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

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Division of Water Rights

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1. Introduction

1.1. Location

The southern Delta, in general, encompasses lands and water channels of the Sacramento-San Joaquin Delta southwest of Stockton, California. The bulk of the lands in the southern Delta are included within the South Delta Water Agency (SDWA), and frequently referred to as the South Delta. Figure 1.1 shows the outline of the South Delta Water Agency relative to the San Joaquin County.line and the legal boundary of the Delta. This report will focus on the area included within the SDWA as being representative of the southern Delta. Of the nearly 150,000 acres within the South Delta, the total irrigated area has declined from over 120,000 acres in the last three decades of the 20th century to about 100,000 acres in recent years. The non-irrigated area includes urban lands, water courses, levees, farm homesteads, islands within channels, and levees.

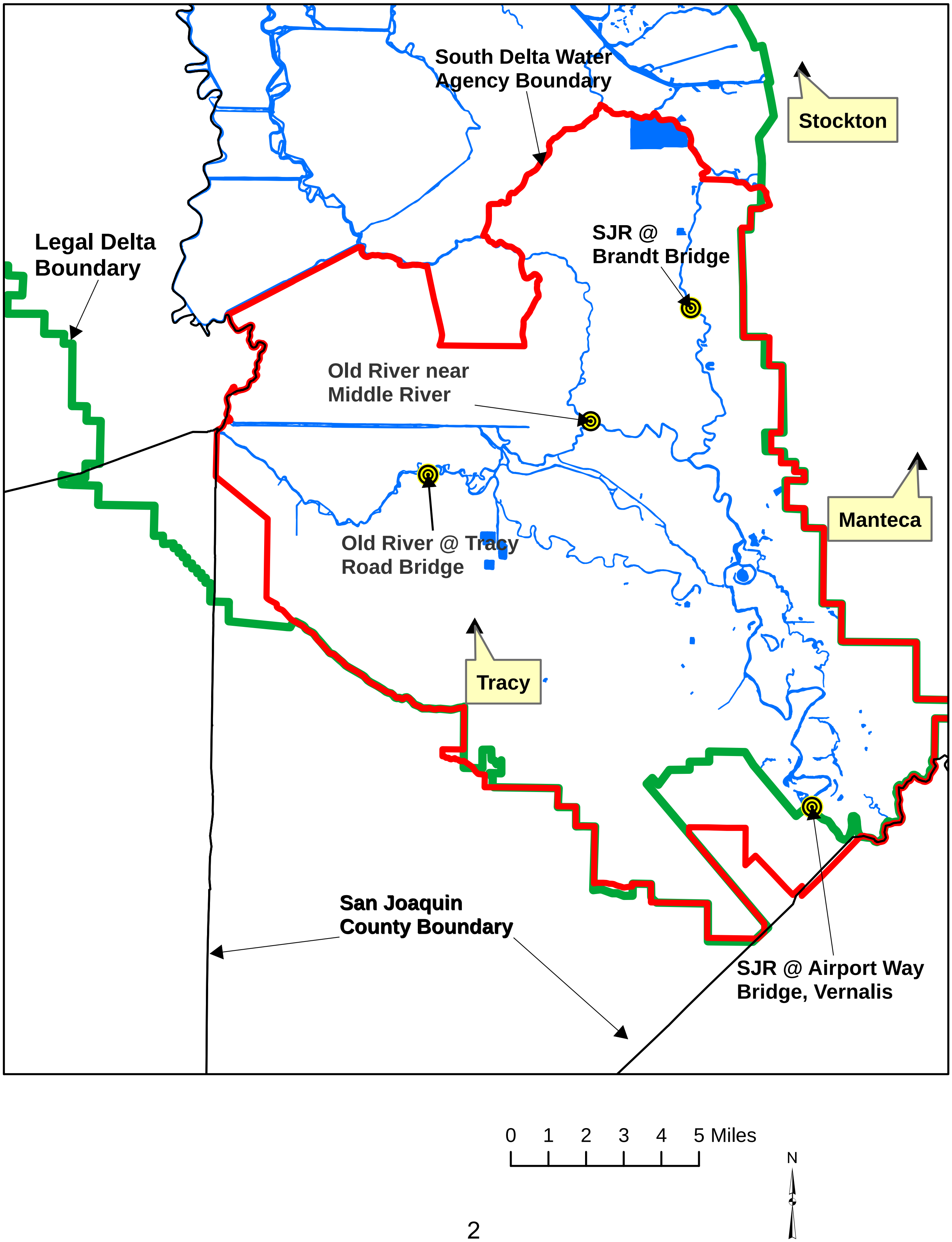
1.2. Regulations

The California Environmental Protection Agency, State Water Resources Control Board (State Water Board) established the current southern Delta salinity objectives in the 1978 Sacramento-San Joaquin Delta and Suisun Marsh Water Quality Control Plan (1978 Delta Plan). The approach used in developing the objectives involved an initial determination of the water quality needs of significant crops grown in the area, the predominant soil type, and irrigation practices in the area. The State Water Board based the southern Delta electrical conductivity (EC) objectives on the calculated maximum salinity of applied water which sustains 100 percent yields of two important salt sensitive crops grown in the southern Delta (beans and alfalfa) in conditions typical of the southern Delta. These calculations were based on guidelines from the University of California's Cooperative Extension and Irrigation and Drainage Paper 29 of the Food and Agriculture Organization of the United Nations (Ayers and Westcot, 1976).

The State Water Board set an objective of 0.7 millimhos per centimeter (mmhos/cm) EC during the summer irrigation season (April through August) based on the salt sensitivity and growing season of beans and an objective of 1.0 mmhos/cm EC during the winter irrigation season (September through March) based on the growing season and salt sensitivity of alfalfa during the seedling stage. Salinity compliance stations within the south Delta are shown in Figure 1.1: San Joaquin River (SJR) at Vernalis, CA (C10); SJR at Brandt Bridge (C6); Old River at Middle River (C8); and Old River at Tracy Road Bridge (P12).

In December of 2006, the State Water Board adopted the 2006 Bay-Delta Plan. The southern Delta salinity objectives originally adopted in 1978 were not substantively changed in the 2006 Bay-Delta Plan due to the fact that adequate scientific information was not available on which to base changes. The State Water Board, however, identified Delta and Central Valley salinity as an emerging issue and cited its pending effort to evaluate the southern Delta salinity objectives and their implementation as part of its larger salinity planning endeavor.

Figure 1.1. Map of southern Delta showing boundary of the South Delta Water Agency and salinity complaince stations.



1.3. Purpose and Objectives

The purpose of this report is to research the scientific literature and provide the state of knowledge on subjects that impact crop productivity with saline irrigation water and analyze the existing information from the South Delta and quantify how the various factors influencing the use of saline water applies to conditions in the South Delta. One of the objectives of this study is the review of existing literature relating to the effect of salinity on a variety of irrigated crops under South Delta conditions, preparation of a comprehensive list of references, and a synopsis of findings from key references. A second objective is the review of the relative strengths and limitations of steady-state and transient models that have been used to determine the suitability of saline water for crop production. As part of this objective, strengths, limitations, and assumptions of each model when applied to field conditions are to be presented. The third objective involves the use of soil information to determine and describe the approximate area and nature of saline and drainage-impaired soils; an estimate of the effectiveness of local rainfall in reducing the irrigation requirement; and compiling and evaluating historical crop types, acreages, and evapotranspiration information. The fourth objective is to provide conclusions and recommendations to the State Water Resources Control Board based upon the literature, modeling, and data evaluation. Among the conclusions and recommendations to be reported the following are considered paramount. (1) Identify significant gaps or uncertainties in the literature and recommend future studies to fill the gaps. (2) Using a steady-state model and appropriate data for the South Delta, estimate the leaching fraction required for salinity control for crops regularly grown on the drainage- and salinity-impaired soils of the South Delta. (3) Using the approach as in (2), recommend a salinity guideline that could provide full protection of the most salt sensitive crop currently grown or suitable to be grown on the drainage- and salinity-impaired soils. The final objective is to present the findings and recommendations in Sacramento to interested watershed stakeholders and representatives of California state agencies.

2. Background information

2.1. General Salinity Information

Soluble salts are present in all natural waters, and it is their concentration and composition that determine the suitability of soils and waters for crop production. Water quality for crop production is normally based on three criteria: (1) salinity, (2) sodicity, and (3) toxicity. Salinity is the osmotic stress caused by the concentration of dissolved salts in the root zone on crop growth. To overcome osmotic stress, plants must expend more energy to take up nearly pure water from the saline soil; thereby leaving less energy for plant growth. When the proportion of sodium compared to calcium and magnesium becomes excessive, soil structure deteriorates and the soil is said to be sodic. This deterioration of the soil structure, particularly near the soil surface, reduces infiltration and penetration of water into the soil; thereby, making it difficult for plants to take up sufficient water to satisfy evapotranspiration (ET) needs. Toxicity encompasses the effects of specific solutes that damage plant tissue or cause an imbalance in plant nutrition. The impact of salinity on plants is well summarized by Maas and Grattan (1999). Much of what follows in this section is taken from that reference.

The most common whole-plant response to salt stress is a reduction in the rate of plant growth. The hypothesis that seems to fit observations best asserts that excess salt reduces plant growth, primarily because it increases the energy that the plant must expend to acquire water from the soil and make the biochemical adjustments necessary to survive. Thus, energy is diverted from the processes that lead to growth and yield, including cell enlargement and the synthesis of metabolites and structural compounds (Rhoades, 1990). Although salinity affects plants in many ways physiologically, overt injury symptoms seldom appear except under extreme conditions of salt stress. Salt-affected plants usually appear normal, except they are stunted and may have darker green leaves which, on some plant species, are thicker and more succulent. Growth suppression seems to be a nonspecific salt effect that is directly related to the total salt concentration of soluble salts or the osmotic potential of the soil water. Within limits, the same osmotic concentration of different combinations of salts cause nearly equal reductions in growth. On the other hand, single salts or extreme ion ratios are likely to cause specific ion effects, such as ion toxicities or nutritional imbalances which cause even further yield reductions. For a discussion of the mechanisms of osmotic and specific ion effects, see Lauchli and Epstein (1990) and Bernstein (1975).

With most crops, including tree species, yield losses from osmotic stress can be significant before foliar injury is apparent. However, salts tend to accumulate in woody tissues, like trees, over time and toxic symptoms may not appear for several years; but, leaf injury can be dramatic when salts accumulate in the leaves (Hoffman, et al., 1989).

While crop salt tolerance values are based solely on desired yield, salinity adversely affects the quality of some crops while improving quality of others. By decreasing the size and/or quality of fruits, tubers, or other edible organs, salinity reduces the market value of many vegetable crops, e.g., carrot, celery, cucumber, pepper, potato, cabbage, lettuce, and yam. Beneficial effects include increased sugar content of carrot and asparagus, increased total soluble solids in tomato and cantaloupe, and improved grain quality of durum wheat. Generally, however, beneficial effects of salinity are offset by decreases in yield.

Soils and waters have no inherent quality independent of the site-specific conditions in question. Thus, soils and waters can only be evaluated fully in the context of a specified set of conditions. There are a number of factors that must be considered when evaluating a salinity standard for water quality in irrigated agriculture. These factors include: plant response to soil salinity, effective rainfall, irrigation management and method, uniformity of water applications, crop root water uptake distribution, climate, preferential (bypass) flow of applied water through the soil profile, leaching fraction, salt precipitation/dissolution in the crop root zone, and extraction of water by crops from shallow groundwater. The current state of knowledge for each of these factors, based upon published literature, is discussed in Section 3. Following the discussion of each factor, the importance of that factor is evaluated using data and information from the South Delta. Factors that appear to be insignificant will be identified and the reason the factor is insignificant will be noted. Factors that are important will be described in detail and their potential impact on a salinity water quality standard will be quantified. Based upon the important factors for the South Delta, Section 5 of this report, using a steady-state model, will be used to estimate the impacts on South Delta agriculture over a range of possible salinity water quality standards.

2.2. Sources & Quality of Irrigation Water in the South Delta

Water conditions in the South Delta are influenced by San Joaquin River inflow; tidal action; water export facilities (primarily water levels and circulation); local pump diversions; agricultural and municipal return flows; channel capacity; and upstream development. The area is irrigated primarily with surface water through numerous local agricultural diversions. A small percentage of the land is irrigated with groundwater.

2.2.1. Salinity

The salinity of the water used for irrigation, reported as electrical conductivity in units of µS/cm, is monitored at several locations in the South Delta. The units of microSiemens per centimeter (µS/cm) are 1000 times larger than units of deciSiemens per meter (dS/m). In keeping with the literature on crop response to salinity the units of dS/m will be used in this report. Another important reason for using dS/m is that it is numerically equal to millimho per centimeter (mmho/cm), an outmoded unit of measure for electrical conductivity that was used for decades in agriculture to quantify salinity.

For information only, the monthly average electrical conductivity (EC) values of the water in the San Joaquin River at Vernalis and at Old River at the Tracy Bridge from January, 2000 until January, 2009 are given in Figure 2.1. Only data from these two southern Delta compliance stations are shown as they tend (but not always) to represent the lowest and highest EC concentrations respectively of the four compliance stations (locations as shown in Figure 1.1). As one would expect there are continuous variations in the measured values. With very few exceptions, the EC remains below 1.0 dS/m (1000 µS/cm) at both sampling locations. Figure 2.2 shows the median and the high and low values of the electrical conductivity by month for the Old River at Tracy Bridge from the data in Figure 2.1. Note that during the months of April through July, the growing season for bean, the median EC is below 0.7 dS/m.

2.2.2. Sodicity

An important consideration in evaluating irrigation water quality is the potential for an excess concentration of sodium to occur in the soil leading to a deterioration of soil structure and reduction of permeability. When calcium and magnesium are the predominant cations adsorbed on the soil exchange complex, the soil tends to have a granular structure that is easily tilled and readily permeable. High levels of salinity reduce swelling and aggregate breakdown (dispersion) and promote water penetration, whereas high proportions of sodium produce the opposite effect. Excess sodium becomes a concern when the rate of infiltration is reduced to the point that the crop cannot be adequately supplied with water or when the hydraulic conductivity of the soil profile is too low to provide adequate drainage. The sodium-adsorption-ratio (SAR), is defined as:

$$SAR = C_{Na} / (C_{Ca} + C_{Mg})^{1/2} \qquad \text{(Eqn. 2.1)}$$

Figure 2.1. 30-day running average of electrical conductivity (dS/m) for Old River at Tracy (in red) and San Joaquin River at Vernalis (in blue) from Jan. 2000 through Jan. 2009 (CDEC Stations OLD and VER).

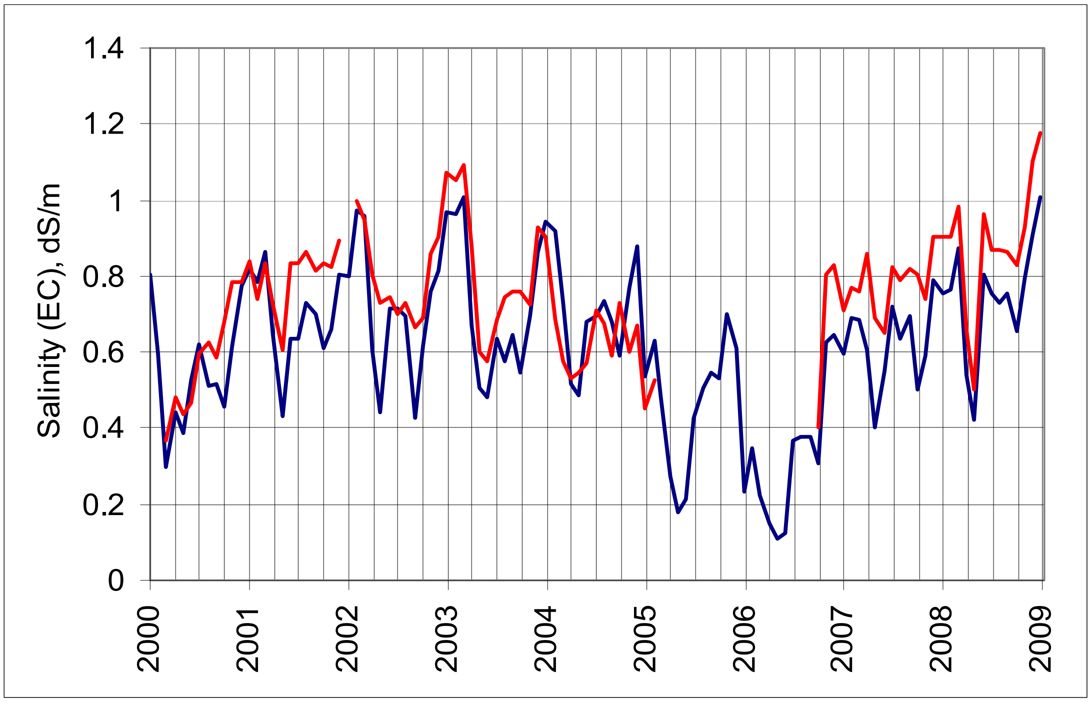
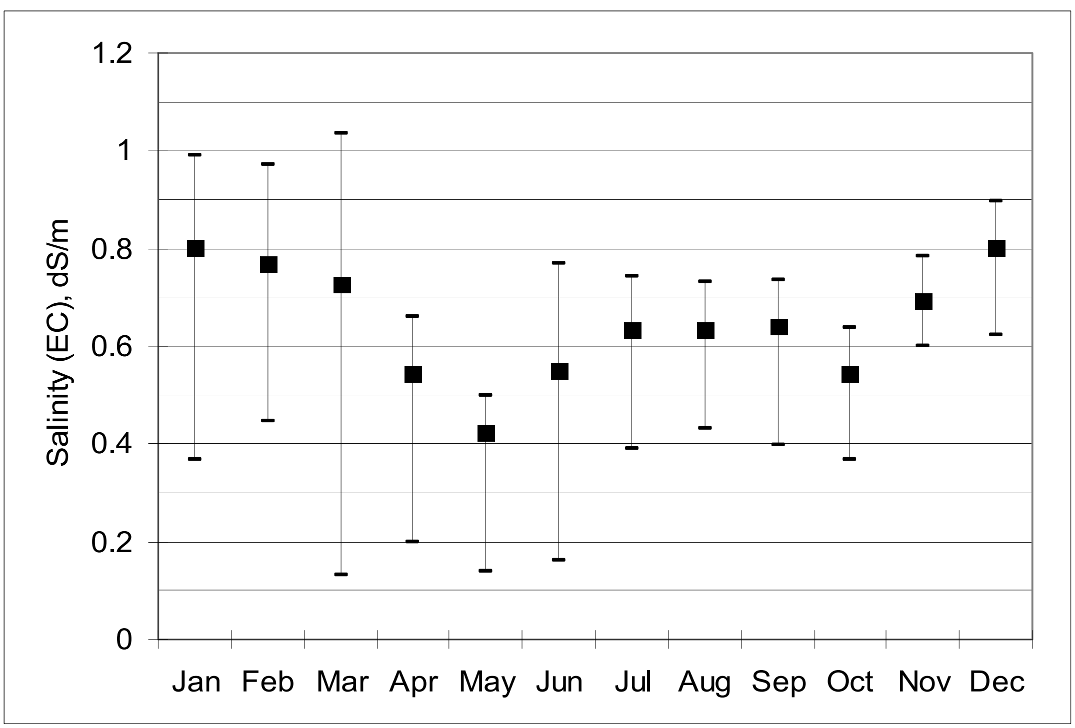


Figure 2.2. Median, high, and low electrical conductivity (dS/m) averaged by month as measured at Old River at Tracy (CDEC Station OLD) from Jan. 2000 through Jan. 2009.



where all ion concentrations (C) are in units of mol/m^3. This equation is used to assess the sodium hazard of irrigation water. Both the salinity and the SAR of the applied water must be considered simultaneously when assessing the potential effects of water quality on soil water penetration.

