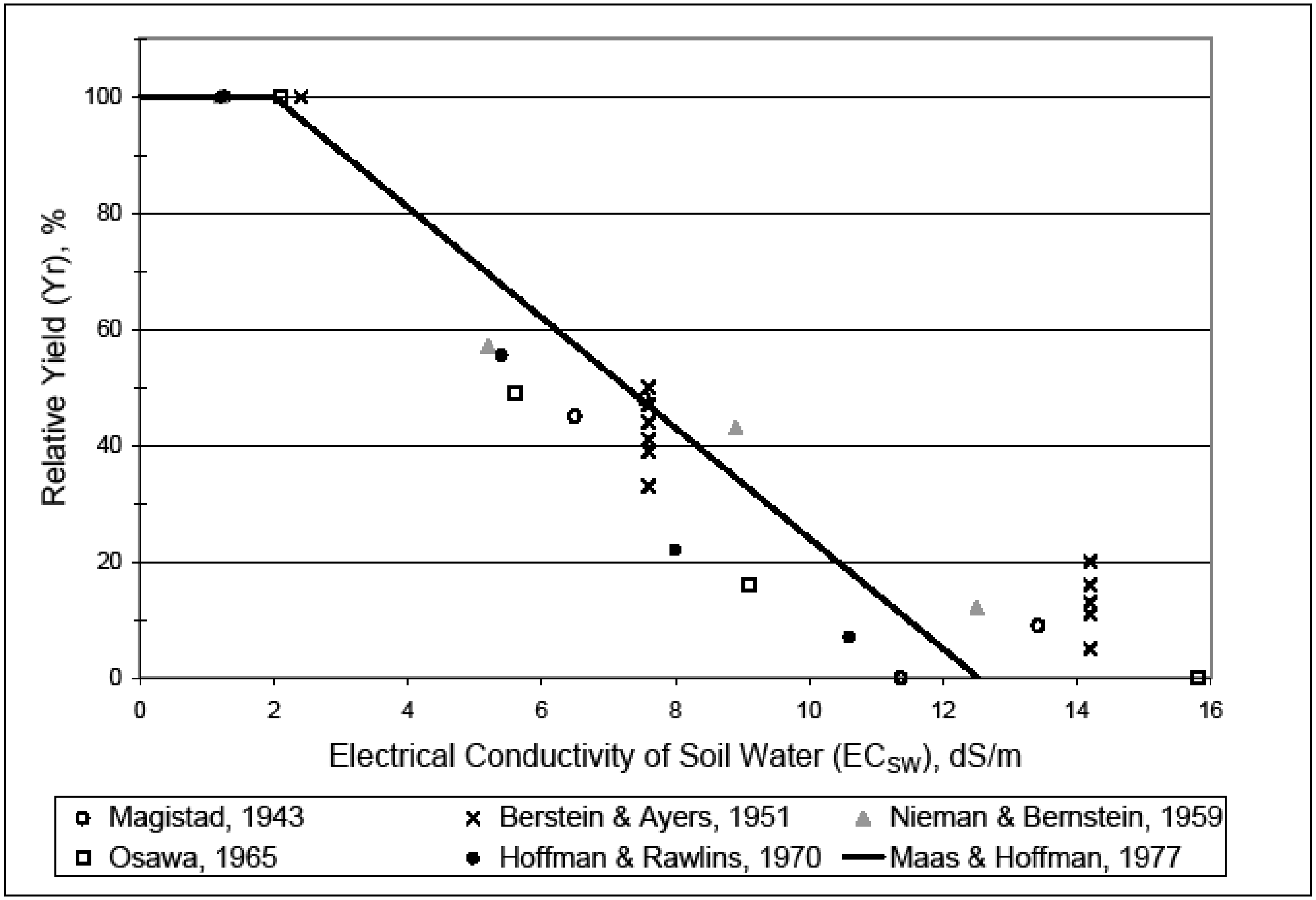
Page 19, Figure 3.5. Distribution of dry beans grown in the South Delta



1976 1988 1996 2007

Season-Long Crop Salt Tolerance

Page 20, Figure 3.6. Original data from five experiments used to establish the salt tolerance of bean



Crop Salt Tolerance at Various Growth Stages

Excerpt from Page 22, Table 3.2. The level of soil salinity required to reduce emergence by 10 % for crops important in the South Delta (Maas and Grieve, 1994).

Common Name	Botanical Name	Electrical Conductivity of Soil Salinity (EC_e) that Reduced Emergence by 10 %
Alfalfa	Medicago sativa	2.5 to 9.5
Bean	Phaseolus vulgaris	5.5
Corn	Zea mays	5 to 16
Oat	Avena sativa	16
Safflower	Carthamus tinctorius	8
Tomato	Lycopersicon Lycopersicum	3 to 7.5
Wheat	Triticum aestivum	1 to 11

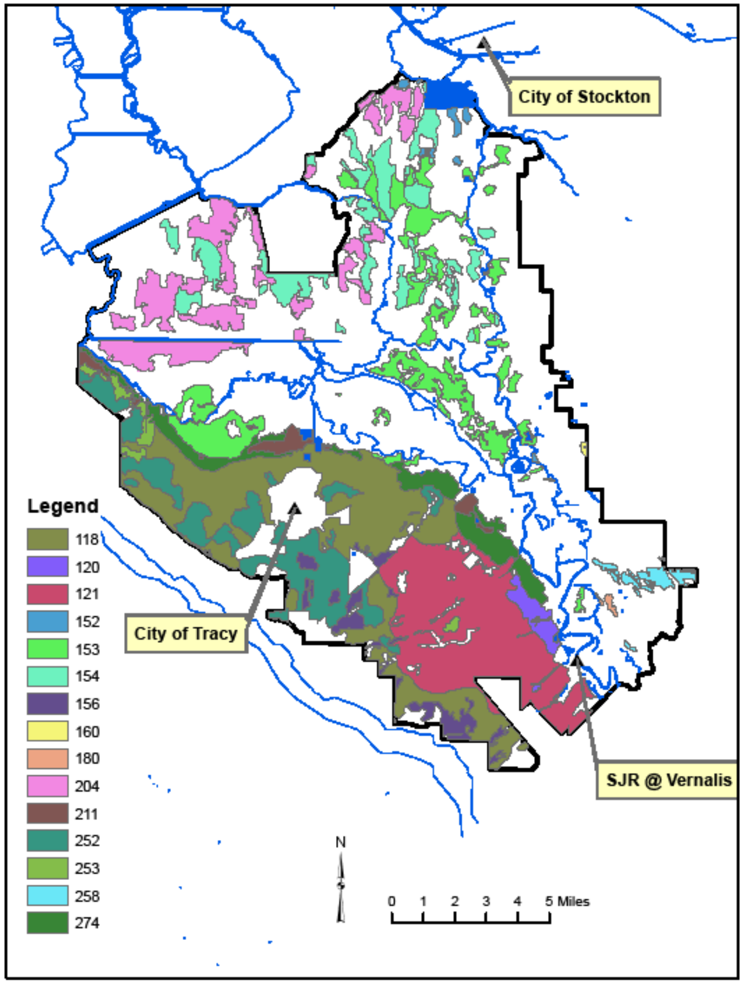
Crop Salt Tolerance at Various Growth Stages

Excerpt from Page 22, Table 3.3. Salinity effects on crops at various stages of plant growth.

Crop	Salt Tolerance Threshold, EC_e (dS/m)				Reference
Asparagus	Germination 4.7	1st Growth 0.8	Fern 1.6	Spears 4.1	Francois, 1987
Corn, sweet	Germination 5.0	Emergence 4.6	Seedling 0.5	Yield 2.9	Maas et al., 1983
Corn, field	No salt affect on seedling density up to EC_e=8 dS/m				Hoffman et al., 1983
Corn (16 cultivars)	Germination 3.1 to 10	Seedling 0.2 to 1.2			Maas et al., 1983
Wheat	Vegetation 6.7	Reproduction 12	Maturity 12		Maas & Poss, 1989a
Wheat, Durum	Vegetation 3.6	Reproduction 5.0	Maturity 22		Maas & Poss, 1989a

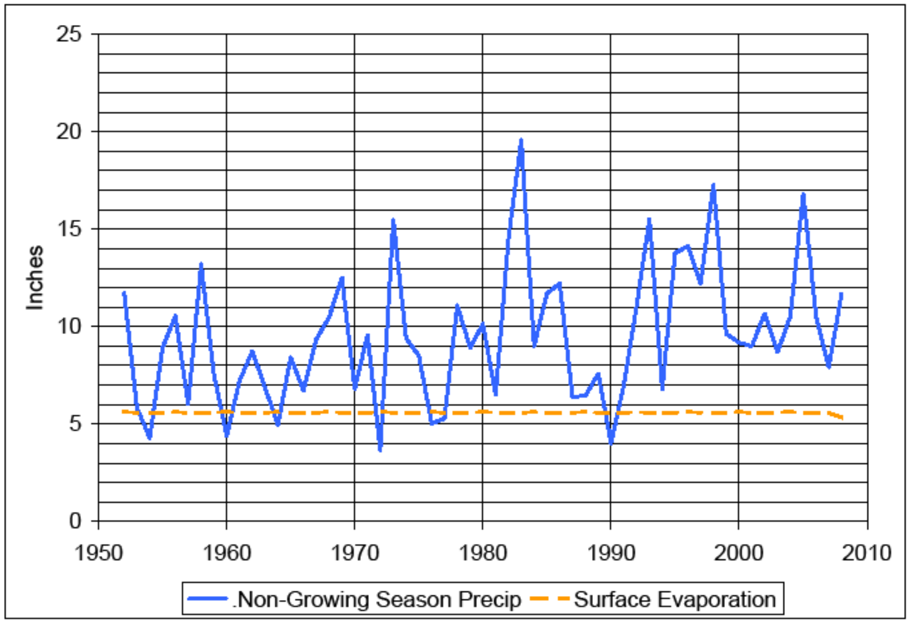
Shrink-Swell Soils with Potential for Bypass Flow

Page 29, Figure 3.9. Location of shrink-swell soils



Effective Rainfall

Page 33, Figure 3.11. NCDC Station No. 8999, Tracy- Carbona, 1952 through 2008



Page 31, Table 3.6. Disposition of average rainfall for two zones, just north and south of the South Delta, along with average of the two zones. (MacGillivray and Jones, 1989).

		Effective Rainfall				
Zone	**Average Annual Rainfall (in.)**	**Growing Season (in.)**	**Non-Growing Season (in.)**	**Total (in.)**	**Surface Evaporation (in.)**	**Deep Percolation (in.)**
4	15.0	1.3	7.5	8.8	5.5	0.7
5	12.5	1.1	6.3	7.4	5.1	0.0
South Delta	13.8	1.2	6.9	8.1	5.3	0.4

Irrigation Method

Page 35, Table 3.7. Irrigation methods in the South Delta based upon DWR 2007 crop survey and estimates by Dr. Pritchard (as percent of total irrigated crop area).

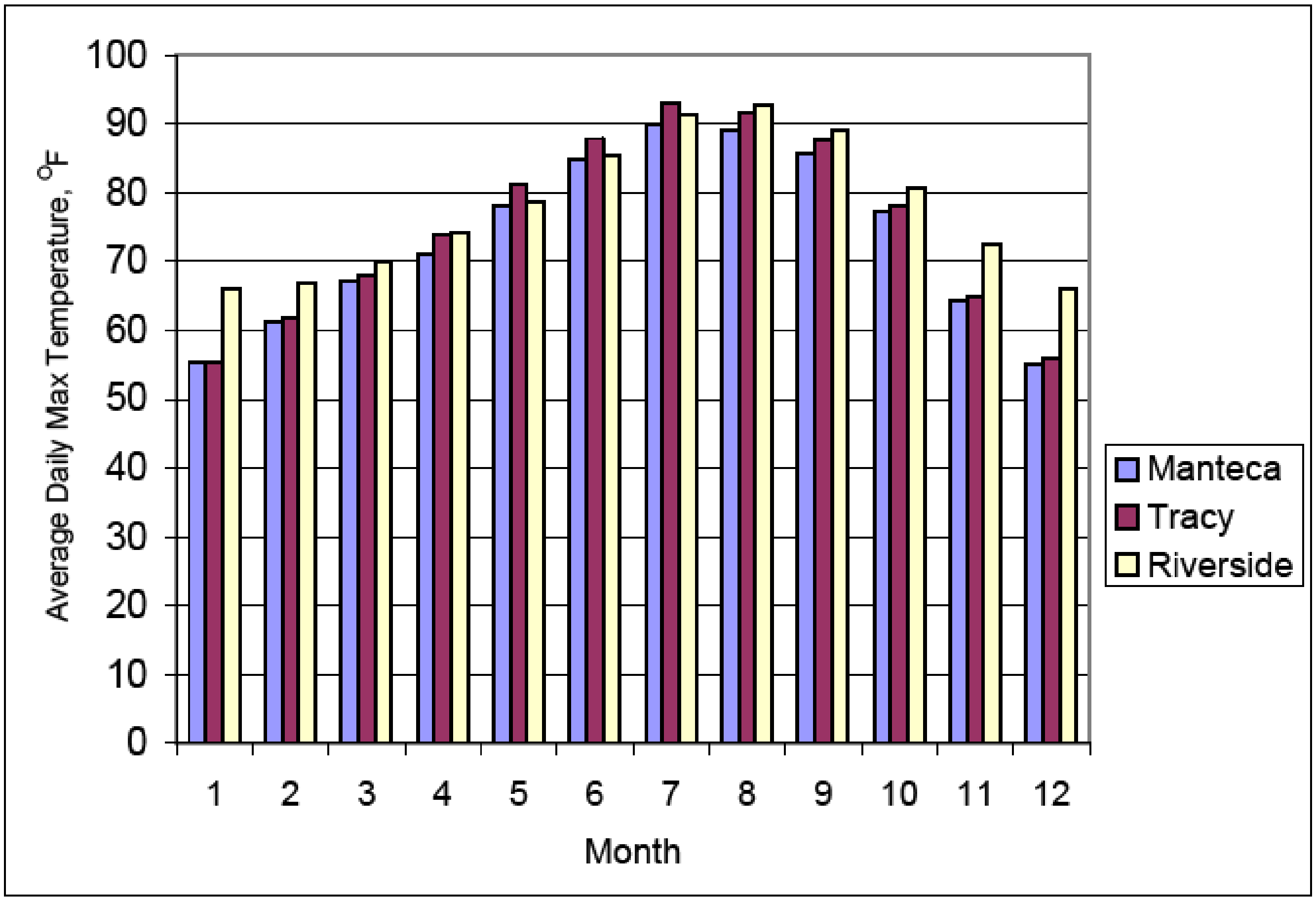
Crop Type	Crop Area (%)	Irrigation Method Border(%)	Furrow (%)	Sprinkler/Drip (%)
Fruit & Nut Trees& Grape Vines	9	3	3	3
Field & Truck Crops (excl. Tomato & Asparagus)	25	0	25	0
Tomato & Asparagus	21	0	19	2
Alfalfa & Pasture	37	37	0	0
Grain & Hay	8	4	4	0
Totals:	100	44	51	5