From the water quality data for the San Joaquin River at Mossdale from 2000 to 2007 (a total of 154 analyses), the average ion concentrations were: Na = 3.2 mol/m^3; Ca = 0.94 mol/m^3; and Mg = 0.77 mol/m^3 (Dahlgren, 2008). Inserting these values into Equation 2.1 gives an SAR of 2.4. This SAR is well below a value that would cause a sodicity problem.

2.2.3. Toxicity

The potentially toxic effects of certain specific solutes, such as boron, sodium, and chloride, are normally associated with their uptake by crop roots and accumulation in the leaves. Some ions, like chloride, can also be absorbed directly into the leaves when moistened during sprinkler irrigation. Many trace elements are also toxic to plants at very low concentrations. Suggested maximum concentrations for these trace elements are given by Pratt and Suarez (1990). Fortunately, most irrigation waters contain insignificant concentrations of these potentially toxic trace elements and are generally not a problem. No information was found that would indicate that toxicity may occur from the irrigation water used in the South Delta.

2.3. South Delta Soils & Crops

2.3.1. Soils

The soils in the South Delta have been identified by a Soil Survey conducted by the Soil Conservation Service (SCS) for San Joaquin County in 1992 (SCS, 1992). Figure 2.3 was developed using the geographic information system (GIS) representation of this survey information from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database (NRCS, 2009). The soils are shown in Figure 2.3 by different colors based on surface soil texture. The associated SCS soil units and some key soil properties are listed in Table 2.1 and grouped by the same general soil texture types.

Based on Montoya (2007), much of the surface geology of the Diablo Range immediately west and up-gradient from the South Delta is generally classified as marine sedimentary rock. Soils in the South Delta originated, to varying degrees, from these marine sedimentary rocks. Based on detailed logs of over 1,500 20-foot deep drill holes by DWR in the 1950's and 1960's, the San Joaquin Valley was partitioned into several general physiographic classifications. Three classifications overlapping the immediate South Delta included alluvial fan material from the Diablo Range, the basin trough, and the basin rim (Montoya, 2007). Land surrounding the City of Tracy (south, west, east, and just north) was characterized as water-laid sediment forming a slightly sloped alluvial fan. This alluvial fan was formed with eroded material from the Diablo Range. The boundary of the distal end of the alluvial fan (basin rim) generally extends in an east-to-west fashion just north of Tracy. The basin rim is a relatively slim band of

Figure 2.3. Map of soil textures in the southern Delta using GIS data from the NRCS-SSURGO Database.

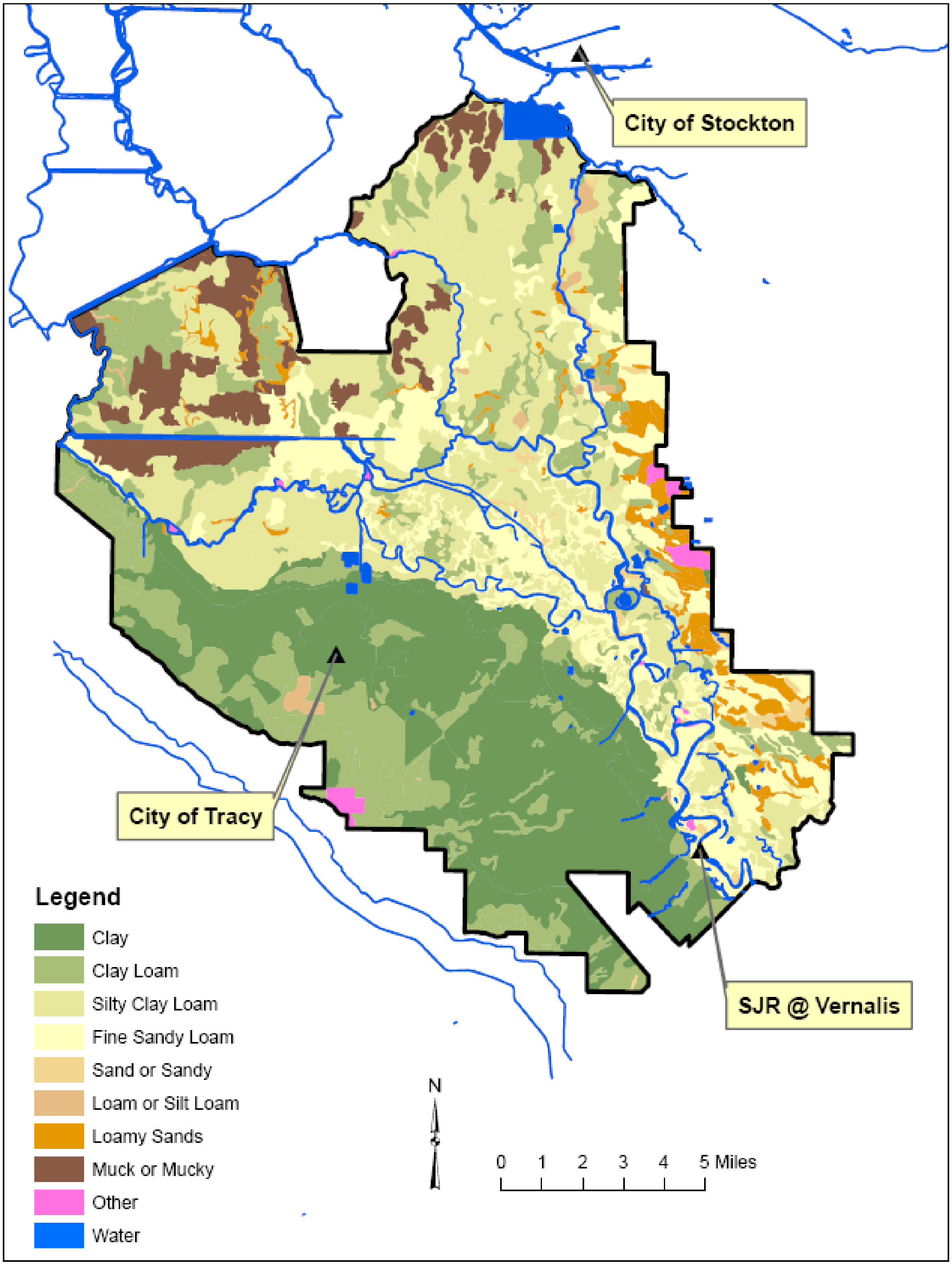


Table 2.1. Properties of the surface layer for soil units within the SDWA from the NRCS-SSURGO database, including key soil properties and sorted by soil texture (with corresponding colors in Figure 2.3).

Texture Category	Soil Unit No.	Soil Unit Name	Ksat (in/hr)	Water Holding Capacity (in./in.)	Depth to Groundwater (feet)	Hydrologic Group	Total Acres	Corresponding color in Figure 2.3
Clay	118	Capay	0.13	0.14 to 0.16	6.6	D	14,910	
	120	Capay	0.13	0.10 to 0.15	5.0	D	943	
	121	Capay	0.13	0.13 to 0.16	5.0	D	12,672	
	122	Capay	0.13	0.14 to 0.16	6.6	D	2,538	
	160	Galt	0.07	0.12 to 0.15	6.6	D	41	
	180	Jacktone	0.13	0.14 to 0.16	5.0	D	102	
	274	Willows	0.03	0.10 to 0.12	5.0	D	3,911	
						Subtotal:	**35,117**	
Clay Loam	110	Boggiano	0.68	0.17 to 0.20	6.6	B	5	
	148	Dello	10.54	0.17 to 0.18	5.0	A	1,220	
	156	El Solyo	0.17	0.17 to 0.20	6.6	C	1,926	
	158	Finrod	0.14	0.18 to 0.20	6.6	C	23	
	167	Grangeville	3.00	0.17 to 0.18	5.0	B	2,861	
	169	Guard	0.18	0.17 to 0.19	5.0	C	1,541	
	211	Pescadero	0.12	0.14 to 0.16	4.5	D	1,082	
	230	Ryde	0.94	0.17 to 0.20	3.5	C	3,691	
	232	Ryde	5.15	0.18 to 0.20	3.5	C	1,754	
	233	Ryde-Peltier	0.94	0.17 to 0.20	3.5	C	491	
	243	Scribner	0.38	0.19 to 0.21	4.0	C	1,287	
	244	Scribner	3.71	0.19 to 0.21	4.0	C	264	
	252	Stomar	0.26	0.16 to 0.18	6.6	C	7,521	
	253	Stomar	0.26	0.17 to 0.19	5.0	C	814	
	258	Trahern	0.16	0.16 to 0.18	5.0	D	798	
	268	Vernalis	1.14	0.17 to 0.18	6.6	B	1,254	
	269	Vernalis	1.14	0.17 to 0.18	5.0	B	1,225	
	281	Zacharias	0.38	0.15 to 0.19	6.6	B	581	
	282	Zacharias	0.83	0.10 to 0.15	6.6	B	456	
						Subtotal:	**28,795**	
Silty Clay Loam	139	Cosumnes	0.16	0.17 to 0.19	6.6	C	33	
	153	Egbert	0.16	0.17 to 0.19	5.0	C	8,574	
	154	Egbert	4.44	0.18 to 0.20	3.5	C	5,849	
	197	Merritt	0.55	0.17 to 0.19	5.0	B	24,580	
	198	Merritt	0.65	0.17 to 0.19	5.0	B	501	
	231	Ryde	5.15	0.18 to 0.20	3.5	C	52	
	267	Veritas	1.92	0.17 to 0.19	6.6	B	404	
						Subtotal:	**39,994**	
Fine Sandy Loam	130	Columbia	3.97	0.10 to 0.12	6.6	B	4,068	
	131	Columbia	3.97	0.10 to 0.12	4.0	C	1,081	
	132	Columbia	3.97	0.10 to 0.12	4.0	C	1,270	
	133	Columbia	3.21	0.10 to 0.12	4.0	C	2,050	
	166	Grangeville	3.97	0.12 to 0.14	5.0	B	7,780	
	196	Manteca	1.84	0.13 to 0.15	6.6	C	3,263	
	266	Veritas	3.05	0.12 to 0.15	6.6	B	2,202	
						Subtotal:	**21,714**	
Sand or Sandy	137	Cortina	3.97	0.07 to 0.14	6.6	B	17	
	144	Dello	13.04	0.06 to 0.08	3.5	C	385	
	147	Dello	6.94	0.10 to 0.13	5.0	B	314	
	175	Honcut	3.97	0.10 to 0.12	6.6	B	207	
	265	Veritas	2.92	0.10 to 0.13	4.5	B	346	
						Subtotal:	**1,269**	
Loam or Silt Loam	140	Coyotecreek		0.18 to 0.20	6.6		28	
	201	Nord		0.13 to 0.15	6.6		32	
	223	Reiff		0.13 to 0.16	6.6		355	
	261	Valdez		0.15 to 0.17	3.5		583	
						Subtotal:	**998**	
Loamy Sands	109	Bisgani	13.04	0.06 to 0.08	4.3	B	715	
	142	Delhi	13.04	0.06 to 0.10	6.6	A	91	
	145	Dello	13.04	0.07 to 0.10	6.6	A	706	
	146	Dello	13.04	0.07 to 0.10	3.5	C	854	
	254	Timor	12.18	0.06 to 0.08	6.6	A	571	
	255	Tinnin	13.04	0.06 to 0.08	6.6	A	2,224	
						Subtotal:	**5,162**	
Muck or Mucky	152	Egbert	0.16	0.18 to 0.20	5.0	C	378	
	190	Kingile	3.71	0.26 to 0.30	3.5	C	332	
	191	Kingile-Ryde	3.71	0.26 to 0.30	3.5	C	114	
	204	Peltier	0.95	0.18 to 0.20	3.5	C	7,777	
	224	Rindge	13.04	0.16 to 0.18	3.5	C	22	
	225	Rindge	13.04	0.26 to 0.30	3.5	C	50	
						Subtotal:	**8,673**	
Other	108	Arents, Saline/Sodic	0.47	n/a	n/a	D	307	
	159	Fluvaquents	0.56	n/a	n/a	D	312	
	214	Pits, Gravel	n/a	n/a	n/a	A	356	
	260	Urban land	n/a	n/a	n/a	n/a	229	
						Subtotal:	**1,204**	
Water	284	Water	n/a	n/a	n/a	n/a	4,402	
						Subtotal:	**4,402**	
Grand Total							**147,327**	

sedimentary deposits from the Diablo Range with a flat or very slightly sloping topography. From the rim, the basin trough extends to Old River. Soils making up the basin trough were a mixture of sedimentary material from the Diablo Range and granitic material from the Sierra Nevada range carried into the floodplain during high flows. Therefore, land in the South Delta is bisected with soils of different types and origins. The alluvial fan material in the southernmost portion of the South Delta originated from the Diablo Range. Further north, the soils transition to a lesser-mineralized mixture of organic deposits, eroded Diablo Range material, and sediment from the Sierra Nevada carried down into the floodplain during periods of high runoff (Montoya, 2007).

2.3.2. Crops

Based upon crop surveys conducted by the California Department of Water Resources (DWR) about every decade during the past 30 years (DWR, 2008 and Woods, 2008), changes in the cropping pattern have been documented (data summarized in Table 2.2). When looking at the total irrigated area and the non-irrigated land for 1976, 1988, and 1996 the values are relatively constant. Due to economics and farmer preference, the types and amounts of the individual crops changed over time. A number of changes occurred between the 1996 and 2007 surveys. For example, the total irrigated area in the South Delta remained at just over 120,000 acres from 1976 to 1996 but dropped to less than 100,000 acres in the 2007 survey and the non-irrigated area averaged about 25,000 acres earlier but increased to almost 45,000 acres in 2007. In an attempt to rectify these changes or differences in acreages, the 2007 crop survey conducted by the San Joaquin County Agricultural Commissioner (SJCAC) is also presented in Table 2.2 (SJCAC, 2008). The irrigated area reported by the SJCAC is about midway between the earlier surveys and the 2007 survey at about 110,000 acres.

Jean Woods of DWR provided the following explanations for the differences between the 2007 survey and the earlier surveys (Woods, 2008). Planned and partially constructed housing developments near Lathrop and Clifton Court Forebay and an expansion of urban land in the northeastern part of the South Delta have resulted in a loss of about 7,000 acres of irrigated land over the last decade. Another difference between surveys was the delineation of field borders. Before 2007, field borders were assumed to be the centers of farm roads and often included canals and ditches. The irrigated acreage was then corrected by multiplying by 0.95. For 2007, the field borders, in most cases, represent just the irrigated crop area. This change in the method of calculating irrigated acreage would result in an additional reduction of almost 6,000 acres. With all of these changes, the total irrigated area is closer to what would be expected. However, because of these differences it is probably more appropriate to compare percentages for each crop or group of crops of interest. Table 2.3 gives the percentage of the general crop types in the irrigated area of the South Delta. This information is important in establishing changes in crop acreage based on economics, farmer preference, salt tolerance, crop water use, and the type of irrigation system. Another potential concern in the crop survey is double and triple cropping, intercropping, and mixed use. These situations are not addressed in Tables 2.2 and 2.3.

Table 2.2. Summary of irrigated crop acreage in SDWA for 1976, 1988, 1996, & 2007 from DWR land use surveys, and for 2007 from San Joaquin County Agricultural Commissioner survey.