Water Crop Uptake Pattern

- 40-30-20-10 (used by Ayers & Westcot)
- Exponential

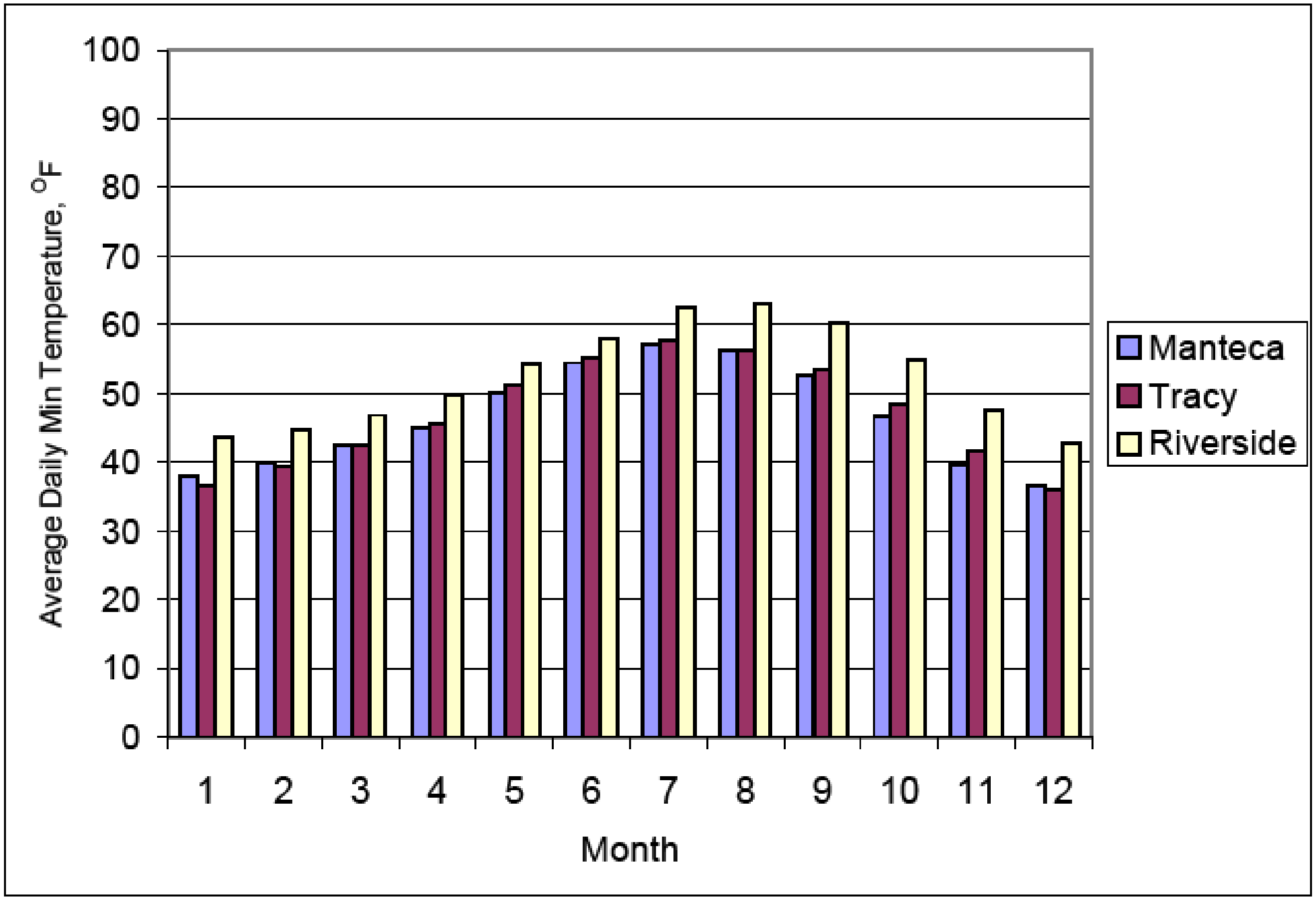
Climate

Page 41, Figure 3.13a. Average daily maximum temperature comparison



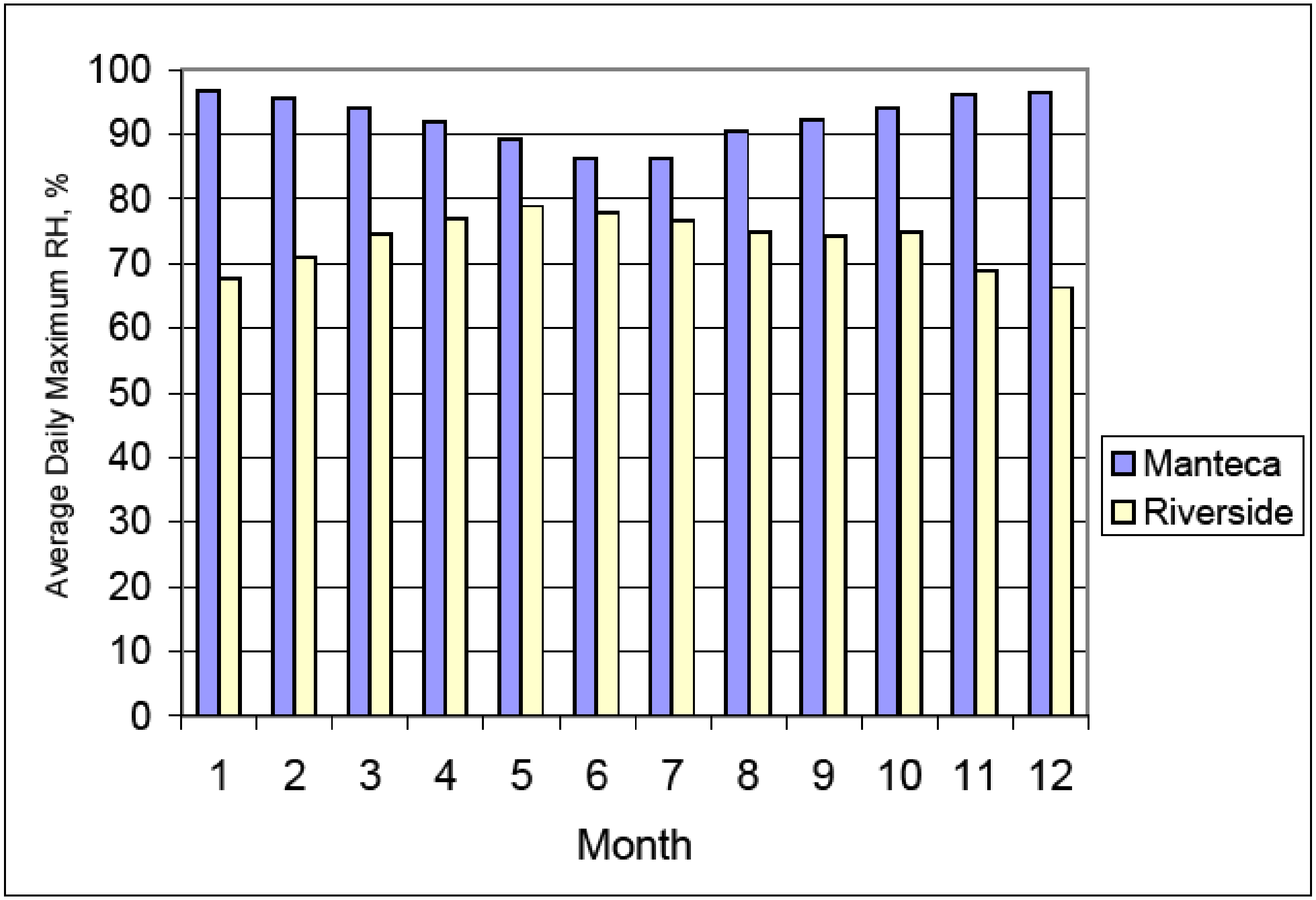
Climate

Page 41, Figure 3.13b. Average daily minimum temperature comparison



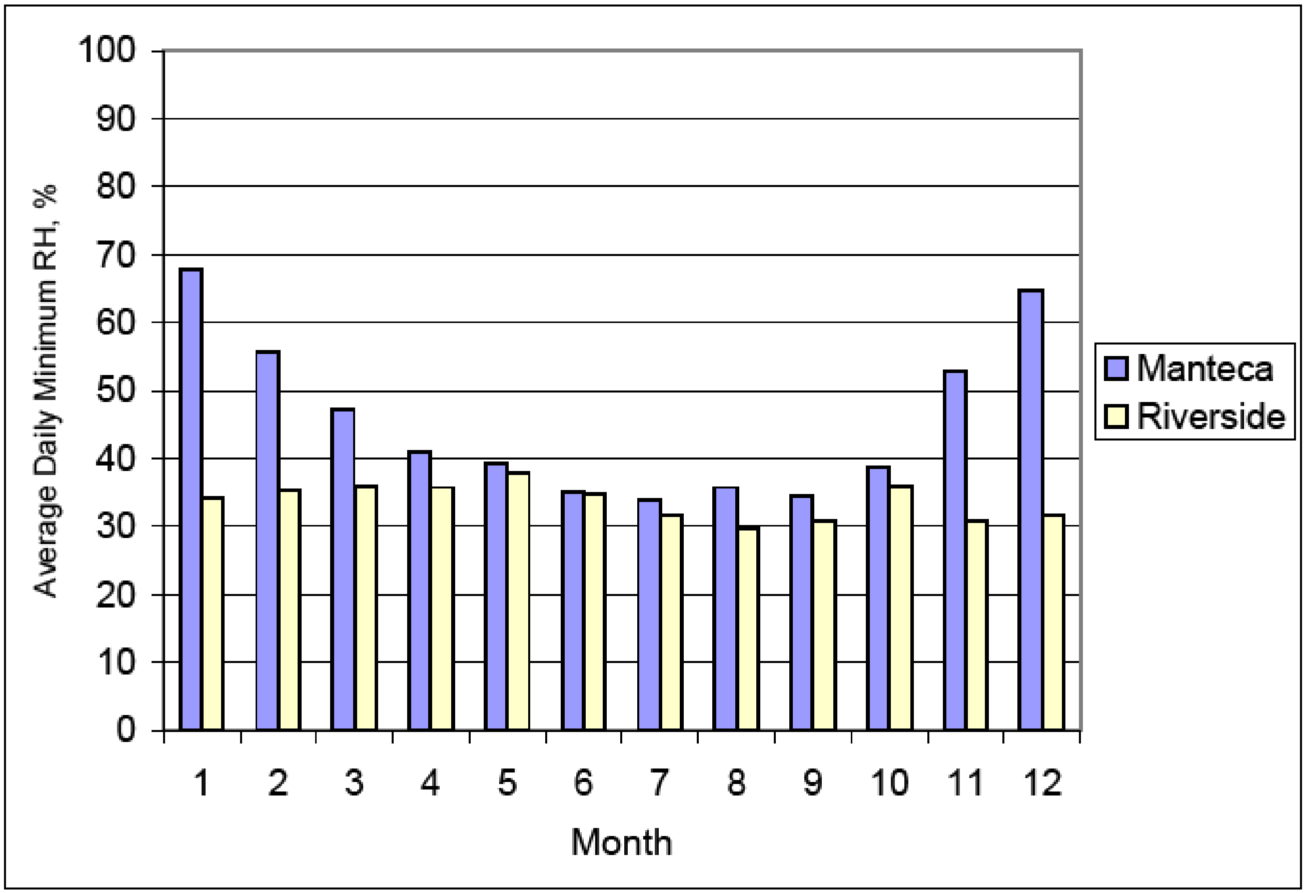
Climate

Page 42, Figure 3.14a. Average daily maximum RH comparison



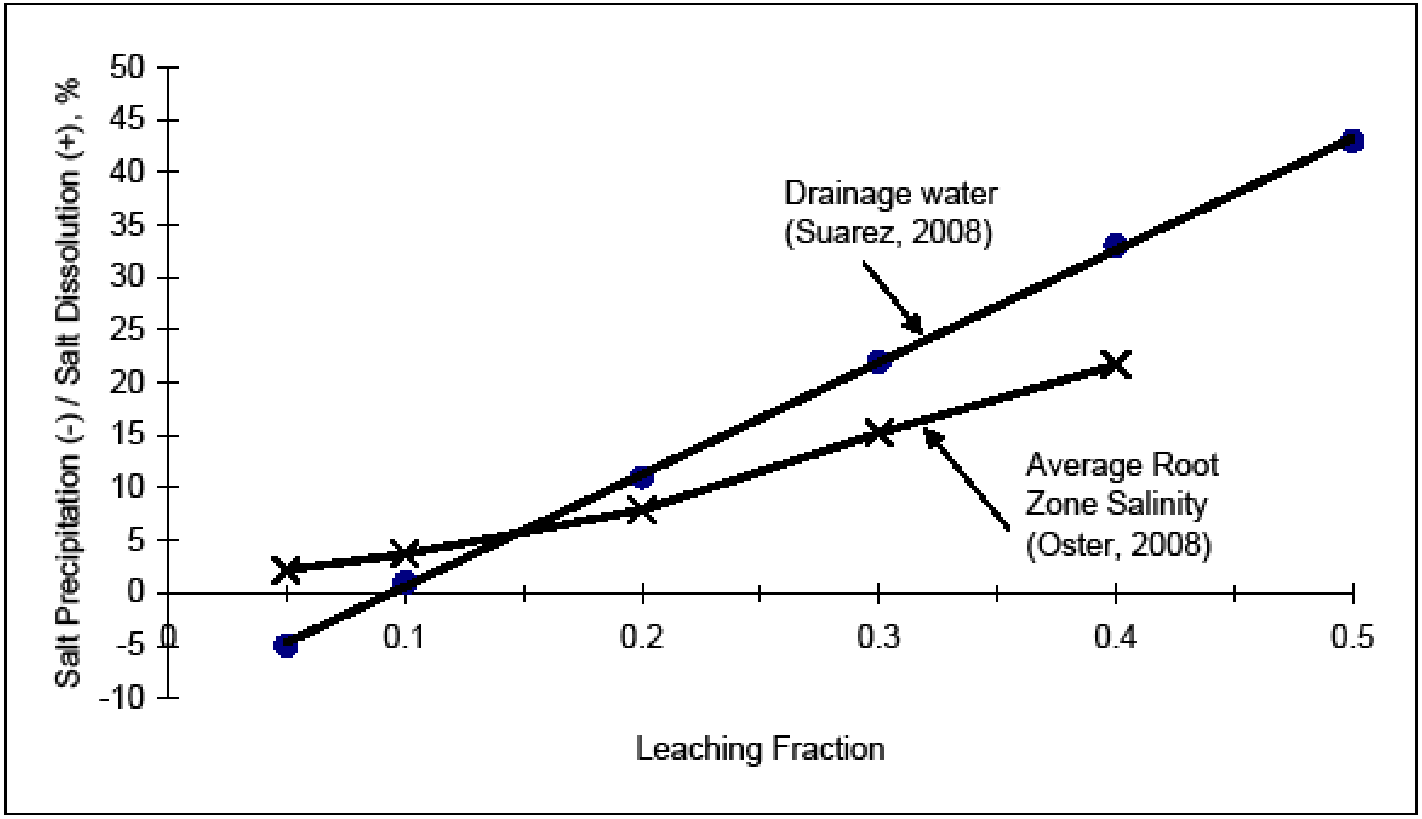
Climate

Page 42, Figure 3.14b. Average daily minimum RH comparison



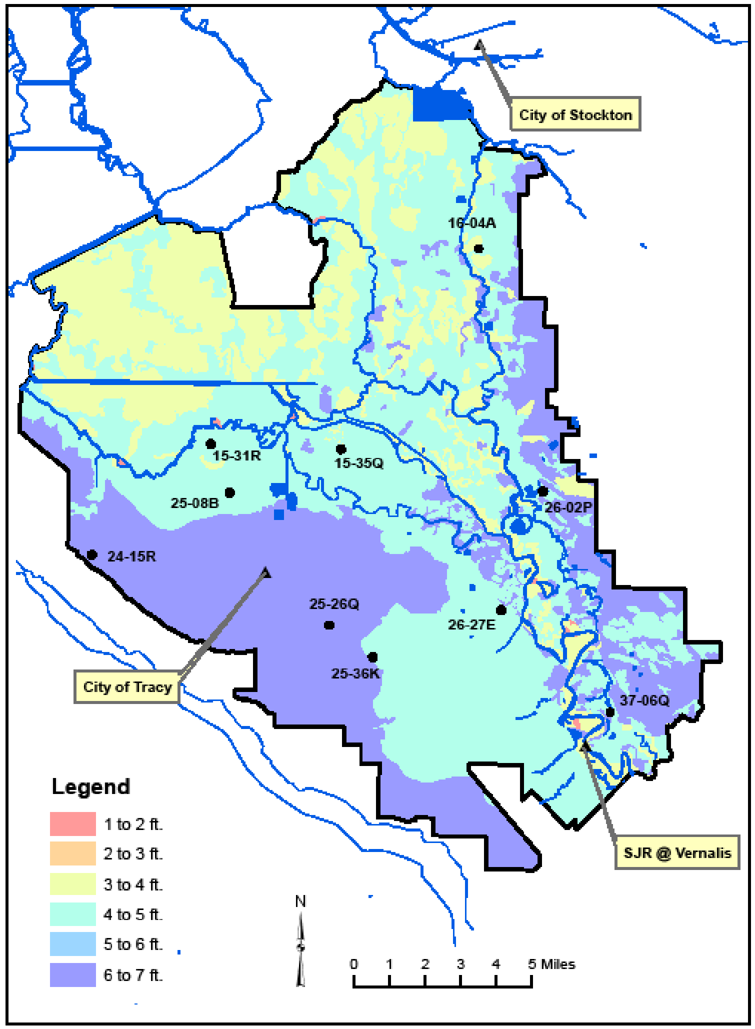
Salt Precipitation / Dissolution

Page 44, Figure 3.15: The relationship between leaching fraction and salt precipitation or dissolution in the soil when using water from the San Joaquinr River.



Shallow Groundwater

Page 48, Figure 3.17. Depth to groundwater.



Shallow Groundwater

Page 51, Table 3.10. Electrical conductivity of subsurface tile drains from 14 sites in the South Delta. (Chilcott et al., 1988.).

Site Location	Electrical Conductivity, dS/m June, 1986	June, 1987	Average