	Salt	DWR Land Use Surveys (acres)				San Joaquin County Ag Commisioner (acres)	
Crop	Tolerance [1]	1976	1988	1996	2007	2007	Remarks
Fruits & Nuts							
Apples	S	31	5	125	18	15	
Apricots	S	0	1,315	1,013	228	128	
Olives	T	0	0	0	77	132	
Peaches & Nectarines	S	0	0	98	0	0	
Pears	S	0	62	0	0	0	
Plums	MS	0	0	48	30	0	
Almonds	S	0	2,950	2,179	3,087	2,860	
Walnuts	S	80	4,132	3,881	2,043	1,699	
Pistachios	MS	0	42	31	18	18	
Fruit or Nut - Misc. or <10 acres	Other	7,473	467	194	185	35	Pecan, Cherry, Pomegranite
Subtotal:		7,584	8,974	7,569	5,688	4,886	
Field Crops							
Cotton	T	0	0	0	34	0	
Safflower	MT	619	4,987	9,492	1,803	2,768	
Sugar Beets	T	14,456	11,285	1,667	135	449	
Corn	MS	9,208	6,368	10,198	11,638	14,242	Corn, human & fodder
Grain Sorghum	MT	482	8	0	0	86	
Sudan	MT	2,447	266	514	1,181	302	
Castor Beans	S	54	0	0	0	0	
Dry Beans	S	3,457	5,204	7,299	3,855	2,998	
Sunflowers	MT	0	544	290	0	0	
Hybrid sorghum/sudan	MT	0	0	0	71	0	
Field Crops - Misc. or <10 acres	Other	316	1,048	444	710	1,720	Lima, Beans, Unspecified
Subtotal:		31,038	29,710	29,903	19,427	22,564	
Grain & Hay Crops							
Wheat	MT	0	0	0	105	5,806	Wheat, human & fodder
Oats	T	0	16	0	0	4,616	Oats, human & fodder
Grain & Hay - Misc.	Other	25,478	10,311	16,159	7,413	1,568	Forage hay, barley, rye for fodder
Subtotal:		25,478	10,327	16,159	7,518	11,990	
Pasture							
Alfalfa	MS	28,133	37,590	31,240	31,356	33,021	
Clover	MS	0	32	0	0	0	
Turf Farm	MT	0	245	366	324	0	
Pasture - Misc.	Other	4,116	2,910	2,661	3,231	956	
Subtotal:		32,249	40,777	34,267	34,911	33,977	
Truck & Berry Crops							
Asparagus	T	5,336	7,784	7,151	3,651	4,137	
Green Beans	S	61	173	0	24	458	
Cole Crops	MS	259	585	20	174	1,097	Brocolli, Cabbage
Carrots	S	0	0	231	197	247	
Celery	S	0	0	0	105	436	
Melons, Squash, Cucumbers	MS	790	2,274	3,925	2,502	2,757	Melon, Pumpkin, Squash, Cucumber
Onions (Garlic)	S	66	343	286	162	906	Dry & green onions
Tomatoes	MS	17,160	15,583	13,514	16,263	18,635	Tomatoes & processing tomatoes
Strawberries	S	0	0	42	4	0	
Peppers	MS	174	81	49	253	531	
Truck Crops - Misc. or <10 acres	Other	102	376	191	734	4,932	Various [3]
Subtotal:		23,948	27,198	25,409	24,069	34,137	
Vineyards							
Unspecified Varieties	MS	804	632	2,328	2,903	2,940	
Other							
Idle Fields	Other	554	2,379	395	2,114	0	
Other	Other		56	1390	693	0	
Subtotal Irrigated Crops:		**121,654**	**120,053**	**117,420**	**97,323**	**110,494**	
Breakdown by Salt Tolerance:	S	3,749	14,185	15,155	9,724	9,747	
	MS	56,527	63,186	61,352	65,137	73,241	
	MT	3,548	6,050	10,661	3,483	8,962	
	T	19,792	19,085	8,818	3,898	9,334	
	Other	38,039	17,547	21,434	15,080	9,210	
Non-Irrigated Land:		19,164	20,826	23,459	43,479	n/a	
Total for SDWA[2]:		140,818	140,879	140,879	140,803	n/a	

[1] Salt tolerance categories as follows:
S = Sensitive; MS = Moderately Sensitive; MT = Moderately Tolerant; T = Tolerant

[2] Total acreage included in Department of Water Resources land use survey for the portion of SDWA within the legal Delta. Actual area of SDWA within legal Delta is 140,879 acres. Total area of SDWA is 147,328 acres.

[3] Includes blueberry, bok choy, celeriac, christmas tree, cilantro, collard, fruit berries, herbs, kale, leek, leaf lettuce, mustard, outdoor plants, spinach, swiss chard

Table 2.3. Percentage of total irrigated land in SDWA for each crop grown in 1976, 1988, 1996, & 2007 from DWR land use surveys, and for 2007 from San Joaquin County Agricultural Commissioner survey.

Crop	Salt Tolerance [1]	DWR Land Use Surveys (%) 1976	1988	1996	2007	San Joaquin County Ag Commisioner (%) 2007	Remarks
Fruits & Nuts							
Apples	S	0.03	0.00	0.11	0.02	0.01	
Apricots	S	0.00	1.10	0.86	0.23	0.12	
Olives	T	0.00	0.00	0.00	0.08	0.12	
Peaches & Nectarines	S	0.00	0.00	0.08	0.00	0.00	
Pears	S	0.00	0.05	0.00	0.00	0.00	
Plums	MS	0.00	0.00	0.04	0.03	0.00	
Almonds	S	0.00	2.46	1.86	3.17	2.59	
Walnuts	S	0.07	3.44	3.31	2.10	1.54	
Pistachios	MS	0.00	0.03	0.03	0.02	0.02	
Fruit or Nut - Misc. or <10 acres	Other	6.14	0.39	0.17	0.19	0.03	Pecan, Cherry, Pomegranite
Subtotal:		6.23	7.48	6.45	5.84	4.42	
Field Crops							
Cotton	T	0.00	0.00	0.00	0.04	0.00	
Safflower	MT	0.51	4.15	8.08	1.85	2.51	
Sugar Beets	T	11.88	9.40	1.42	0.14	0.41	
Corn	MS	7.57	5.30	8.69	11.96	12.89	Corn, human & fodder
Grain Sorghum	MT	0.40	0.01	0.00	0.00	0.08	
Sudan	MT	2.01	0.22	0.44	1.21	0.27	
Castor Beans	S	0.04	0.00	0.00	0.00	0.00	
Dry Beans	S	2.84	4.33	6.22	3.96	2.71	
Sunflowers	MT	0.00	0.45	0.25	0.00	0.00	
Hybrid sorghum/sudan	MT	0.00	0.00	0.00	0.07	0.00	
Field Crops - Misc. or <10 acres	Other	0.26	0.87	0.38	0.73	1.56	Lima, Beans, Unspecified
Subtotal:		25.51	24.75	25.47	19.96	20.42	
Grain & Hay Crops							
Wheat	MT	0.00	0.00	0.00	0.11	5.25	Wheat, human & fodder
Oats	T	0.00	0.01	0.00	0.00	4.18	Oats, human & fodder
Grain & Hay - Misc.	Other	20.94	8.59	13.76	7.62	1.42	Forage hay, barley, rye for fodder
Subtotal:		20.94	8.60	13.76	7.73	10.85	
Pasture							
Alfalfa	MS	23.13	31.31	26.61	32.22	29.88	
Clover	MS	0.00	0.03	0.00	0.00	0.00	
Turf Farm	MT	0.00	0.20	0.31	0.33	0.00	
Pasture - Misc.	Other	3.38	2.42	2.27	3.32	0.87	
Subtotal:		26.51	33.97	29.18	35.87	30.75	
Truck & Berry Crops							
Asparagus	T	4.39	6.48	6.09	3.75	3.74	
Green Beans	S	0.05	0.14	0.00	0.02	0.41	
Cole Crops	MS	0.21	0.49	0.02	0.18	0.99	Brocolli, Cabbage
Carrots	S	0.00	0.00	0.20	0.20	0.22	
Celery	S	0.00	0.00	0.00	0.11	0.39	
Melons, Squash, Cucumbers	MS	0.65	1.89	3.34	2.57	2.49	Melon, Pumpkin, Squash, Cucumber
Onions (Garlic)	S	0.05	0.29	0.24	0.17	0.82	Dry & green onions
Tomatoes	MS	14.11	12.98	11.51	16.71	16.87	Tomatoes & processing tomatoes
Strawberries	S	0.00	0.00	0.04	0.00	0.00	
Peppers	MS	0.14	0.07	0.04	0.26	0.48	
Truck Crops - Misc. or <10 acres	Other	0.08	0.31	0.16	0.75	4.46	Various [2]
Subtotal:		19.69	22.65	21.64	24.73	30.89	
Vineyards							
Unspecified Varieties	MS	0.66	0.53	1.98	2.98	2.66	
Other							
Idle Fields	Other	0.46	1.98	0.34	2.17	0.00	
Other	Other	0.00	0.05	1.18	0.71	0.00	
Subtotal Irrigated Crops:		**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	
Breakdown by Salt Tolerance:	S	3.08	11.82	12.91	9.99	8.82	
	MS	46.47	52.63	52.25	66.93	66.29	
	MT	2.92	5.04	9.08	3.58	8.11	
	T	16.27	15.90	7.51	4.01	8.45	
	Other	31.27	14.62	18.25	15.50	8.34	

[1] Salt tolerance categories as follows:
S = Sensitive; MS = Moderately Sensitive; MT = Moderately Tolerant; T = Tolerant

[2] Includes blueberry, bok choy, celeriac, christmas tree, cilantro, collard, fruit berries, herbs, kale, leek, leaf lettuce, mustard, outdoor plants, spinach, swiss chard

3. Factors Affecting Crop Response to Salinity

3.1. Season-Long Crop Salt Tolerance

3.1.1. State of Knowledge

Salinity, salt stress, can damage crops in three different ways. First, and of major concern in the South Delta, is season-long crop response to salinity. The most common whole-plant response to salt stress is a general stunting of growth. As soil salinity increases beyond a threshold level both the growth rate and ultimate size of crop plants progressively decreases. However, the threshold and the rate of growth reduction vary widely among different crop species. Second, crop sensitivity to soil salinity continually changes during the growing season. Many crops are most sensitive to soil salinity during emergence and early seedling development. Third, when crops are irrigated with sprinkler systems, foliar damage can occur when the leaves are wet with saline water. Sprinkler foliar damage is most likely to occur under hot, dry, and windy weather conditions. Crop salt tolerance at various growth stages is discussed in the following section. The impact of sprinkling crops with saline water is described within the section on irrigation methods. Here, the impact of soil salinity over the cropping season is presented.

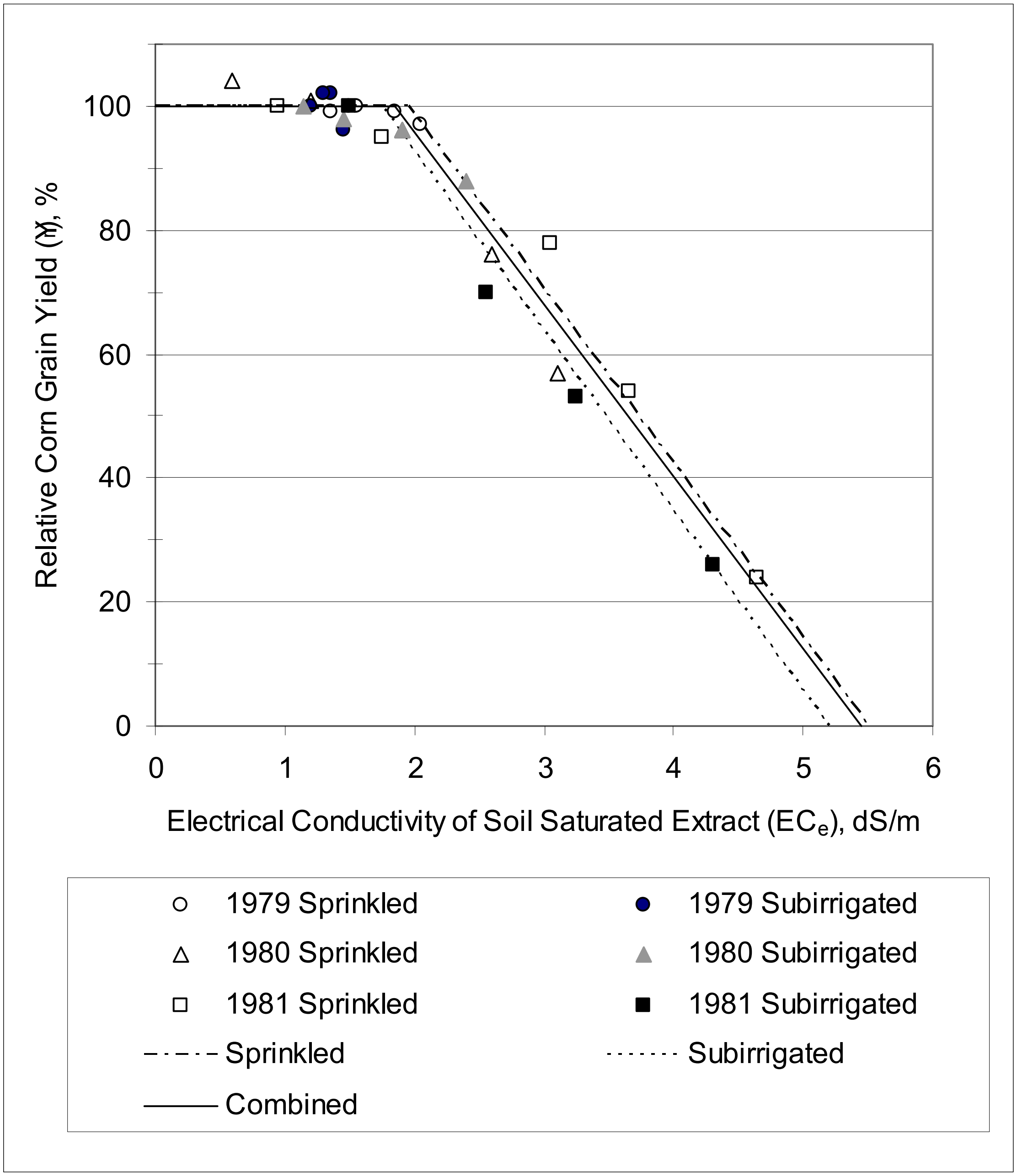
Maas and Hoffman (1977) proposed that the yield response of crops to soil salinity for the growing season could be represented by two line segments: one, a tolerance plateau with a zero slope; and the second, a salt concentration-dependent line whose slope indicates the yield reduction per unit increase in salinity. The point at which the two lines intersect designates the “threshold”, i.e., the maximum soil salinity that does not reduce yield below that obtained under non-saline conditions. This two-piece linear response function provides a reasonably good fit for commercially acceptable yields plotted against the electrical conductivity of the saturated-soil extract (EC_e). Electrical conductivity of the saturated-soil extract is the traditional soil salinity measurement with units of decisiemens (dS) per meter (1 dS/m = 1 mmho/cm, the traditional units for reporting electricity conductivity; or 1 dS/m = 1000 µS/cm, units frequently used by DWR). One decisiemen per meter is approximately equal to 640 mg/L or 640 parts per million total dissolved solids. For soil salinities exceeding the threshold of any given crop, relative yield (Y_r) can be estimated by:

$$Y_r = 100 - b\,(EC_e - a) \qquad \text{(Eqn. 3.1)}$$

where a = the salinity threshold expressed in decisiemens per meter; b = the slope expressed in percentage per decisiemens per meter; EC_e = the mean electrical conductivity of a saturated-soil extract taken from the root zone. An example of how this piecewise linear response function fits data can be seen in Figure 3.1 for data taken from a field experiment on corn in the Sacramento-San Joaquin Delta near Terminus, CA (Hoffman et al., 1983).

Crop salt tolerance has been established for a large number of crops in experimental plots, greenhouse studies, and field trials (Maas and Hoffman, 1977 and Maas and

Figure 3.1. Relative grain yield of corn grown in the Sacramento - San Joaquin River Delta as a function of soil salinity by sprinkled and subirrigated methods.



Grattan, 1999). The salt tolerance coefficients, threshold (a) and slope (b), presented in these publications and applied to Equation 3.1 are used throughout the world and are used in steady-state and transient models dealing with salinity control. Most of the data used to determine these two coefficients were obtained where crops were grown under conditions simulating recommended cultural and management practices for commercial production. Consequently, the coefficients indicate the relative tolerances of different crops grown under different conditions and not under some standardized set of conditions. Furthermore, the coefficients apply only where crops are exposed to fairly uniform salinities from the late seedling stage to maturity.

3.1.2. South Delta Situation

The crop salt tolerance threshold and slope values for the 18 crops that exceed 1 % of the irrigated area in the South Delta are given in Table 3.1.The relative salt tolerance rating of a given crop compared to other agricultural crops is also given in Table 3.1 and the definition of these relative ratings is given Figure 3.2. Bean is the most salt sensitive crop grown on significant acreage in the South Delta. Tree crops are also salt sensitive but not to the same degree as bean.

Unfortunately, some of the crops in the DWR crop surveys (DWR, 2008 and Woods, 2008) are reported as pasture, grain and hay, fruit and nut, citrus, field crops, and truck crops. A salt tolerance can not be assigned to these general categories. However, there is a sufficient number of crops identified that the range of crop salt tolerance in the South Delta is known (see Tables 2.2 and 2.3).

Of particular interest is the amount and location of crops based upon their salt tolerance. Figure 3.3 shows the percentage of crops grown in the South Delta based upon relative crop salt tolerance. The data are from the crop surveys taken about every decade since 1976. Of note is the increase in the percentage of moderately salt sensitive crops and a decrease in the salt tolerant percentage. This may indicate that the farmers have become more confident in the economics of growing more salt sensitive crops and the near elimination of sugar beet, a salt tolerant crop, in recent years. In Figure 3.4, the locations where crops are grown based upon salt tolerance are illustrated for the four DWR crop surveys. The area where salt sensitive and moderately salt sensitive crops are grown has increased with time. Although salt sensitive crops are grown throughout, the majority are grown in the southwest corner of the South Delta.

Bean is the most salt sensitive crop with any significant acreage in the south Delta. If bean is to be the crop upon which the water quality standard is to be based then it is instructive to see how the acreage and location of bean has changed over the past three decades. Although beans are predominately grown in the southern portion of the South Delta, the location of bean fields has spread into the central portion of the area in recent years (see Figure 3.5). If the 2007 data for dry and green beans for the two surveys are combined the total acreage is not too different (3,879 acres from the DWR survey and 3,456 acres from the SJCAC report). The acreage for lima beans reported in the SJCAC survey is not added with the other bean acreages because lima bean is more salt tolerant than dry and green beans.

Table 3.1. Crop salt tolerance coefficients for important crops in the South Delta (Maas and Grattan, 1999).

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
Apricot	Prunus armeniaca	Shoot growth	1.6	24	S
Asparagus	Asparagus officinalis	Spear yield	4.1	2.0	T
Barley	Hordeum vulgare	Grain yield Shoot DW	8.0 6.0	5.5 7.1	T MT
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
Cucumber	Cucumis sativus	Fruit yield	2.5	13	MS
Grape	Vitus vinifera	Shoot growth	1.5	9.6	MS
Muskmelon	Cucumis melo	Fruit yield	1.0	8.4	MS
Oat	Avena sativa	Grain yield Straw DW	--- ---	--- ---	T T
Safflower	Carthamus tinctorius	Seed yield	---	---	MT
Squash	Curcubita-pepo Scallop Zucchini	 Fruit yield Fruit yield	 3.2 4.9	 16 10.5	 MS MT
Sugar beet	Beta vulgaris	Storage root	7.0	5.9	T
Tomato	Lycopersicon lycopersicum	Fruit yield	2.5	9.9	MS
Walnut	Juglans	foliar injury	---	---	S
Watermelon	Citrullus lanatus	Fruit yield	---	---	MS
Wheat	Triticum aestivum	Grain yield	6.0	7.1	MT
		Shoot DW	4.5	2.6	MT

* Values of threshold = (a) and slope = (b) for Equation 3.1.

** Relative salt tolerance ratings noted as (S) sensitive, (MS) moderately sensitive, (MT) moderately tolerant, and (T) tolerant, see Fig. 3.2.

Figure 3.2. Classification of crop tolerance to salinity based on relative crop yield against electrical conductivity of saturated soil extract (EC_e), dS/m.

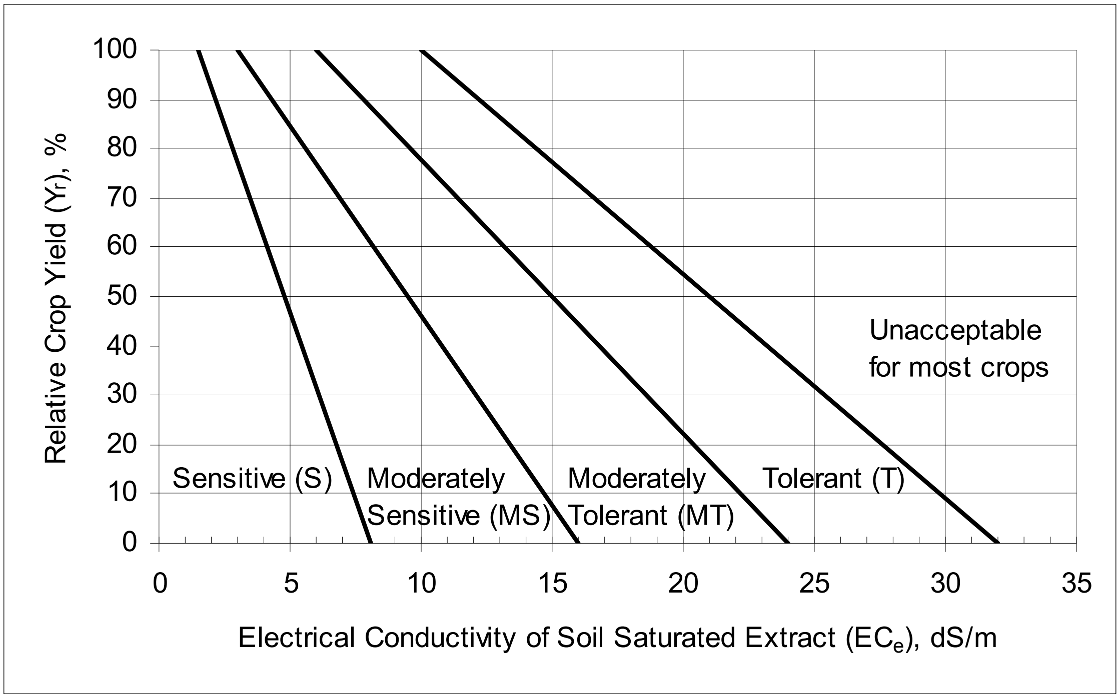
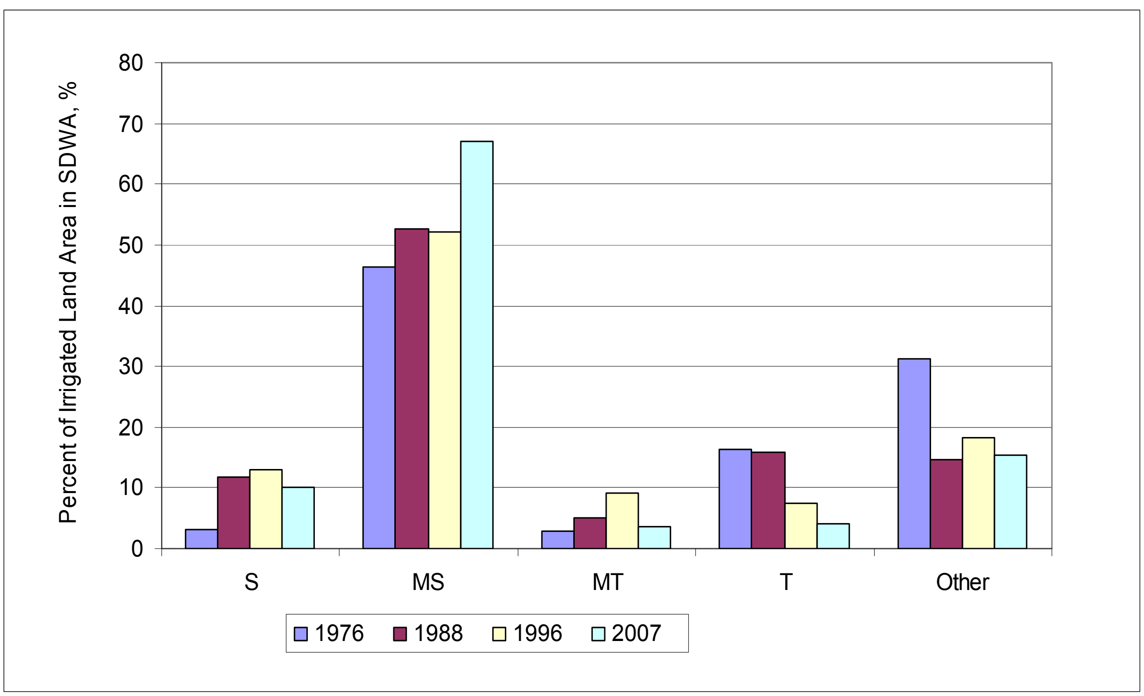


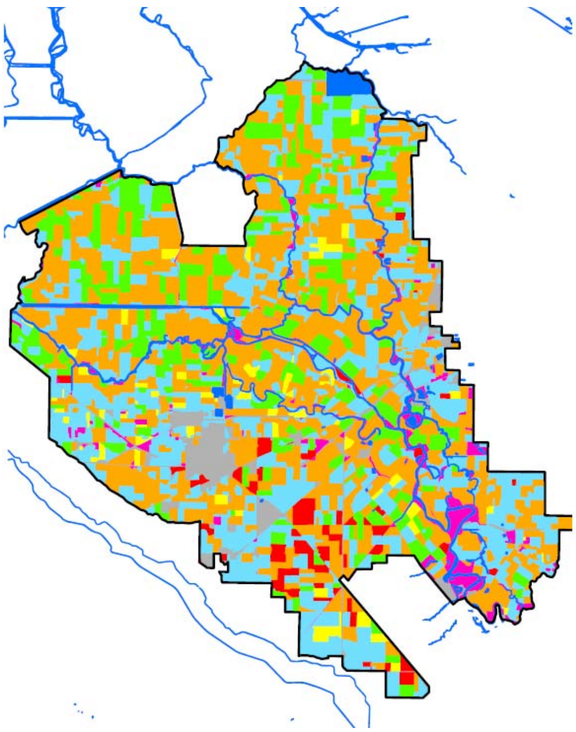
Figure 3.3. Distribution of crops based on salt tolerance relative (as a percent) to total irrigated acres in the SDWA in 1976, 1988, 1996 and 2007 (based on DWR land use surveys).



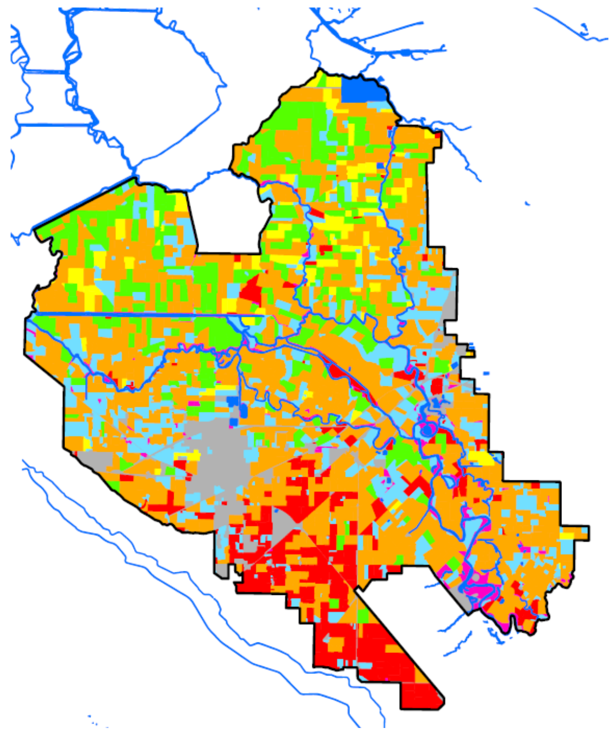
S = Sensitive; MS = Moderately Sensitive; MT = Moderately Tolerant; T = Tolerant

Figure 3.4. Distribution of crops in the southern Delta for 1976, 1988, 1996, and 2007 based on salt tolerance (from DWR land use surveys).

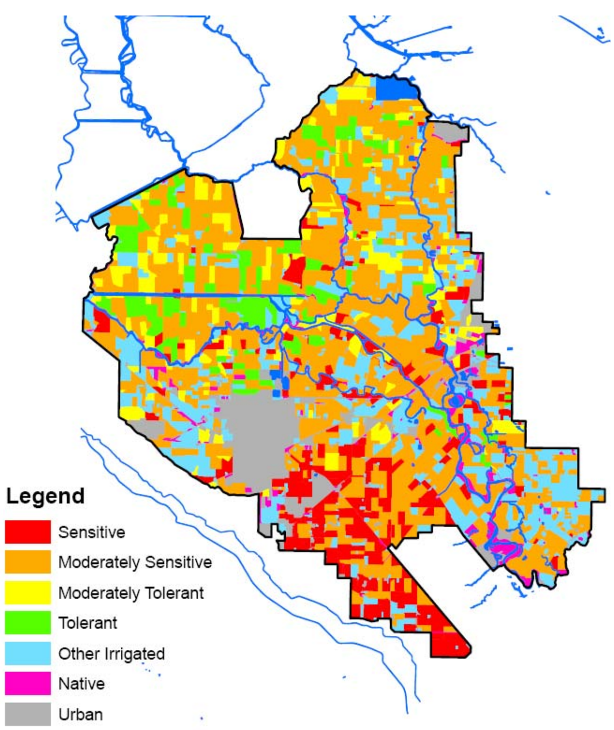
a) 1976



b) 1988



c) 1996



d) 2007

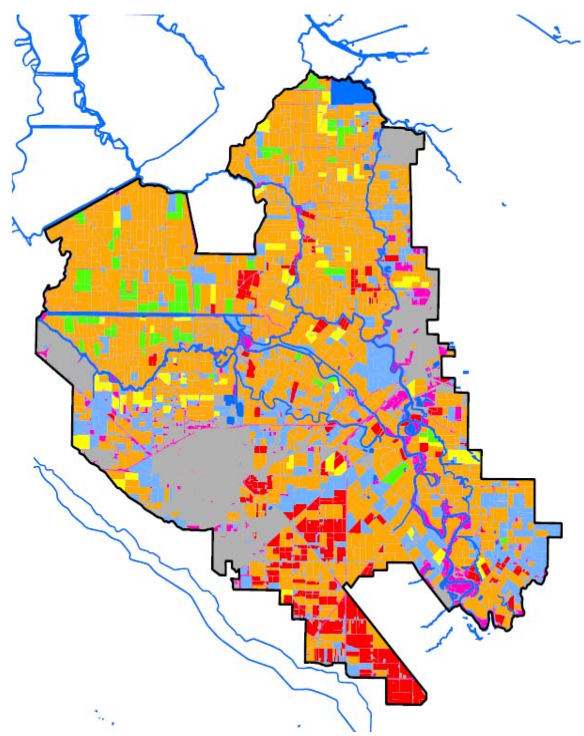
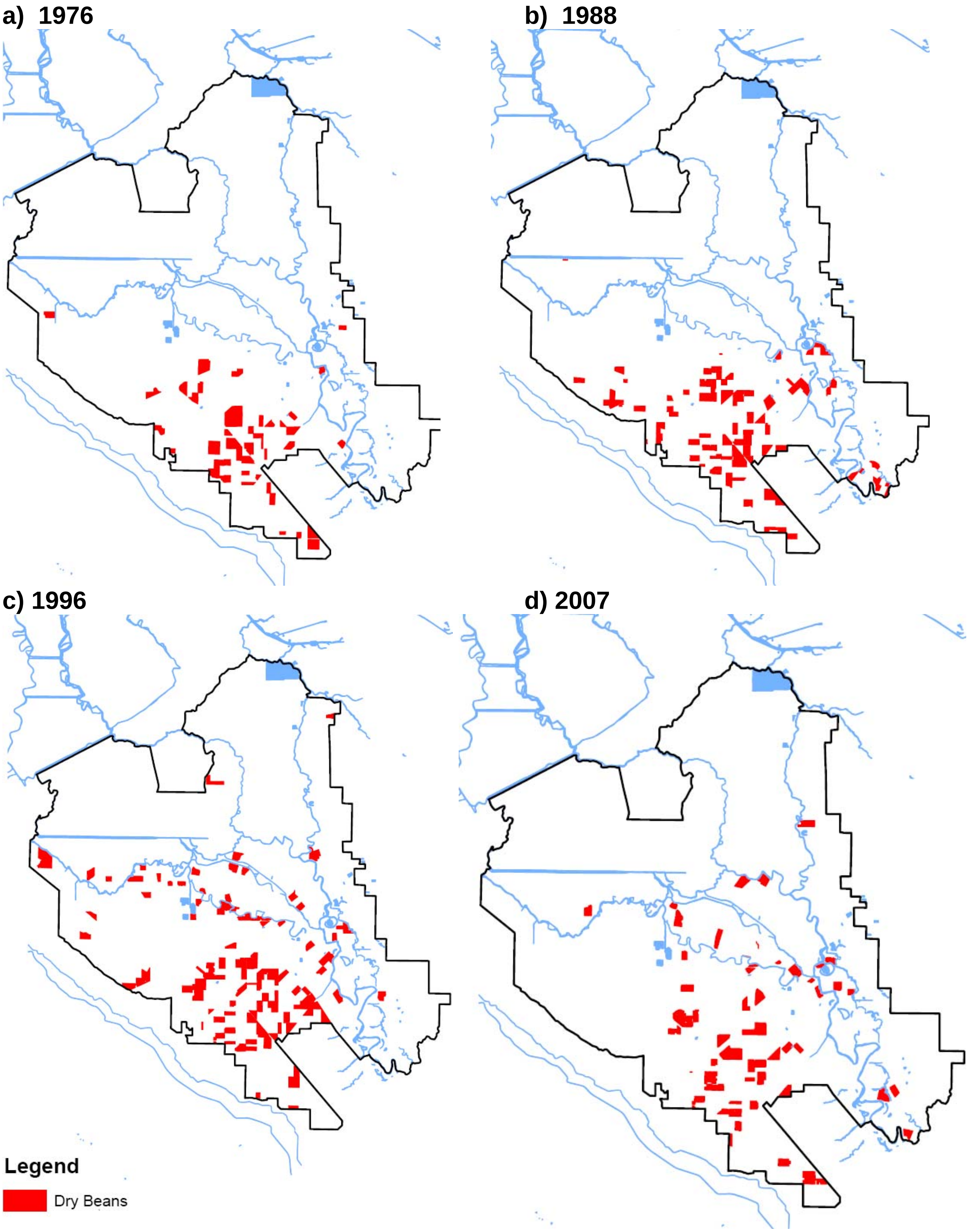


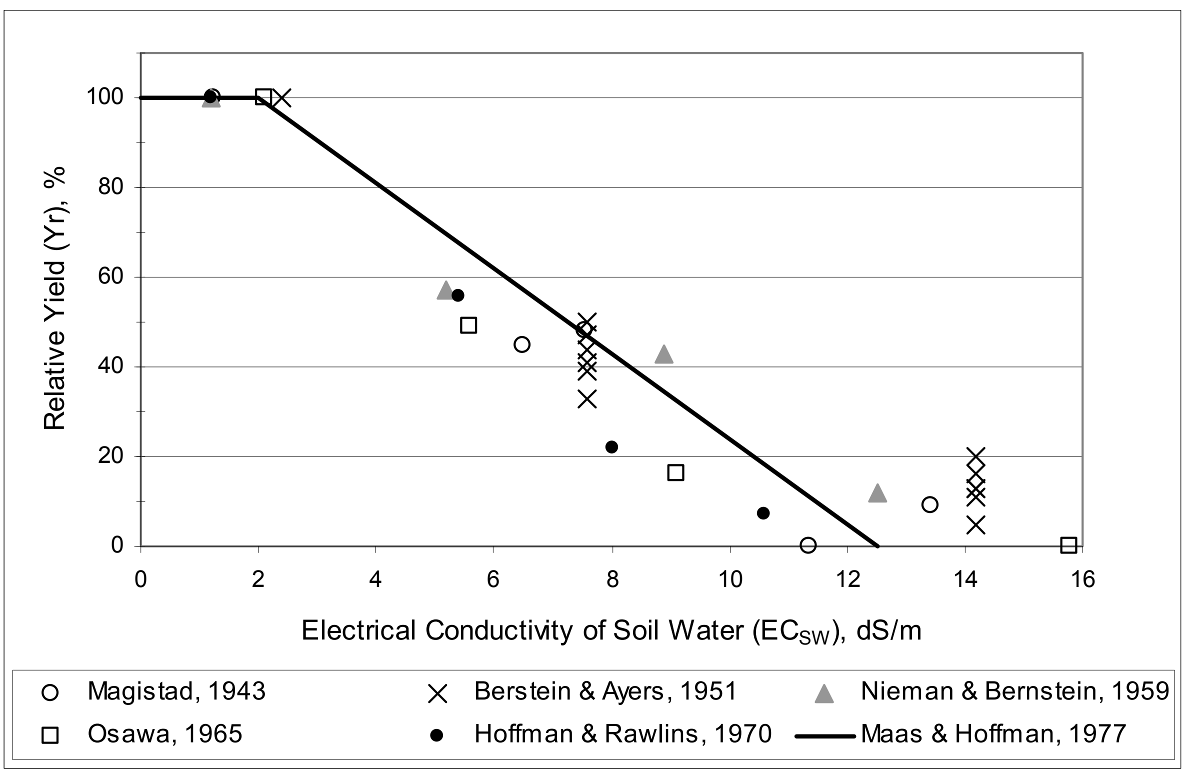
Figure 3.5. Distribution of dry beans grown in the southern Delta for 1976, 1988, 1996, and 2007 (from DWR land use surveys).