C2	3.4	3.2	3.3
C5	2.5	2.5	2.5
C10	1.9	2.3	2.1
C11n	2.3	2.9	2.6
C11s	3.3	no data	3.3
C13	4.0	4.2	4.1
C14	3.1	4.0	3.6
C16	2.5	3.0	2.8
C17	4.0	3.8	3.9
C36	2.3	2.4	2.4
C37	3.1	3.1	3.1
C38	3.4	3.6	3.5
C39	2.3	2.4	2.4
C41	4.0	4.2	4.1
Average	3.0	3.2	3.1

Leaching Fraction

Assuming EC_i = 0.7 dS/m

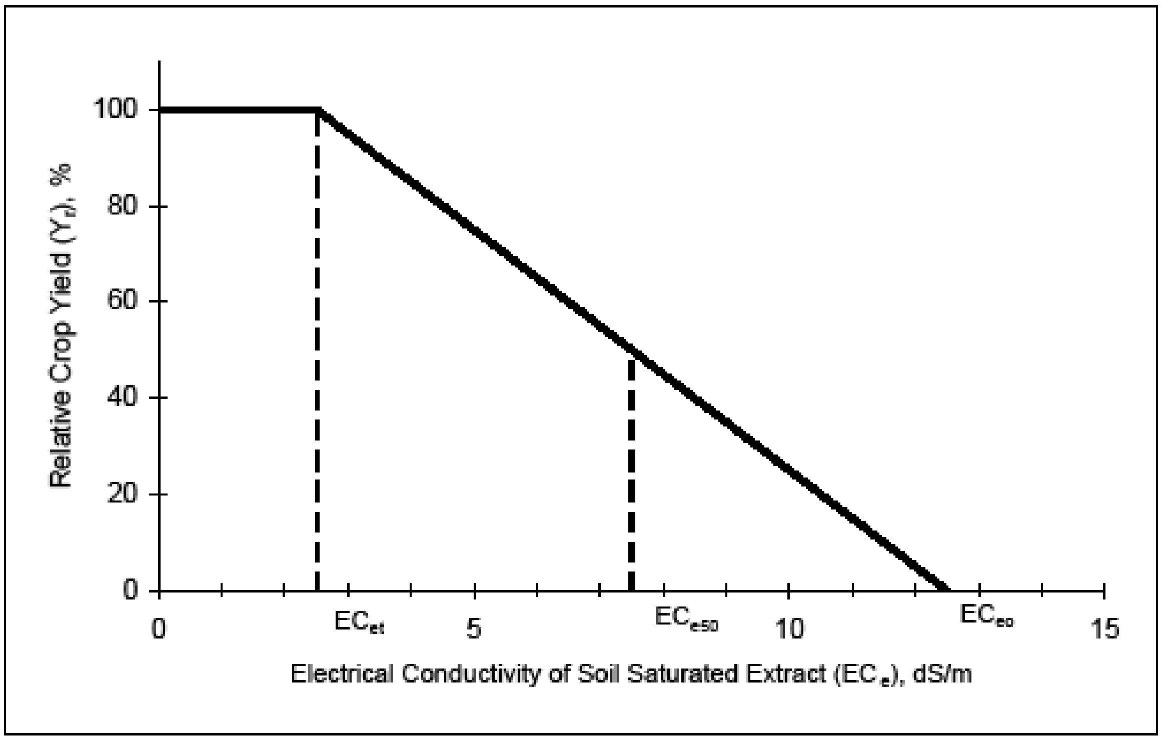
- 14 tile drain discharge sites (Chilcott et al., 1988)
  - L = 0.7 / 3.1 = 0.23
- 74 discharge sites (Montoya, 2007)
  - L = 0.7 / 1.5 = 0.47
- 9 Soil samples (Meyer et al., 1976)
  - L > 0.15 for 6 sites
  - L < 0.10 for 3 sites

Steady-State Models for Soil Salinity

- Bernstein (1964): $L_r = EC_i / EC_{e50}$
- Bernstein and Francois (1973b) & van Schilfgaarde et al. (1974): $L_r = EC_i / (2^*EC_{e0})$
- Rhoades (1974): $L_r = EC_i / (5^*EC_{et} - EC_i)$
- Rhoades and Merrill (1976): $L_r = EC_i / EC_{e\ 40\text{-}30\text{-}20\text{-}10}$
- Hoffman and van Genuchten (1983):
  $C/C_a = 1/L + (\delta/Z \times L) \times \ln [L + (1 - L) \times \exp^{(-Z/\delta)}] - 1.73$
  (corrected equation for Table 5.2)

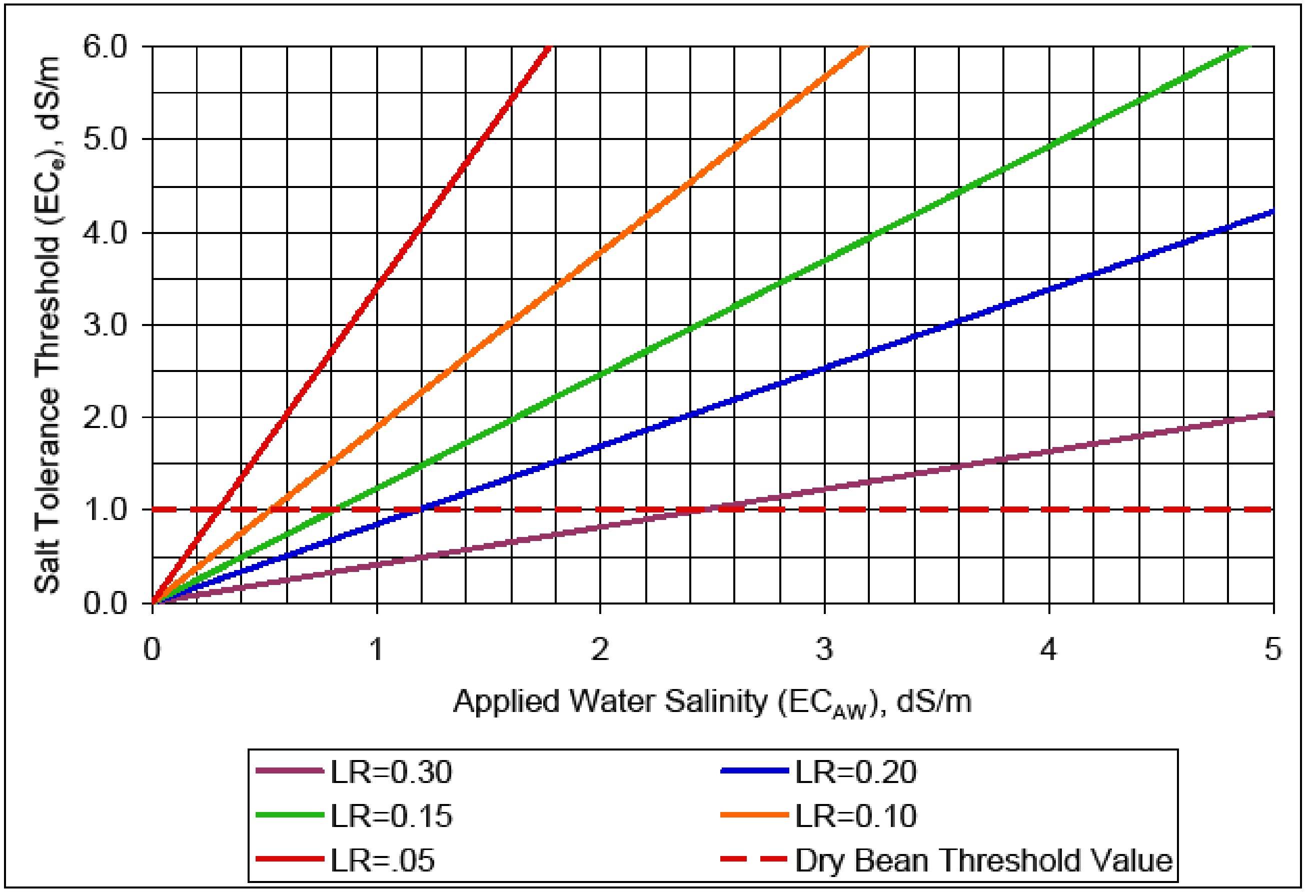
Definition of Variables in Steady-State Models

Page 55, Figure 4.1 - Three of the salt tolerance variables used in various steady-state models illustrated for tomatoes.



Graphical Solution of Exponential Model

Page 55, Figure 4.2. Graphical solution with exponential uptake function (assuming no precipitation)



Steady-State Model Predictions of L_r Compared to Experimental Results

Cereals

Excerpt from Page 61, Table 4.1. Leaching requirement predicted by 5 different methods.

Crop	Experimental Results L_r	Experimental Results EC_i	L_r Prediction Using EC_{e50}	$2EC_{e0}$	$5EC_{et}-EC_i$	40-30-20-10	Exp.
Barley	0.10	2.2	0.12	0.04	0.06	0.01	0.05
Oat	0.10	2.2	0.18	0.06	0.11	0.04	0.09
Sorghum	0.08	2.2	0.22	0.08	0.07	0.01	0.06
Wheat	0.07	1.4	0.11	0.03	0.05	0.03	0.04
Wheat	0.08	2.2	0.17	0.05	0.08	0.01	0.07

Steady-State Model Predictions of L_r Compared to Experimental Results

Vegetables

Excerpt from Page 61, Table 4.1. Leaching requirement predicted by 5 different methods.

Crop	Experimental Results		L_r Prediction Using				
	L_r	EC_i	EC_{e50}	$2EC_{e0}$	$5EC_{et}-EC_i$	40-30-20-10	Exp.
Cauliflower	0.17	2.2	0.31	0.09	0.25	0.22	0.18
Celery	0.14	2.2	0.22	0.06	0.32	0.34	0.20
Cowpea	0.16	2.2	0.24	0.08	0.10	0.03	0.09
Lettuce	0.26	2.2	0.43	0.12	0.51	0.72	0.24
Lettuce	0.22	1.4	0.27	0.08	0.27	0.36	0.18
Tomato	0.21	2.2	0.29	0.09	0.21	0.16	0.16

Steady-State Model Predictions of L_r Compared to Experimental Results

Forages

Excerpt from Page 61, Table 4.1. Leaching requirement predicted by 5 different methods.

Crop	Experimental Results L_r	Experimental Results EC_i	L_r Prediction Using EC_{e50}	$2EC_{e0}$	$5EC_{et}$-EC_i	40-30-20-10	Exp.
Alfalfa	0.20	2.0	0.18	0.05	0.15	0.16	0.13
Alfalfa	0.32	4.0	0.36	0.11	0.36	0.52	0.22
Alfalfa	0.06	1.0	0.11	0.03	0.11	0.09	0.09
Alfalfa	0.15	2.0	0.23	0.06	0.25	0.31	0.17
Barley	0.13	2.2	0.17	0.05	0.08	0.02	0.07
Cowpea	0.17	2.2	0.31	0.09	0.38	0.45	0.22
Fescue	0.10	2.0	0.17	0.05	0.17	0.17	0.13
Fescue	0.25	4.0	0.25	0.07	0.40	0.58	0.23
Oat	0.17	2.2	0.31	0.0	0.25	0.22	0.18
Sudan Grass	0.16	2.0	0.14	0.04	0.19	0.17	0.13
Sudan Grass	0.31	4.0	0.28	0.08	0.49	0.58	0.23

Performance of Steady-State Models

- EC_{e50} – consistently over estimated L_r
- $2*EC_0$ – consistently under estimated L_r
- $5*EC_{et} - EC_i$ – reasonable at low L_r, over estimated severely at high L_r
- 40-30-20-10 – large swings between over and under estimating L_r
- **Exponential** – correlated best with measured L_r but underestimated at high L_r

Transient Models for Salinity Control

- Grattan – modified 40-30-20-10
- Corwin - TETrans
- Simunek - UNSATCHEM
- Letey – ENVIRO-GRO

(see Section 4.2 of report)

Factors to Consider when Evaluating Transient Models*

- Appropriate water uptake function
- Feedback mechanism for soil-water status, plant growth & transpiration
- Allow for extra water uptake from non-stressed portion of the root zone
- Account for salt precipitation / dissolution
- Comparison with field experimental results

* *From Letey & Feng, 2007*

Performance of Transient Models with Factors given by Letey & Feng, 2007

Factor	Grattan	Corwin	Simunek	Letey
Water uptake function	Yes	Yes	Yes	Yes
Feedback mechanism	No	Yes	No	Yes
Water uptake based on stress	No	Yes	No	Yes
Salt precipitation / dissolution	No	No	Yes	No
Field tested	No	Yes	Yes	Yes

Comparison Between Steady-State and Transient Models

Page 62, Table 4.2. Summary of leaching requirements (L_r) as estimated by two steady-state and two transient models. (Corwin et al., in press).

Model	Leaching Requirement Crop or Cropping Period Alfalfa	Wheat	Lettuce	Crop Growth*	Overall Rotation*
Steady-State					
$5EC_{et}$ – ECi	0.14	0.04	0.23	0.14	0.13
WATSUIT	0.09	0.03	0.13	0.09	0.08
Transient					
TETrans	<0.14	<0.04	<0.17		<0.13
UNSATCHEM	<0.10	0.00	<0.13		<0.08

**Crop Growth refers to period included in crop simulation and Overall Rotation includes entire rotation with fallow periods.*

Page 63, Table 4.3. Comparison of leaching requirement for a steady-state model and the ENVIRO-GRO (Letey and Feng, 2007).

Irrigation Salinity dS/m	Leaching Requirement $5EC_{et}$ – EC_i steady-state model	ENVIRO-GRO transient-state model
1.0	0.14	<0.05
2.0	0.32	0.15

Specific Conclusions Reported for Transient Models

- Grattan
  – EC_i of 1.1 dS/m would protect bean in Davis, CA area
- Corwin
  - Steady-state models over-estimate L_r compared to transient models, but only to a minor extent
  - Where irrigation water quality and amount minimizes the temporal dynamic effects of plant water uptake, L_r can be adequately estimated by exponential steady-state
- Letey
  – Water quality standard could be raised to 1.0 dS/m and protect bean and other crops in South Delta

Steady-State Modeling for South Delta

Steady-state assumptions

a) $I + P = ET_C + D$
b) No changes in water or salt storage on an annual water year basis