If bean is chosen as the crop to protect all irrigated crops in the South Delta from salinity, it is unfortunate that the salt tolerance of bean is only based on five published reports of laboratory studies with only one experiment being conducted in soil. Furthermore, these experiments were all conducted more than 30 years ago and there are probably new and improved varieties now being grown.

I have gone back to the original analysis performed by Maas and Hoffman (1977) and reviewed the experimental results used to establish the salt tolerance of bean. Everyone who has published the salt tolerance of bean based upon Equation 3.1 have used their results. A total of nine experiments were analyzed. Of these nine, Maas and Hoffman (1977) used five. Results from the remaining four were not considered because the control (non-saline) treatment exceeded the salt tolerance threshold determined from the other five experiments or only pod weights were measured. The bean varieties were red kidney or wax. All of the experimental data used to establish the salt tolerance of bean are shown in Figure 3.6. The relationship for the salt tolerance of bean published by Maas and Hoffman (1977) is also shown in Figure 3.6 for comparison with the experimental results. If such an important decision as the water quality standard is to be based on the salt tolerance of bean, it is recommended that a field experiment be conducted in the South Delta similar to the corn experiment near Terminus, CA (Hoffman et al., 1983).

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



3.2. Crop Salt Tolerance at Various Growth Stages

3.2.1. State of Knowledge

Sensitivity of plants to soil salinity continually changes during the growing season. Most crops are tolerant during germination but the young developing seedlings are susceptible to salt injury during emergence from the soil and during early development. Once established, most crops generally become increasingly tolerant during later stages of growth. One of the effects of salt stress is that it delays germination and emergence. Furthermore, because of evaporation at the soil surface, the salt concentration in the seed bed is often greater than at deeper soil depths. Consequently, the juvenile roots of emerging seedlings are exposed to greater salt stress than indicated by salinity values averaged over deeper soil depths. The loss of plants during this critical growth phase may reduce the plant population density to suboptimal levels which would significantly reduce yields.

Salt tolerance during emergence does not correlate well with salt tolerance expressed in terms of yield and varies considerably among crops. Unfortunately, different criteria must be used to evaluate plant response to salinity during different stages of growth. Tolerance at emergence is based on survival, whereas tolerance after emergence is based on decreases in growth or yield. Maas and Grieve (1994) summarized the scientific literature on the relative salt tolerance for seedling emergence for 31 crops.

Most published data indicate that plants are more sensitive to salinity during the seedling stage than germination, e.g. barley, corn, cotton, peanut, rice, tomato, and wheat (Maas and Grattan, 1999). Seedlings are also more sensitive than older plants. Greenhouse experiments on corn and wheat indicated that dry matter yields of 3-week-old plants were reduced by salt concentrations that were lower than the salinity thresholds for grain production. In sand culture experiments designed to test the relative effects of salt stress at different stages of growth on grain production, sorghum (Maas et al., 1986), wheat (Maas and Poss, 1989a) and cowpea (Maas and Poss, 1989b) were most sensitive during the vegetative and early reproductive stages, less sensitive during flowering, and least sensitive during the grain-filling stage. Increased tolerance with age also has been observed in asparagus, a perennial that was more tolerant after the first year’s growth (Francois, 1987).

3.2.2. South Delta Situation

Of the 18 crops important in the South Delta, seedling emergence data have been reported for nine. The soil salinity level that reduced emergence by 10 % is reported in Table 3.2. Where more than one reference was reported for the same crop, the range of soil salinity that reduced emergence by 10 % is given.

Except for the relatively salt tolerant crops of barley, sugar beet, and wheat, all of the crops reported that are important in the South Delta have a higher salt tolerance at emergence than for yield. Only one reference for barley (Ayers and Hayward, 1948) had a low tolerance at emergence compared to four other references that reported a higher tolerance. There was only one published reference for sugar beet and it reported a low tolerance, also Ayers and Hayward (1948). Two of the four references for wheat (as report by Maas and Grieve, 1994) found a low tolerance for some cultivars while other cultivars had a very high salt tolerance at emergence. Thus, it appears that salt tolerance at emergence may not be a concern if more tolerant cultivars are chosen.

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
Barley	Hordeum vulgare	6 to 18
Bean	Phaseolus vulgaris	5.5
Corn	Zea mays	5 to 16
Oat	Avena sativa	16
Safflower	Carthamus tinctorius	8
Sugar beet	Beta vulgarus	4.5
Tomato	Lycopersicon Lycopersicum	3 to 7.5
Wheat	Triticum aestivum	1 to 11

Table 3.3 summarizes the salinity effects at various stages of growth for several crops. Unfortunately, only a few crops important in the South Delta have been studied. The data given in Table 3.3 are not very helpful for many of the crops in the South Delta. Of particular importance is the sensitivity of bean and other salt sensitive crops at various growth stages. Also the apparent sensitivity of asparagus in the first year of growth is another concern. Thus, it is recommended that laboratory and/or field trials be conducted to establish the change in sensitivity to salt with growth stage on crops like bean, asparagus, and perhaps other crops that are salt sensitive and important in the South Delta.

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
Cowpea	Vegetation 0.8	Flowering 0.8	Pod-Filling 3.3		Maas & Poss, 1989b
Sorghum NK 265 DTX	Vegetation 3.3 3.3	Reproduction 10 7.8	Maturity 10 10		Maas et al., 1986
Wheat	Vegetation 6.7	Reproduction 12	Maturity 12		Maas & Poss, 1989a
Wheat, Durum	Vegetation 3.6	Reproduction 5.0	Maturity 22		Maas & Poss, 1989a

3.3. Saline/Sodic Soils

3.3.1. State of Knowledge

Saline Soils

A soil is said to be saline if salts have accumulated in the crop root zone to a concentration that causes a loss in crop yield. In irrigated agriculture, saline soils often originate from salts in the irrigation water or from shallow, saline groundwater. Yield reductions occur when salts accumulate in the root zone to an extent that the crop is unable to extract sufficient water from the salty soil solution, resulting in an osmotic (salt) stress. If water uptake is appreciably reduced, the plant slows its rate of growth and yield loss occurs. Salts that contribute to a salinity problem are water soluble and readily transported by water. A portion of the salts that accumulate from prior irrigations can be drained (leached) below the rooting depth if more irrigation or precipitation infiltrates the soil than is used by the crop or evaporates from the soil surface and barriers to drainage do not occur in the soil profile.

Sodic Soils

An important property of a soil is its friability (tilth). In sodic soils, physicochemical reactions cause the slaking of soil aggregates and the swelling and dispersion of clay minerals, leading to reduced permeability and poor tilth. The loss of permeability causes a reduction in the infiltration of applied water and water remains on the soil surface too long or infiltrates too slowly to supply the crop with sufficient water to obtain acceptable yields. The two most common water quality factors influencing infiltration are the salinity of the applied water and its sodium content relative to the calcium and magnesium content. Water high in salinity will increase infiltration while a water low in salinity or with a high ratio of sodium to calcium plus magnesium will decrease infiltration.

3.3.2. South Delta Situation

The Soil Survey published by the Soil Conservation Service in 1992 (SCS, 1992) shows saline soils in the South Delta to be in two general areas. The largest area traverses the South Delta from the northwest to the southeast in what may be a previous water channel and generally follows the area described by Montoya (2007) as the basin rim. It begins just south of Clifton Court Forebay, follows along the south side of Old River passing just north of Tracy, then southwest of the junction of interstate highways 5 and 205, and continuing southeast passing beyond the Banta Carbona Canal and ending just before meeting the San Joaquin River. The soils in this area are Capay clay, Pescadero clay loam and Willow clay. The other soils noted as saline are on the eastern boundary of the South Delta. These soils are designated as Arents sandy loam or loam and Trahern clay loam. Table 3.4 gives each soil that was mapped as saline in 1992 in the South Delta. Note in Table 3.4 that the total area mapped as saline by the SCS was 5 % of the total irrigated area. Figure 3.7 shows the location of these soils in the South Delta.

Based on the DWR crop surveys and the saline soils identified by the SCS (1992), the distribution of crops between the South Delta as a whole and just the saline soils is presented in Figure 3.8. Very few salt sensitive crops are on the saline soils. While moderately salt sensitive and more tolerant crops are grown on the saline areas with the same or higher percentage as elsewhere in the South Delta.

No sodic soils were identified in the 1992 Soil Survey. This is not unexpected based on the calculation of the SAR for waters from the San Joaquin River (see Section 2.2.2).

Table 3.4. Saline soils according to the Soil Survey of San Joaquin County, California (Soil Conservation Service, 1992).

Soil Map Unit	Soil Series	Range of Soil Salinity (dS/m)	Area (acres)	% of South Delta irrigated lands
108	Arents sandy loam or loam	not given	307	0.2
120	Capay clay	4-8	943	0.7
211	Pescadero clay loam	4-16	1082	0.8
258	Trahern clay loam	4-8	798	0.6
274	Willows clay	2-8	3911	2.7
		TOTAL:	7041	5.0

Figure 3.7. Location of saline soils in the SDWA using GIS data from the NRCS-SSURGO database (legend shows soil map units from Table 3.4).

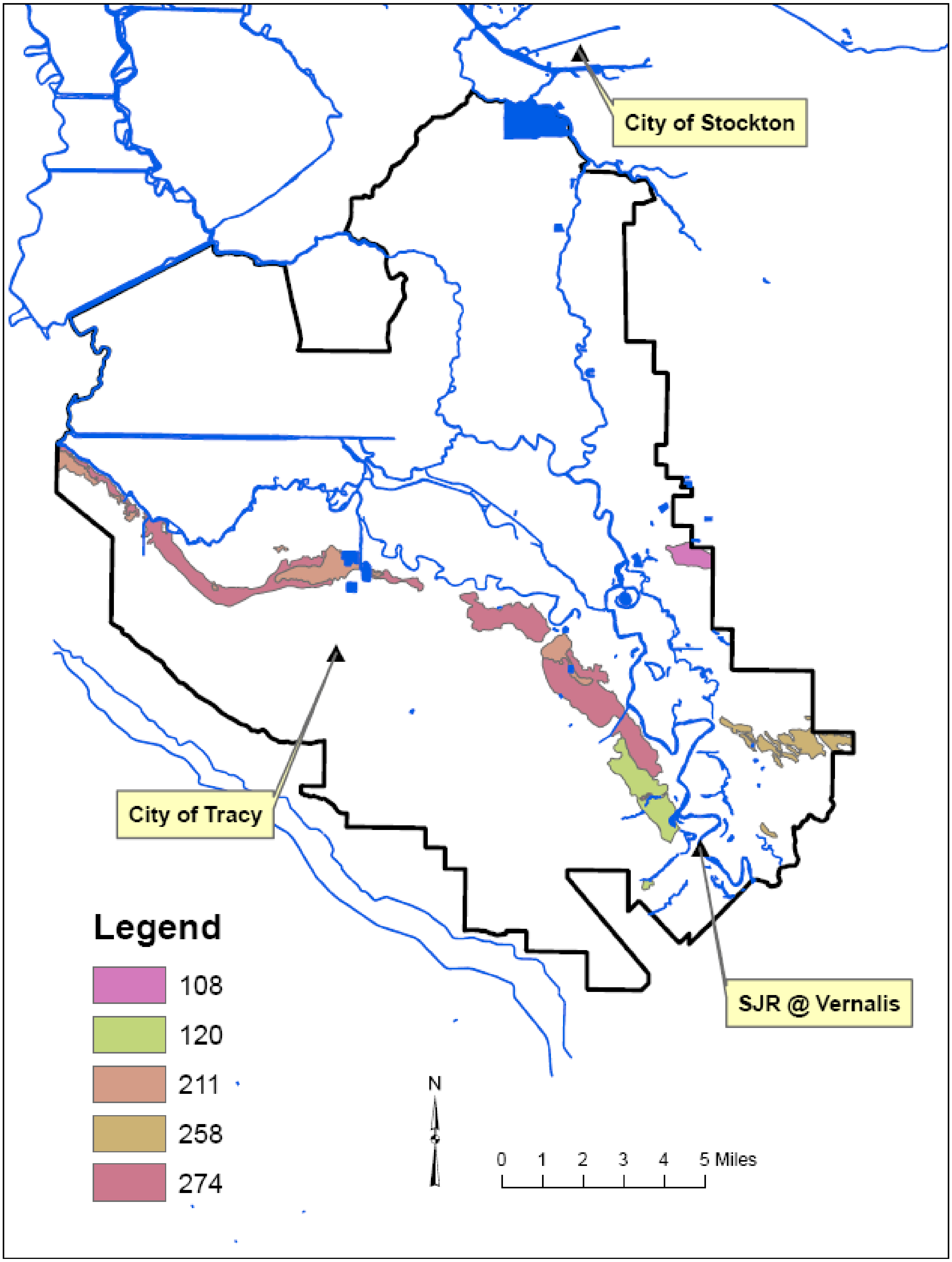
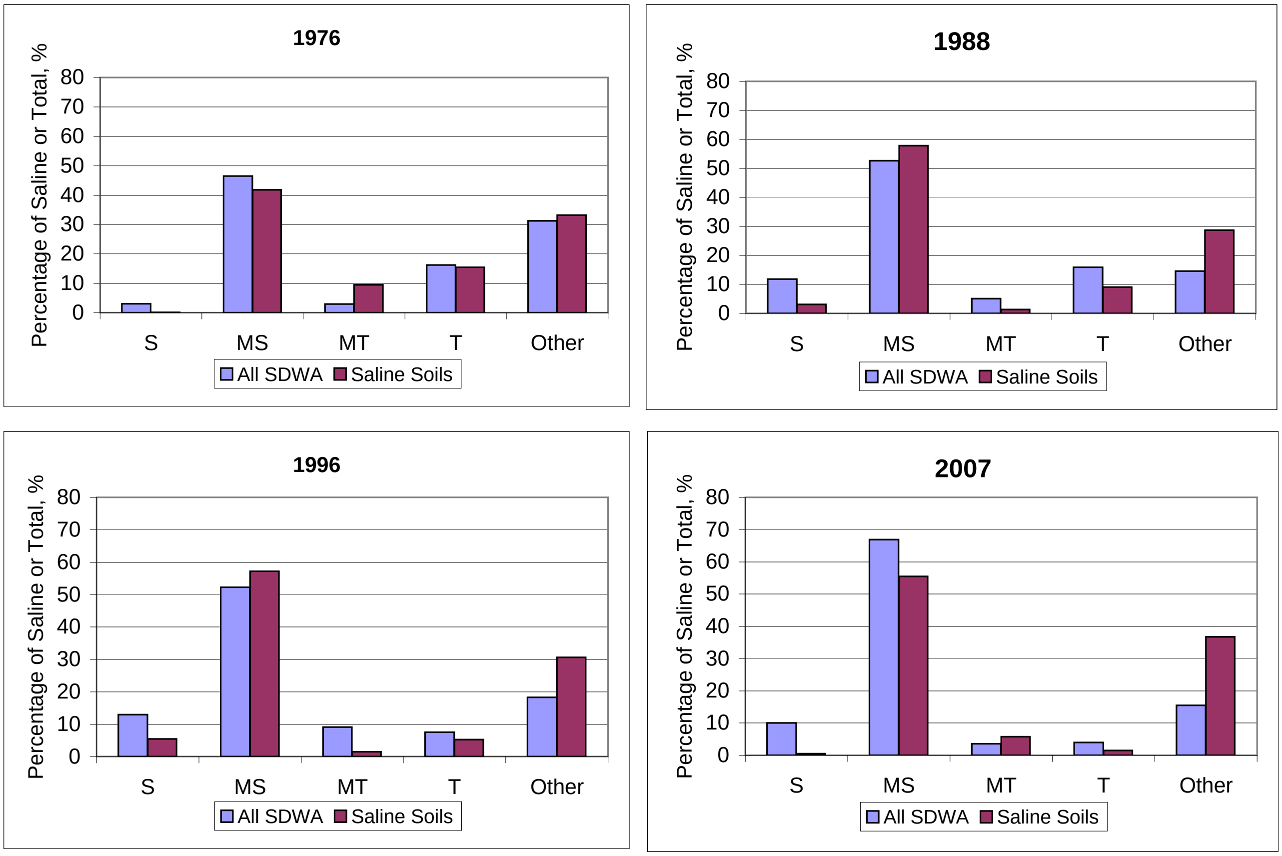


Figure 3.8. Distribution of crops based on salt tolerance relative (as a percent) to: a) total irrigated crops grown on saline soils and b) total irrigated crops grown in SDWA for 1976, 1988, 1996, 2007 (based on DWR land use surveys).