Cropping assumptions

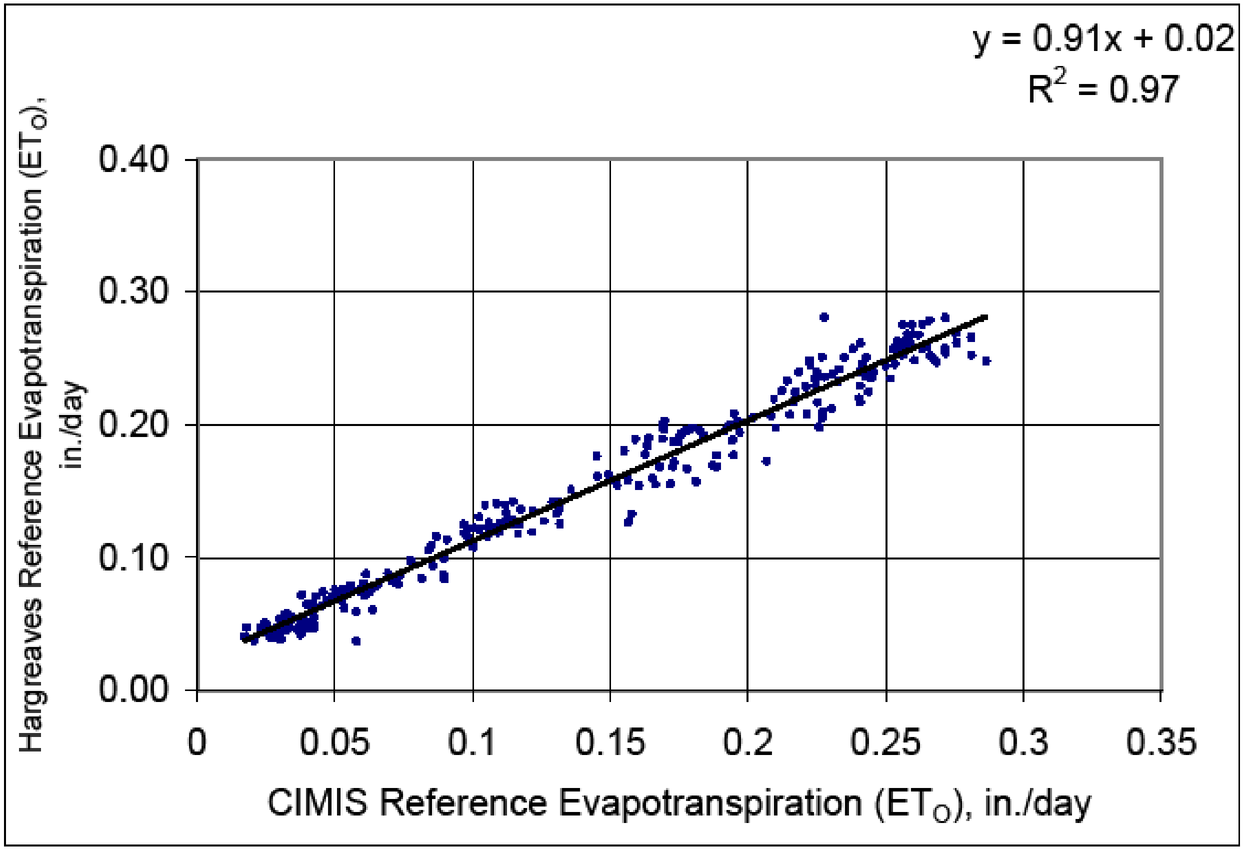
a) Bean used as indicator crop
b) Bean planted April 1 and harvested July 31
c) Soil bare remainder of the year

Crop evapotranspiration

a) Used Hargreaves equation
b) Bean crop coefficients

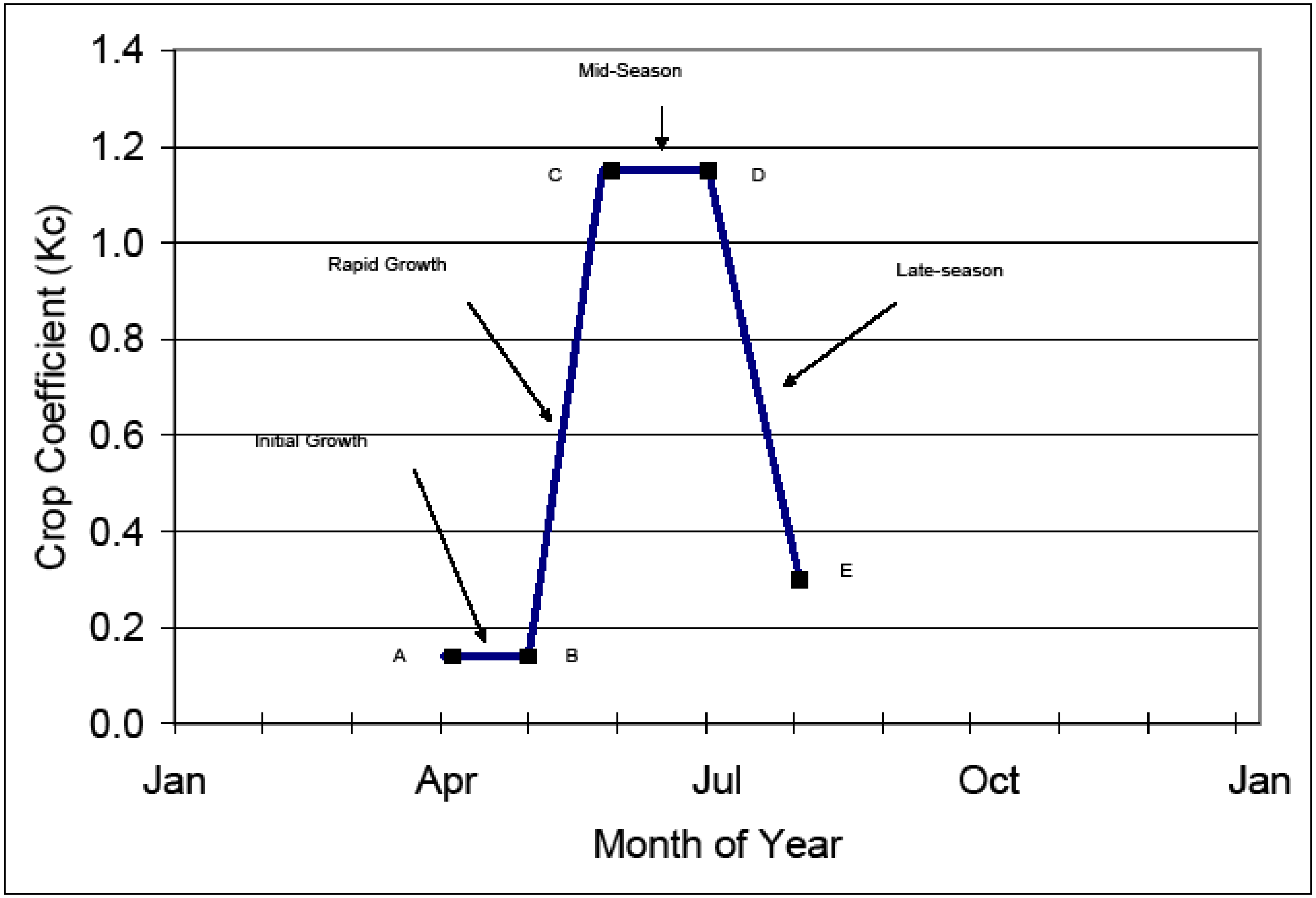
Crop Evapotranspiration

Page 65, Figure 5.1 Hargaeves equation vs. CIMIS ET_O



Bean Crop Coefficients

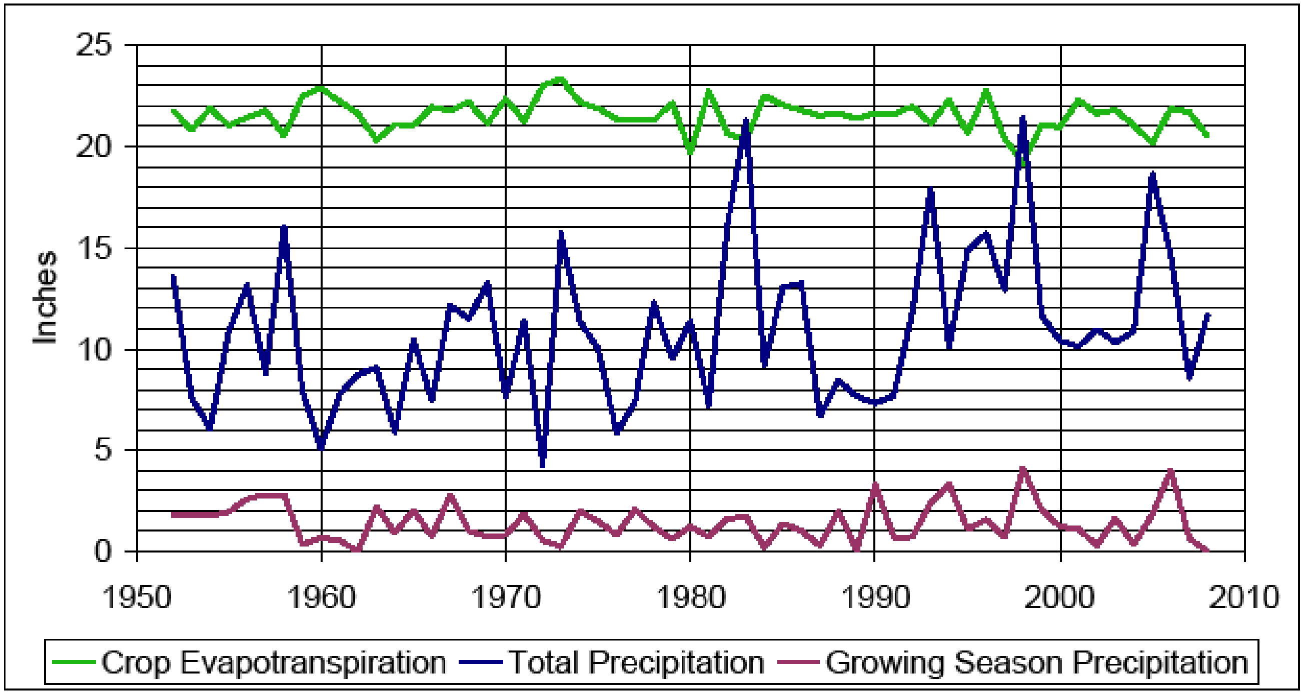
Page 67, Figure 5.3. Crop coefficients for bean growth and development periods.