S = Sensitive **MS = Moderately Sensitive** **MT = Moderately Tolerant** **T = Tolerant**

3.4. Bypass Flow in Shrink-Swell Soils

3.4.1. State of Knowledge

Over the past few decades the impact of applied water bypassing the upper reaches of the soil profile has been studied and modeled (i.e., Corwin et al., 1991). The phenomenon in which infiltrating water passes a portion or all of the upper soil profile via large pores or cracks without contacting or displacing water present within finer pores or soil aggregates is referred to as bypass (preferential) flow. It is most likely to occur in aggregated soils or soils high in clay content. These types of soils tend to form channels beginning at the soil surface as the soil starts to dry. This may be of particular importance in soils high in clay content when water is applied infrequently. Bypass flow is more prevalent during the summer when high temperatures and low humidity produce a noticeably drier soil surface which results in more cracks than are noticed in the winter.

An example of bypass flow is the Imperial Valley of California where many soils are high in clay and crops like alfalfa are irrigated about twice monthly in the summer and less frequently during the winter. In a recent publication, Corwin et al., 2007 evaluated the impact of bypass flow for California's Imperial Valley. The study assumed a rotation of 4 years of alfalfa and one crop of wheat followed by one crop of lettuce. They simulated soil properties of Imperial and Holtville silty-clay soils. These soils account for almost 60% of the irrigated portion of the Imperial Valley and are characterized by low infiltration rates. The shrink-swell properties of the Imperial soil are high while the Holtville varies from high to low. In their lysimeter study, bypass flow occurred through surface cracks during irrigations until the cracks were swollen closed, after which preferential flow was substantially reduced and subsequently dominated by flow through pores scattered throughout the profile. The simulations revealed that when less than 40% of the applied water bypassed the surface soils, salinity was less than the crop salt tolerance threshold for each crop in the rotation even though the irrigation water simulated was Colorado River water (EC_i =1.23 dS/m). At most, the yield of alfalfa was reduced by 1.5% only during the first season. They concluded that the levels and distribution of soil salinity would not be affected significantly by bypass flow up to at least 40%. Although the extent of bypass flow in the Imperial Valley has not been established, it has been concluded that it is doubtful that crop yields would be reduced by bypass flow (Corwin et al., in press).

3.4.2. South Delta Situation

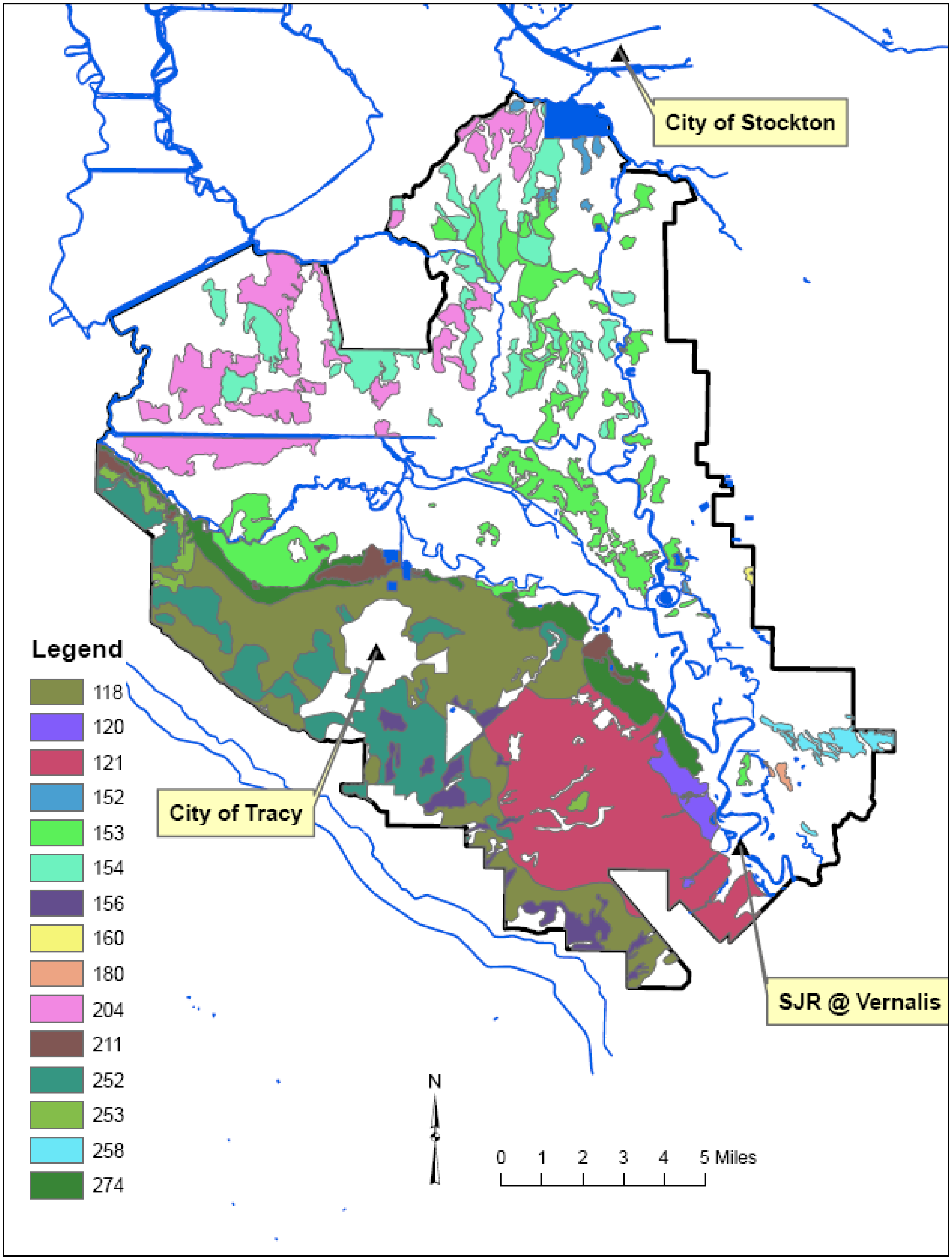
According to the SCS Soil Survey (1992) there are 15 soil series that have the potential to shrink and swell as the soil dries and is then rewet. These soil series are listed in Table 3.5 along with the per cent of the South Delta area they represent. Figure 3.9 shows the location of these soils within the South Delta. The color reference to identify each soil series is given in Table 3.5.

The percent of the South Delta with soils that have the potential to shrink and swell is somewhat less then reported by Corwin et al. (2007) for the Imperial Valley but the severity of the shrink/swell potential is probably similar. As stated above, Corwin and co-workers concluded that shrink/swell should not be a problem in the Imperial Valley. Without any evidence to the contrary for the South Delta, it is probably safe to assume that shrink/swell should not cause bypass flow in the South Delta to the extent that it would cause a salt management problem.

Table 3.5. Soil series in the South Delta that have the potential to shrink and swell (SCS Soil Survey, 1992), with color identification used in Figure 3.9.

Soil Map Unit	Soil Unit Name	% of South Delta Area	Color on Fig. 3.9
118	Capay clay	10.4	
120	Capay clay, saline-sodic	0.6	
121	Capay clay, wet	8.9	
152	Egbert mucky clay loam	0.3	
153	Egbert silty clay loam	6.0	
154	Egbert silty clay loam, sandy substratum	4.1	
156	El Solyo clay loam	1.3	
160	Galt clay	0.02	
180	Jacktone clay	0.07	
204	Peltier mucky clay loam	5.4	
211	Pescadero clay loam	0.8	
252	Stomar clay loam	5.3	
253	Stomar clay loam, wet	0.6	
258	Trahern clay loam	0.6	
274	Willows clay	2.7	
	% of Total Area	47.1	

Figure 3.9. Location of NRCS SURRGO soil map units with shrink-swell potential in the SDWA (as listed in Table 3.5).



3.5. Effective Rainfall

3.5.1. State of Knowledge

Rainfall can be an important source of water for crops in California. Depending on location and crop, rain provides from very little to all of the water available to a crop. The amount of rain actually used by crops, called effective rainfall or effective precipitation, is largely influenced by climate and plant and soil characteristics.

Methods to estimate the effectiveness of rain falling during the growing season are available (i.e., Patwardnan et al., 1990; NRCS, 1993). Patwardnan and co-workers reported that using a daily soil water balance equation to estimate effective rainfall was significantly more accurate than more simple and vague procedures such as the SCS monthly effective precipitation method (NRCS, 1993). The daily soil water balance approach requires a computer program and these methods are not presented here because in most of California and particularly in the South Delta, rain falls primarily during the winter – the non-growing season for many crops. However, winter rain can help meet part of the water requirement of summer crops, because rainwater can infiltrate the soil and be carried into the following growing season as stored soil water. Of course, if a winter crop is being grown, rainfall can be treated like irrigation in determining effectiveness.

Relatively involved techniques have been developed to account for winter rains being stored in the soil profile when determining crop evapotranspiration (ETc) (Allen et al., 2007). However, a field measurement program was conducted by the California Department of Water Resources (MacGillivray and Jones, 1989) to validate the techniques of estimating the effectiveness of winter rains. The study was designed to determine the broad relationships between monthly amounts of winter rain and the portion stored in the soil and available for crop use during the following growing season. Total monthly rainfall and the corresponding change in soil water content were measured during winter at about 10 sites in the Central Valley of California. The 4-year study, started in 1983, drew several important conclusions. First, the relationship between total rainfall and change in soil water content is remarkably similar for November, December, January, and February. The relationship is:

$$\text{Change in stored soil water} = -0.54 + 0.94 \times (\text{rainfall amount}). \qquad \text{(Eqn. 3.2)}$$

The second conclusion was that soil water content increases linearly with increased monthly rainfall for each of the four months. Third, soil surface evaporation is relatively constant, at 0.6 to 0.8 inches per month. The DWR report also concluded that in October, when the soil is initially dry, both the amount of stored soil water and the amount of evaporation from the soil surface increase with increasing amounts of total monthly rain. The relationship for October is:

$$\text{Change in stored soil water} = -0.06 + 0.635 \times (\text{rainfall amount}). \qquad \text{(Eqn. 3.3)}$$

In contrast, for March, when initial soil water content is generally high and evaporative demand is also high, surface evaporation rates are twice those for the four winter months, and the amount of rain going to stored soil water is correspondingly low. The relationship for March is:

Change in stored soil water = -1.07 + 0.837 x (rainfall amount). (Eqn. 3.4)

3.5.2. South Delta Situation

The average annual rainfall for locations along the 400-mile axis of the Central Valley of California is shown in Figure 3.10 (MacGillivray and Jones, 1989). The rainfall gradient along the axis of the Valley is remarkably uniform. During any given year, however, rainfall can vary significantly from these long-term averages.

Table 3.6 from MacGillivray and Jones (1989) summarizes the disposition of average annual rainfall for several zones in the Central Valley of California. The eight zones depicted in their table cover the distance from Red Bluff to Bakersfield. Zone 4 is north of Stockton and zone 5 is south of Modesto. Values for these two zones and the average of the two (noted as representing the South Delta) are presented in Table 3.6. The South Delta values in Table 3.6 are the best estimate of effective rainfall that was found in the literature based on field measurements.

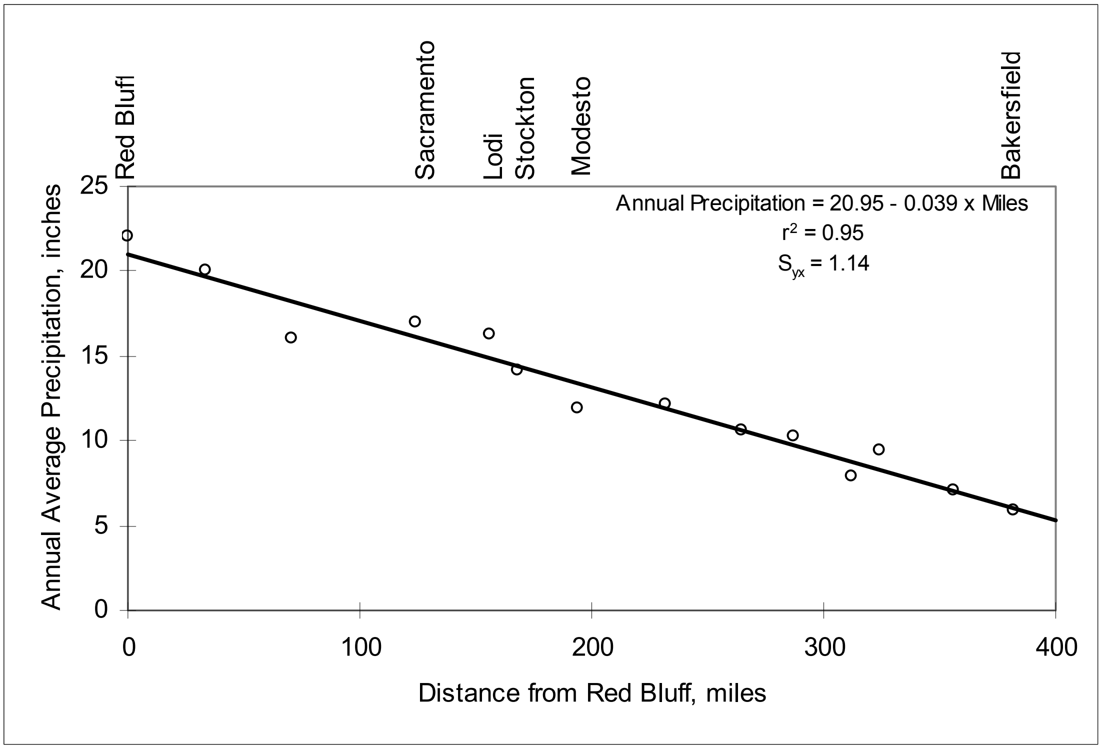
Table 3.6. Disposition of average rainfall for two zones, one just north and one just south of the South Delta, along with the average of these two zones to represent the South Delta. (MacGillivray and Jones, 1989).

		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

Assumptions to develop Table 3.6 were average rainfall amounts, frequency, and intensity; no surface runoff; deep, medium-textured soil with water storage capacity of 1.5 inches/foot; bare soil surface during winter; crop planted in early April and harvested in late September; and 5-foot rooting depth.

As noted in section 3.5.1, an average evaporation rate from the soil surface can be taken as 0.7 inches per month. This value is used in the steady-state models reported in Section 5 for the South Delta.

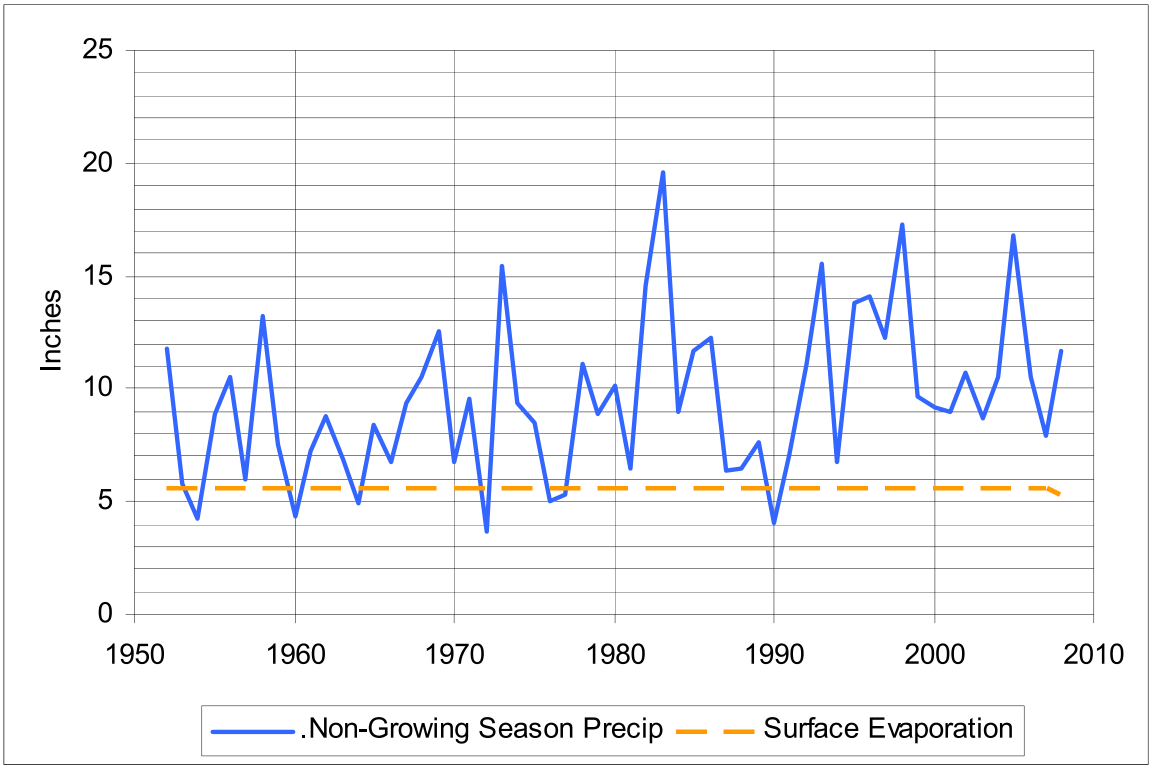
Figure 3.10. Annual precipitation totals along a longitudinal transect of the Central Valley of California (MacGillivray and Jones, 1989).



Precipitation during the non-growing season (P_{NG}) can be beneficial in the overall soil-water balance by contributing water for evaporation from the soil surface (E_S) during the non-growing season, adding to the amount of water stored in the crop root zone, or leaching if precipitation is in excess of these two amounts. Non-beneficial aspects are surface runoff if P_{NG} is excessive and a depletion of stored soil water if precipitation is minimal. Assuming that surface evaporation is 5.6 in. (0.7 in./month during 8 month non-growing season) then P_{NG} of at least 5.6 in. would be consumed by surface evaporation (E_S). If P_{NG} were below 5.6 in. then water would be taken from stored water or surface evaporation would be reduced. Figure 3.11 shows P_{NG} for the 56 years of record plus surface evaporation, E_S. In only 7 years is P_{NG} not large enough to satisfy the E_S of 5.6 in. For the other 49 years, P_{NG} can reduce the irrigation requirement each year more than 3 in.

A potential factor in reducing effective rainfall is surface runoff. Surface runoff from rain in the South Delta is probably low. First, rainfall in the South Delta is normally of low to moderate intensity. Unfortunately, rainfall records only consist of daily amounts and do not report intensity to verify this statement. Second, irrigated fields in the South Delta have been leveled with a slope typically of about 0.2 % to enhance irrigation management. This low slope is not conducive to runoff. Third, crop residue after harvest, cultivations throughout the year, and harvesting equipment traffic are all deterrents to surface runoff. Thus, without definitive measurements to the contrary, surface runoff is assumed to not be a significant factor in reducing effective rainfall in the South Delta.

Figure 3.11. Comparison of non-growing season precipitation (P_{NG}) with estimate of surface evaporation (E_S); using precipitation data from NCDC station no. 8999, Tracy-Carbona for water years 1952 through 2008.



3.6. Irrigation Methods

3.6.1. State of Knowledge

The method of irrigation can affect salinity management and the crop's response to salinity. The irrigation method: (1) influences the distribution of salts in the soil profile, (2) determines whether leaves will be subjected to wetting, and (3) provides different efficiencies and uniformities of water application. These impacts of the irrigation method are described in the following discussions.

Salt Distribution in Soils

The pattern of salt distribution within a given field varies with location in the field and with soil depth. The distribution pattern also changes with differences in soil properties, variances in water management, and the design of the irrigation system. The soil salinity profile that develops as water is transpired or evaporated depends, in part, on the water distribution pattern inherent with the irrigation method. Distinctly different salinity profiles develop for different irrigation methods. Each irrigation method has specific advantages and disadvantages for salinity management. The basic irrigation methods are flood, furrow, sprinkler, microirrigation (trickle), and subirrigation.

The major types of flood irrigation are borders and basins. Border methods commonly have excessive water penetration (low salinity levels) near the levees, at the edge of the border where water is applied, and at the low end of the borders if surface drainage is prevented. Inadequate water penetration midway down the border may result in detrimental salt accumulations. If insufficient amounts of water are applied, the far end of the borders may have excessive salt accumulations. The basin method of flooding has the potential for more uniform water applications than other flooding methods provided the basins are leveled, sized properly, and have uniform soils.

With furrow irrigation, salts tend to accumulate in the seed beds because leaching occurs primarily below the furrows. If the surface soil is mixed between crops and the irrigation water is not too saline, the increase in salt in the seed bed over several growing seasons may not be serious. In furrow and flood methods, the length of run, irrigation application rate, soil characteristics, slope of the land, and time of application are factors that govern the severity of salinity concerns.

Flooding and sprinkler irrigation methods that wet the entire soil surface create a profile of salt that increases with soil depth to the bottom of the crop root zone, provided that moderate leaching occurs, irrigation application is uniform, and no shallow, saline groundwater is present.

Microirrigation (trickle or drip) systems, where water is applied from point or line sources, have the advantage of high leaching near the emitters and high soil water contents can be maintained in the root zone near the emitters by frequent but small water applications. Plant roots tend to proliferate in the leached zone of high soil water content near the water sources. This allows water of relatively high salt content to be used successfully in many cases. Possible emitter clogging, the redistribution of water required to germinate seeds, and the accumulation of salts at the soil surface between emitters are management concerns.

The salinity profile under line sources of irrigation, such as furrow and either porous or multi-emitter microirrigation systems, has lateral and downward components. The typical cross-sectional profile has an isolated pocket of accumulated salts at the soil surface midway between the line sources of water and a second, deep zone of accumulation, with the concentration depending on the amount of leaching. A leached zone occurs directly beneath the line source of irrigation. Its size depends on the irrigation rate, the amount and frequency of irrigation, and the crop’s water extraction pattern.

Whereas the salt distribution from line sources increases laterally and downward, the distribution from point irrigation sources, such as micro-basins and drip systems with widely spaced emitters, increases radially from the water source in all directions below the soil surface. As the rate of water application changes, the shape of the salinity distribution changes. For tree crops irrigated with several emitters per tree, the wetting patterns may overlap, thereby reducing the level of salt accumulation midway between the emitters under a tree.

The continuous upward water movement from a subirrigation system results in salt accumulation near the soil surface as water is lost by evapotranspiration. Subsurface systems provide no means of leaching these shallow salt accumulations. The soil must be leached periodically by rainfall or surface irrigation to displace these shallow accumulations down out of the crop root zone.

Figure 3.12 presents illustrations of the salt distribution under different irrigation methods with non-saline and saline irrigation water. Note the concentration of salts near the top of the seedbed for furrow irrigation. The sketches in this figure are idealized and many soil, plant, and management factors will distort the soil salinity pattern.

3.6.2. South Delta Situation

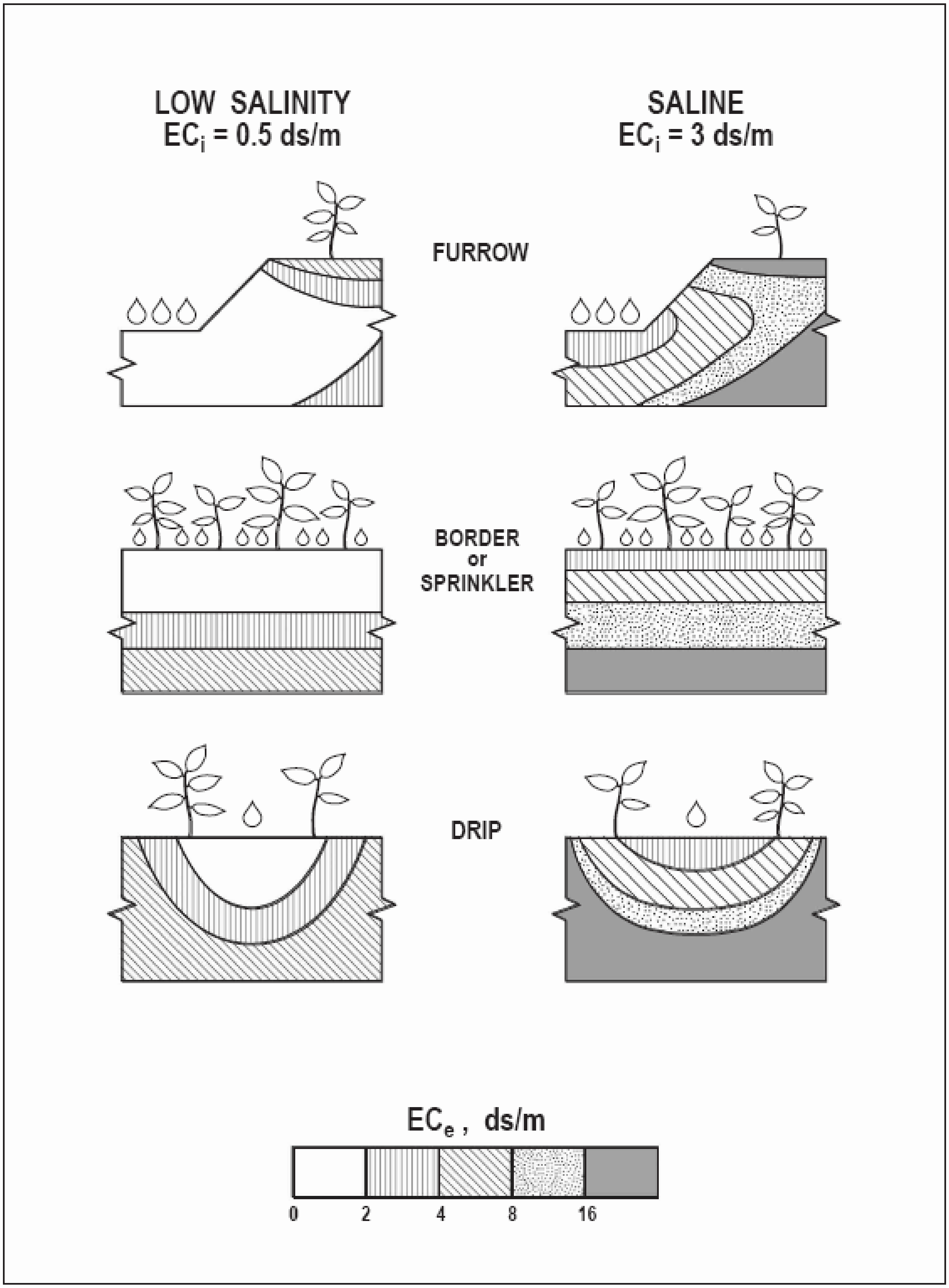
I have been unable to locate definitive information on the types and areas covered by the various irrigation systems in the South Delta. According to Dr. Terry Pritchard of the University of California Cooperative Extension, located in Stockton, the dominant irrigation systems are border and furrow but the proportion of these systems change as the growers change from one crop to another based primarily on economics. Dr. Prichard's expert opinion is that all hay and pasture crops are irrigated by borders. While wheat, barley and oats were split about equal between border and furrow. All row crops, including vegetables, are irrigated by furrow with the exception that approximately 10 % of the tomato and asparagus fields are irrigated by microirrigation. His best estimate on the irrigation method on tree crops and grape vines was 1/3 border, 1/3 furrow, and 1/3 pressurized (sprinkler and microirrigation) systems. Based upon these estimates, Table 3.7 was prepared to show the percentage of the irrigated area provided by these irrigation methods.

Table 3.7. Irrigation methods in the South Delta based upon crop surveys 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	7.9	2.6	2.6	2.6
Field & Truck Crops (excl. Tomato & Asparagus)	28.6	0	28.6	0
Tomato & Asparagus	18.4	0	16.6	1.8
Alfalfa & Pasture	29.7	29.7	0	0
Grain & Hay	14.6	7.3	7.3	0
Totals:	99.2	39.6	55.1	4.4

Based upon the estimates in Table 3.7, it is reasonable to assume that 40 % of the South Delta is irrigated by border, 55 % by furrow, and 5% by sprinkler or microirrigation. These percentages are used in the next section for determining irrigation efficiency.

Figure 3.12. Influence of irrigation water quality and the irrigation method on the pattern of soil salinity.



3.7. Sprinkling with Saline Water

3.7.1. State of Knowledge

In addition to yield loss from soil salinity, crops irrigated by sprinkler systems are subject to salt injury when the foliage is wetted with saline water. Additional yield reduction can be expected for those crops that are susceptible to foliar damage caused by salts absorbed directly through the leaves. Tomatoes sprinkled with 3.6 dS/m water produced only 38% as much fruit as plants that were drip irrigated with the same water (Gornat et al., 1973). Bernstein and Francois (1973a) found that pepper yields were decreased 16% when furrow irrigated with 4.5 dS/m water as compared with 0.6 dS/m water; but were decreased 54% when irrigated by sprinkler. Sprinkling barley with 9.6 dS/m water reduced grain yield by 58% compared to non-sprinkled plants (Benes et al., 1996).

Obviously, saline irrigation water is best applied through surface distribution systems. If sprinkling with marginally saline water can not be avoided, several precautions should be considered. If possible, susceptible crops should be irrigated below the plant canopy to eliminate or reduce wetting of the foliage. Intermittent wetting by slowly rotating sprinklers that allow drying between cycles should be avoided. Perhaps the best strategy to minimize foliar injury is to irrigate at night when evaporation is lower because of lower temperatures and higher humidity and salt absorption is lower because leaf stomata are closed. If daytime sprinkling is necessary, hot, dry, windy days should be avoided.

Except for the few studies described above, there are no data available to predict crop yield losses as a function of the salt concentration of sprinkler irrigation water. There are, however, sufficient data for some crops to allow estimates of the threshold concentrations of Cl and Na of the irrigation water based on sprinkling induced foliar injury (Table 3.8). These thresholds can be compared with EC_i thresholds based on yield attributed to soil salinity. Those crops that have foliar injury thresholds below the soil salinity threshold have a high likelihood of foliar injury when sprinkled with waters that have salt concentrations equal to or above the soil salinity threshold. At concentrations above both thresholds, both foliar injury and yield reductions can be expected.

3.7.2. South Delta Situation

The only crops that may be irrigated by sprinklers apparently are tree crops and vines. From April, 2003 until December, 2007, the concentration of chloride in the San Joaquin River at Mossdale (Dahlgren, 2008) never exceeded 5 mol/m^3 and averaged about 2.5 mol/m^3. Over the same time period, the concentration of sodium averaged about 3 mol/m^3. However, during the winter months of January to April from 2001 to 2003 average concentrations were between 5 and 6 mol/m^3. Of course, trees and vines are not irrigated during the winter. Based upon the estimates of the types of irrigation methods and the chloride and sodium concentrations reported for the San Joaquin River, it is not likely that yield loss from sprinkling is a concern.

Table 3.8. Relative susceptibility of crops to foliar injury from saline sprinkling waters (Maas and Grattan, 1999).

Na or Cl concentration causing foliar injury, mol/m³*			
<5	**5-10**	**10-20**	**>20**
Almond	Grape	Alfalfa	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Potato	Corn	Sugar beet
Plum	Tomato	Cucumber	Sunflower
		Safflower	
		Sesame	
		Sorghum	

**To convert mol/m³ to mg/L or ppm divide Cl concentration by 0.02821 and Na concentration by 0.04350. The conversion from mg/L to EC is EC = mg/L / 640.*

Note: These data are to be used as general guidelines for daytime sprinkling. Foliar injury is also influenced by cultural and environmental conditions.

3.8. Irrigation Efficiency and Uniformity

3.8.1. State of Knowledge

Irrigation efficiency is defined as the ratio of the amount of water which is beneficially used to the amount of water applied. Beneficial uses include crop water use, salt leaching, frost protection, crop cooling, and pesticide and fertilizer applications. Excessive deep percolation, surface runoff, water use by weeds, wind drift, and spray evaporation are not beneficial uses and thus decrease irrigation efficiency. The non-uniformity of water applications by an irrigation system within a given field can be a major contributor to low irrigation efficiency. An irrigation system that does not apply water uniformly must apply excess water in some areas to provide enough water in other areas, such that water stress over the entire field is minimized. The excess water may cause surface runoff and/or deep percolation below the crop root zone. Generally, irrigation uniformity is based on indirect measurements. For example, the uniformity of water that enters the soil is assumed to be related to that caught in catch cans for sprinkler systems, to emitter discharge for microirrigation systems, and to intake opportunity time and infiltration rates for surface irrigation systems.

Relatively high irrigation efficiencies are possible with surface irrigation methods, but it is much easier to obtain these potential high efficiencies with the basin method on relatively uniform soil types within the basin. The following range of irrigation efficiencies are taken from Heermann and Solomon (2007). Irrigation efficiencies for basin systems can be as high as 80 to 90%. Reasonable efficiencies for border systems are from 70 to 85%, and from 65 to 75% for furrow irrigation. There are many types of sprinkler systems. The efficiency of solid set or permanent sprinkler systems ranges from 70 to 80%. Center pivot and linear move systems have attainable efficiencies of 75 to 90%. Properly designed and managed microirrigation systems are capable of efficiencies from 80 to 95%. The irrigation efficiency for all of these irrigation methods can be much lower than the values quoted here if the system is poorly designed or mismanaged.

3.8.2. South Delta Situation

From the estimates reported in Table 3.7 and average values for irrigation efficiency (78 % for border, 70 % for furrow, 75 % for sprinkler, and 87% for microirrigation), it is reasonable to assume that the irrigation efficiency for the South Delta is about 75 %. Because bean is the most salt sensitive crop and is furrow irrigated, an irrigation efficiency of 70% is reasonable. A range of irrigation efficiencies could be assumed to determine the impact on a water quality standard.

3.9. Crop Water Uptake Distribution

3.9.1. State of Knowledge

Different crops have different water uptake patterns, but all take water from wherever it is most readily available within the rooting depth (Ayers and Westcot, 1989). Many field and laboratory experiments have been conducted over the years to determine the actual root water extraction pattern and models have also been proposed to predict crop water uptake (Feddes, 1981). Unfortunately, the water uptake distribution is very hard to quantify and there are numerous factors that impact the uptake pattern. Among the soil factors are: texture, hydraulic conductivity, water-holding capacity, aeration, temperature, and fertility. Among the plant factors are: plant age, rooting depth, root distribution, and distribution of root hairs that take up water. Needless to say, the water uptake distribution is very complex and varies with crop, soil, and environmental conditions. For lack of a better scheme, Ayers and Westcot (1989) assumed that about 40 % of the soil water is taken up in the upper quarter of the crop root zone, 30 % from the second quarter, 20 % from the third quarter, and 10 % from the lowest quarter. This water uptake distribution has been assumed in many models to determine the leaching requirement to control salinity. As will be seen in Section 4.3, an exponential water uptake distribution fits field and plot experiments to determine leaching requirement under saline conditions better than the 40-30-20-10 pattern (Hoffman, 1985).

3.9.2. South Delta Situation

There are no measurements or estimates of crop water uptake patterns for the South Delta. Thus, both the exponential and the 40-30-20-10 distribution patterns are used in the steady-state models developed for the South Delta in Section 5..