Steady-State Modeling for South Delta

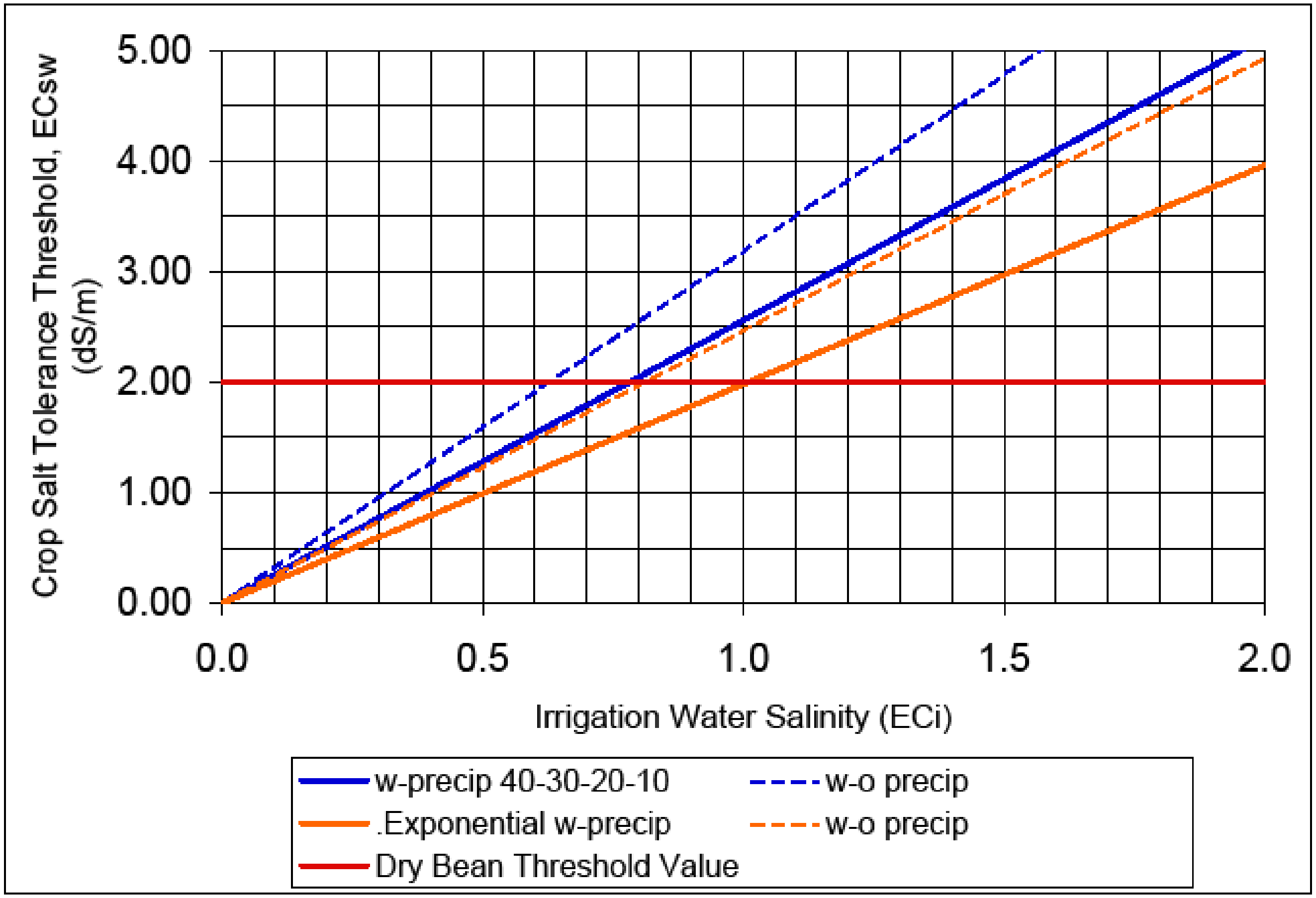
- Precipitation
  - All growing season precipitation is effective
  - Non-growing season precipitation less surface evaporation is effective

Page 68, Figure 5.4. Comparison of precipitation and crop evapotranspiration



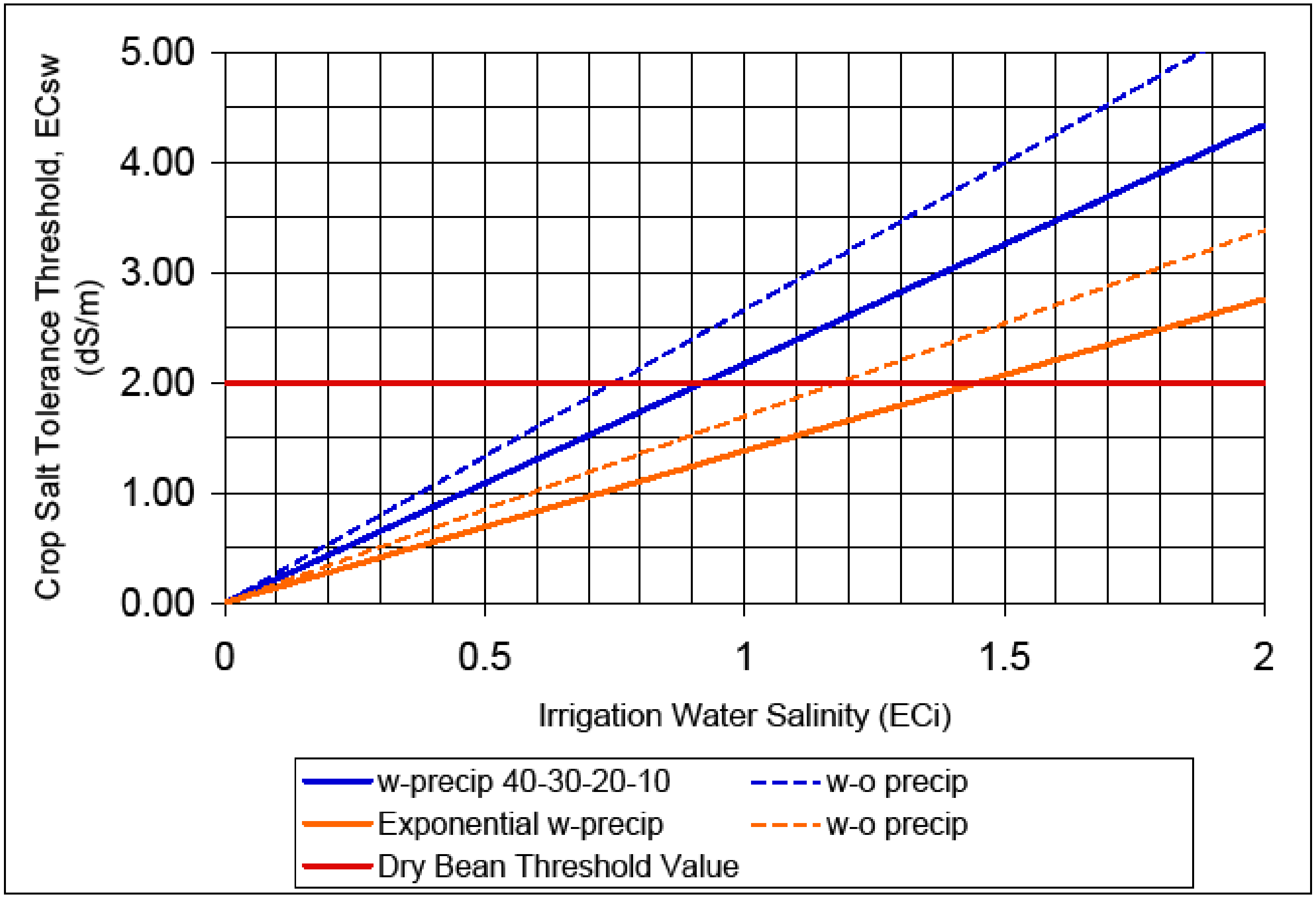
Steady-State Modeling for South Delta

Page 71, Figure 5.5.a. Crop salt tolerance threshold as function of EC_i at LF = 0.15.



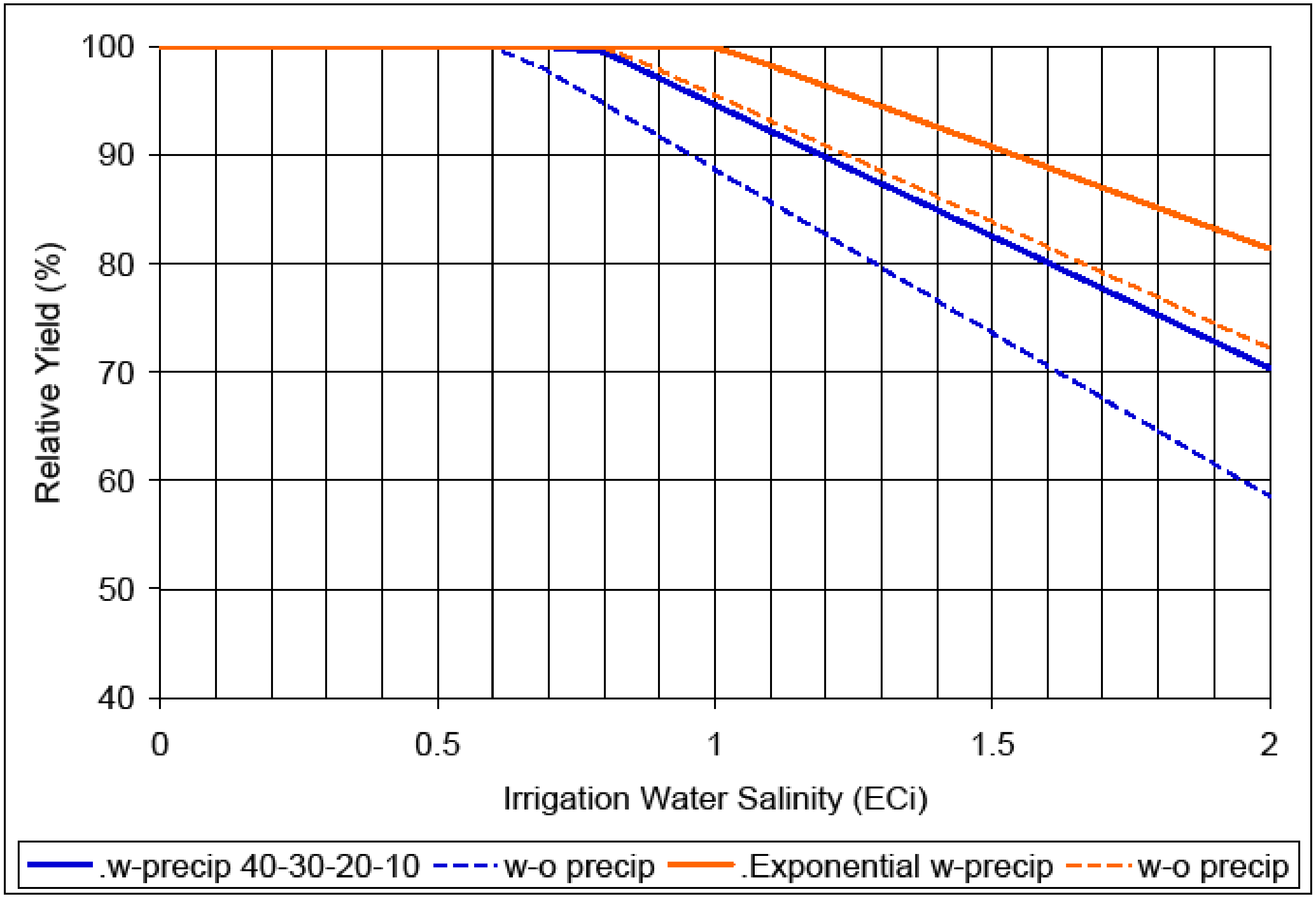
Steady-State Modeling for South Delta

Page 71, Figure 5.5.b. Crop salt tolerance threshold as function of EC_i at LF = 0.20.



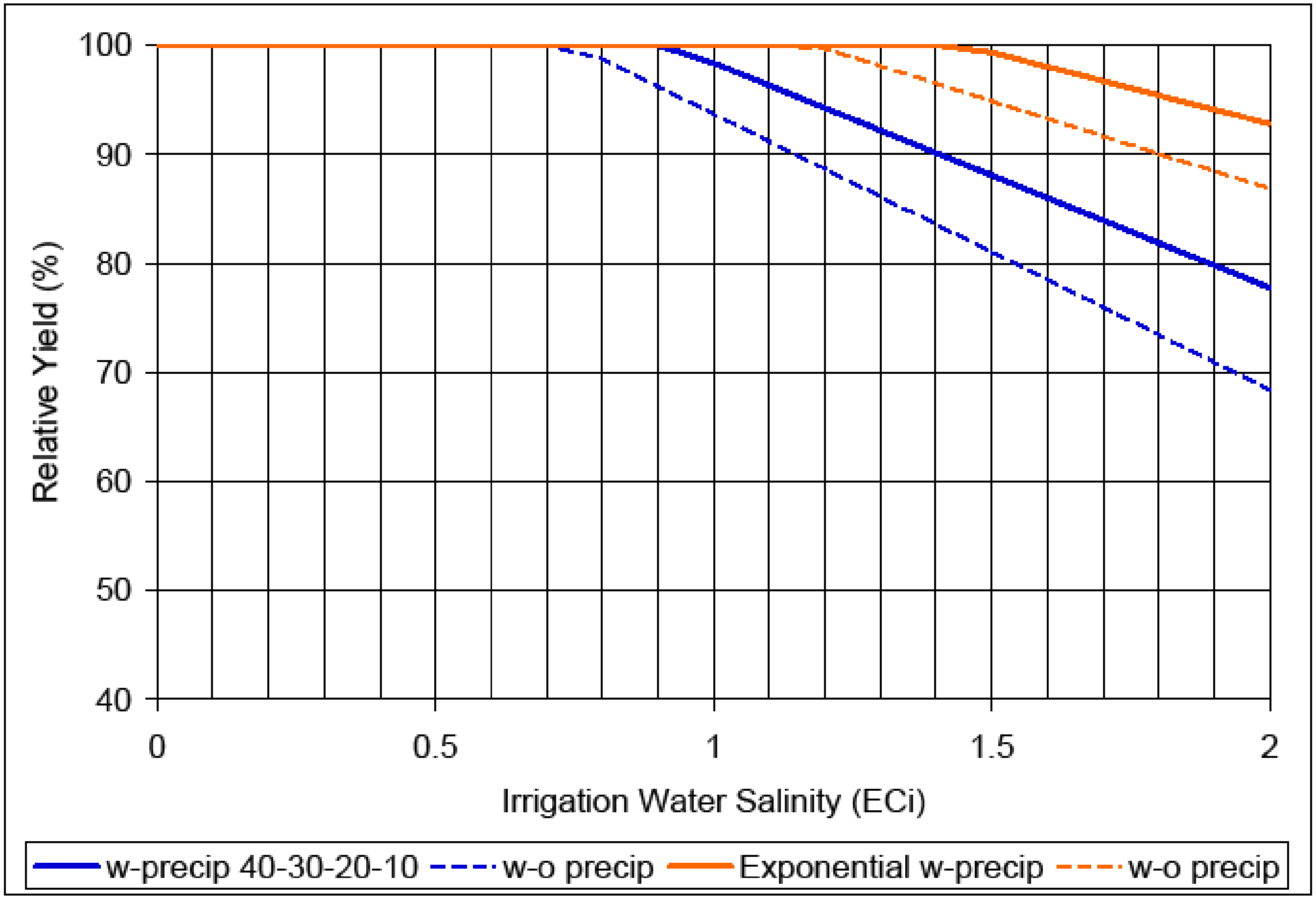
Steady-State Modeling for South Delta

Page 72, Figure 5.6.a. Relative crop yield as function of EC_i at LF = 0.15.



Steady-State Modeling for South Delta

Page 72, Figure 5.6.b. Relative crop yield as function of EC_i at LF = 0.20.



Summary and Conclusions

Factors Influencing Water Quality Standards

1) San Joaquin River salinity
   – EC_i averaged 0.7 dS/m from 1990 to 2006
   – Neither sodicity nor toxicity are a concern
2) Soil survey (NRCS, 1992)
   – Saline soils occupy 5% of irrigated land
   – No sodic soils reported
   – Shrink / swell soils occupy 50% of the irrigated area. Based on similar soils in the Imperial Valley, bypass flow should not cause a salinity management problem.

Summary and Conclusions

Factors Influencing Water Quality Standards

3) Crop surveys

- Surveys over past three decades averaged: 8% trees and vines; 24% field crops; 22 % truck crops; 13% grain and hay; and 31% hay and pasture.
- Of the predominant crops, the most salt sensitive are almond, bean, and walnut, with bean being most sensitive.

4) Effective rainfall

- DWR study shows all precipitation surpassing 5.6 inches should be useful for evapotranspiration.

Summary and Conclusions

Factors Influencing Water Quality Standards

5) Irrigation methods and efficiencies for 2007

Irrigation Method	Area, %	Efficiency, %
Border	44	78
Furrow	51	70
Sprinkler, drip	5	75, 87
Overall Efficiency		75

6) Crop water uptake pattern

- 40-30-20-10 and exponential patterns used
- Exponential slightly better

Summary and Conclusions

Factors Influencing Water Quality Standards

7) Climate

- Temperature and humidity in South Delta similar to Riverside, CA for purpose of using experimental salt tolerance data.

8) Salt precipitation / dissolution

- Two analyses indicate about 5% more salt added to salt load because of dissolution at LF = 0.15.

Summary and Conclusions

Factors Influencing Water Quality Standards

9) Water table depth
   - Depth appears to be at least 3 feet with water tables over much of the area at least 5 feet.

10) Leaching fraction
   - 14 tile drain discharge sites: LF = 0.23
   - 74 discharge sites: LF = 0.47
   - Soil samples: LF highly variable

Summary and Conclusions

Models to Determine Acceptable Water Quality

1) Steady-state models
   - Exponential model performed best of 5 models compared with experimentally measured L_r for 14 crops.
   - Finding supported by comparisons between steady-state and transient models.

Summary and Conclusions
Models to Determine Acceptable Water Quality

2) Transient models

Model	Location	Water Quality Standard, EC_i, dS/m
Grattan	Davis, CA	1.1 for bean
Corwin	Imperial Valley, CA	Steady-state models over-estimate slightly compared to transient models
Letey	---	1.0 for bean

Summary and Conclusions

Models to Determine Acceptable Water Quality

3) Steady-state model for South Delta

(assuming precipitation)

Model	Leaching Fraction	Water Quality Standard, EC_i, dS/m
Exponential	0.15	1.0
	0.20	1.4
40-30-20-10	0.15	0.8
	0.20	0.9

Recommendations

- A field experiment should be conducted to establish the salt tolerance of bean under local conditions using current varieties.
- If water quality standard is changed throughout the year, knowing salt sensitivity of bean at different growth stages would be beneficial.
- If a steady-state model is to be used, include effective rainfall, and employ either the exponential or the 40-30-20-10 model.
- Support should be given to test one or more transient models using South Delta data.
- It is recommended that the source of drain discharge be determined.