3.10. Climate

3.10.1. State of Knowledge

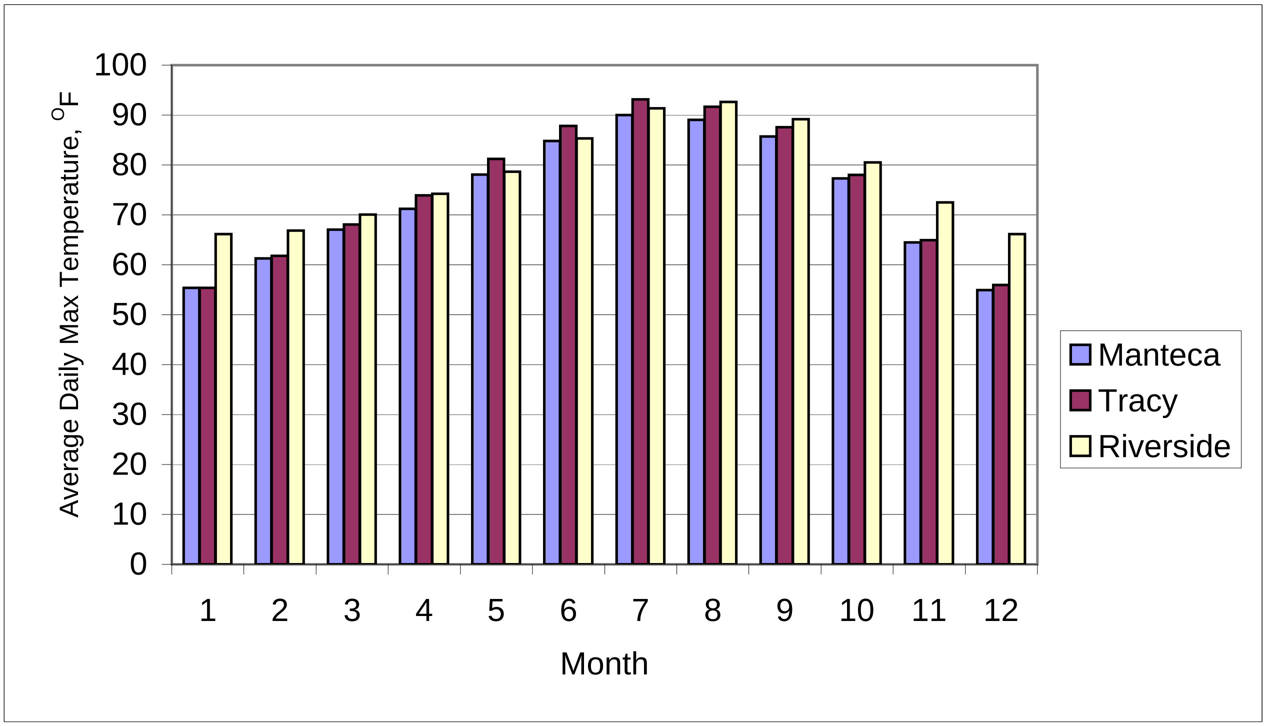
Climatic conditions can influence plant response to salinity. Most crops can tolerate greater salt stress if the weather is cool and humid than if it is hot and dry. The combined effects of salinity and conditions of high evaporative demand, whether caused by temperature, low humidity, wind, or drought, are more stressful than salinity under low evaporative demand conditions. Studies on several crops including alfalfa, bean, beet, carrot, cotton, onion, squash, strawberry clover, saltgrass, and tomato have shown that salinity decreased yields more when these crops were grown at high temperatures (Ahi and Powers, 1938; Magistad et al., 1943; Hoffman and Rawlins, 1970). Yields of many crops also are decreased more by salinity when atmospheric humidity is decreased. Experiments indicate that barley, bean, corn, cotton, onion, and radish were more sensitive to salt at low than high humidity; however, the tolerances of beet and wheat were not markedly affected by humidity (Hoffman and Rawlins, 1970, 1971; Hoffman et al., 1971; Nieman and Poulsen, 1967).

3.10.2. South Delta Situation

The vast majority of experiments to establish crop salt tolerance have been conducted in Riverside, California at the U. S. Salinity Laboratory. The average monthly temperature and relative humidity in Riverside, California are compared with average monthly values at Tracy and/or Manteca, California, which are located in the South Delta. Maximum and minimum daily temperatures and maximum and minimum relative humidity values reported in Figures 3.13 and 3.14 are from November 1987 through September 2008. As seen in Figure 3.13, the average daily maximum temperature by month is slightly higher in Riverside for all months except May, June, and July when the maximum is slightly higher in the South Delta. The average daily minimum temperature is higher in Riverside than the South Delta for every month. Figure 3.14 shows the comparison between average daily minimum and maximum relative humidity for Manteca and Riverside. A record was not available for Tracy over the same time period. The relative humidity was always lower in Riverside than in Manteca. Thus, on average, plants experience higher evaporative demands in Riverside than in the South Delta and, under otherwise identical conditions, plants in Riverside would experience slightly more salt stress than plants in the South Delta. These slight differences in climate would result in a slightly smaller reduction in crop yields than the published salt tolerance responses. Thus, using the crop salt tolerance values above should be slightly conservative with respect to climatic conditions.

Figure 3.13. Average over the month of a) daily maximum temperature and b) daily minimum temperature as measured at Manteca (CIMIS #70), Riverside (CIMIS #44), and Tracy (NCDC #8999) between November 1987 and September 2008 (Month 1 = January; 12 = December).

a) Average over the month of daily maximum temperature.



b) Average over the month of daily minimum temperature.

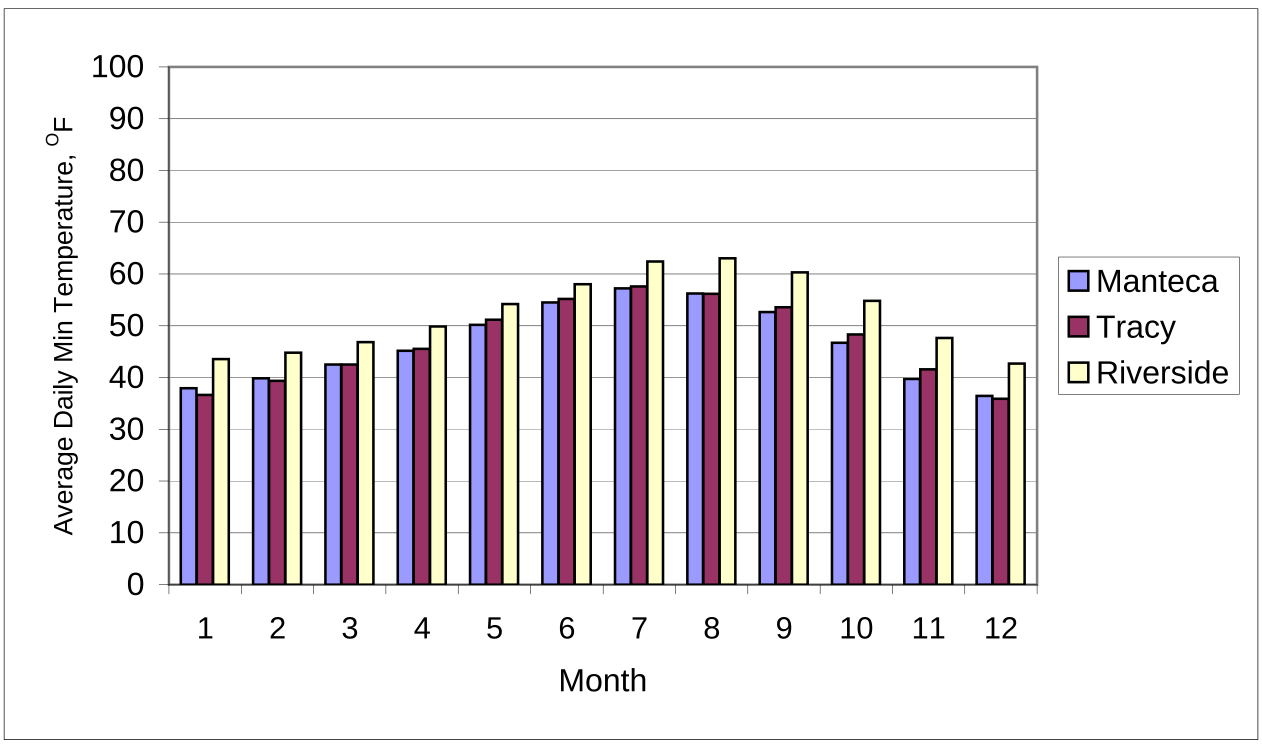
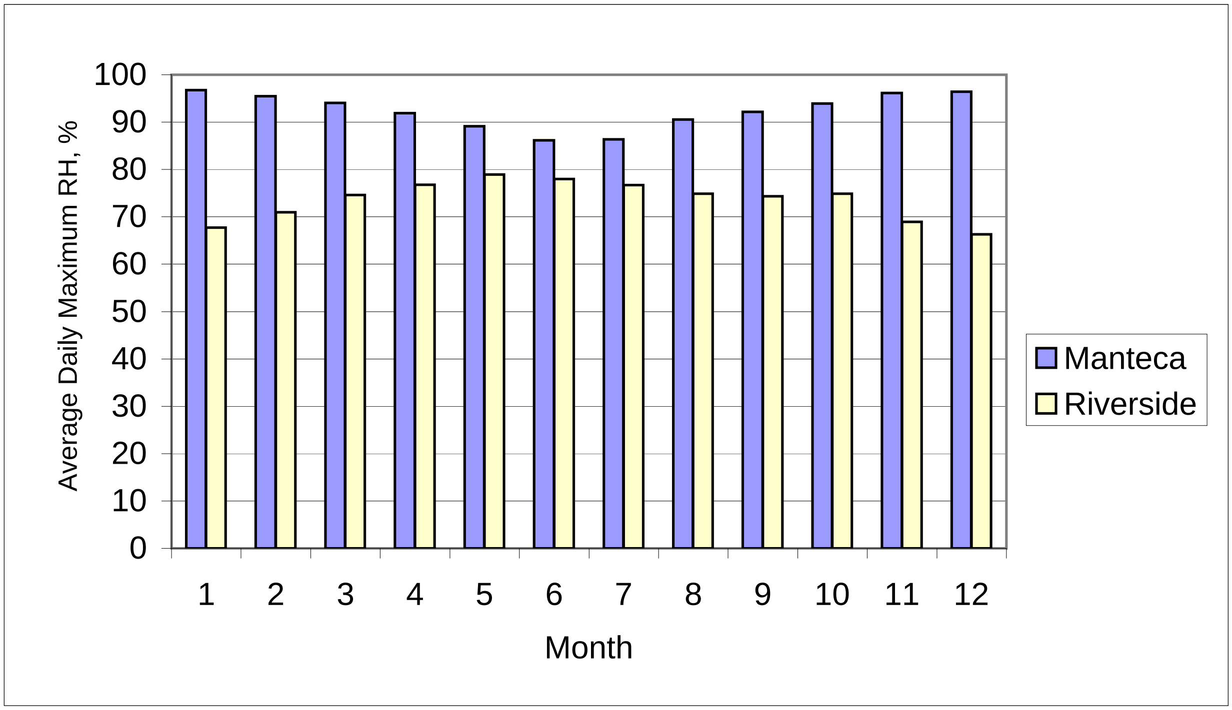
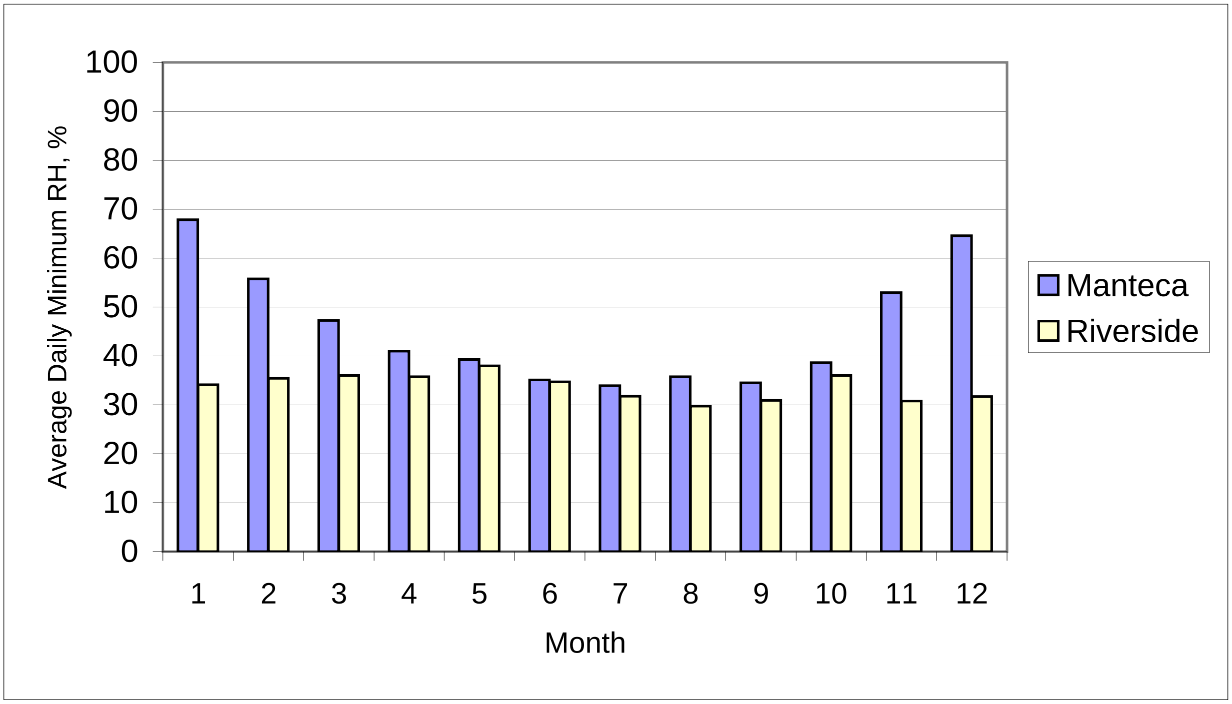


Figure 3.14. Average over the month of a) daily maximum relative humidity and b) daily minimum relative humidity as measured at Manteca (CIMIS #70) and Riverside (CIMIS #44) between November 1987 and September 2008 (Month 1 = January; 12 = December).

a) Average over the month of daily maximum relative humidity (RH).



b) Average over the month of daily minimum relative humidity (RH).



3.11. Salt Precipitation or Dissolution

3.11.1. State of Knowledge

Depending upon the constituents of the irrigation water and their concentrations, salts may precipitate out of the soil solution or salts in the soil may be dissolved by irrigation waters as it passes through the soil. The salt balance in the soil profile is affected by chemical reactions involving slightly soluble salts, such as gypsum, carbonates, or silicate minerals. Consequently, the amount of salt leached below the crop root zone may be less or more than that applied over a long time period depending on whether salts precipitate or dissolve in the crop root zone.

Soils in arid and semi-arid regions, like the South Delta, are relatively un-weathered. Un-weathered minerals provide plant nutrients, but are also a source of salinity. Studies using simulated irrigation waters from the western U.S., Rhoades and colleagues (Rhoades et al., 1973, 1974) showed that the dissolution of primary minerals is most important when the irrigation water's salt content is low – less than 100 mg/l to 200 mg/l (EC_i = 0.15 to 0.3 dS/m) and when the leaching fraction is at least 0.25. For example, irrigation with water from California's Feather River, which has a salt content of 60 mg/l, results in more salt in the drain water due to dissolution (weathering) than due solely to the salt content of the irrigation water at high leaching fractions (Rhoades et al., 1974).

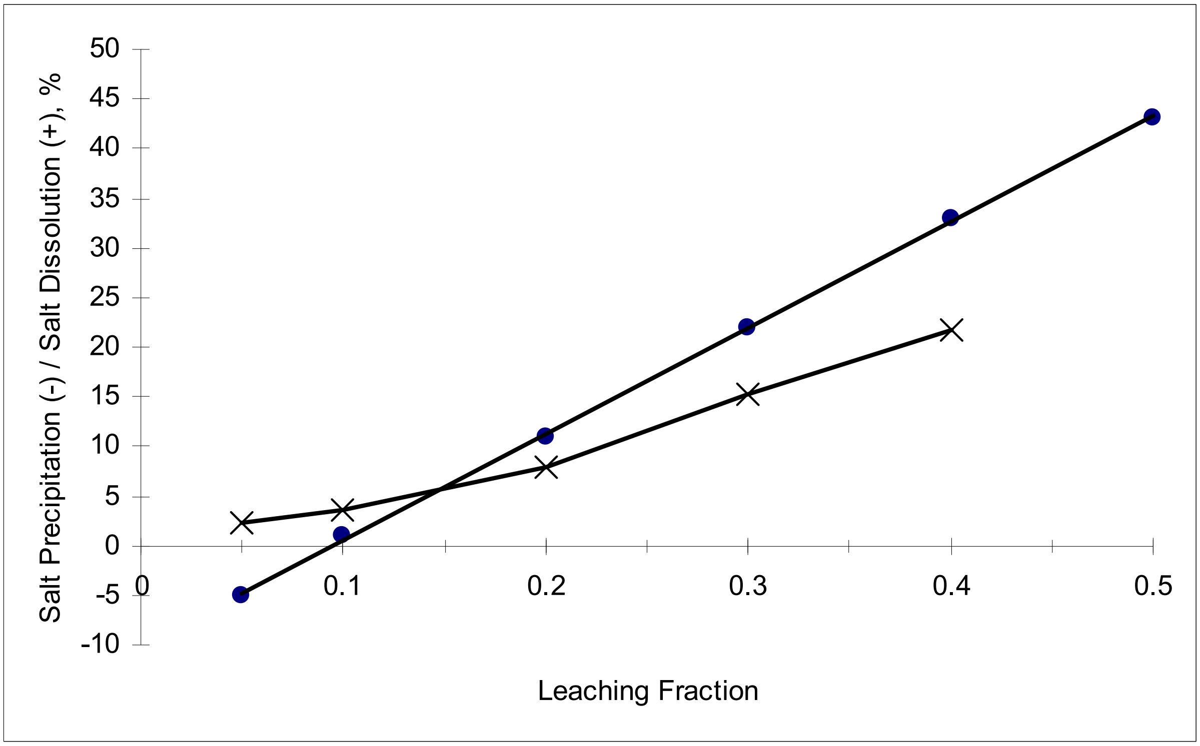
3.11.2. South Delta Situation

Based upon the salt constituents of the water from the San Joaquin River at Mossdale,CA from 2000 to 2003 and from 2005 to 2007 (Dahlgren, 2008), the relationship between the leaching fraction and whether salt would precipitate or be dissolved was calculated (Figure 3.15). The salt constituent data were analyzed by Dr. Don Suarez, Director of the U. S. Salinity Laboratory in Riverside, CA, and he determined the relationship shown in Figure 3.15 using the WATSUIT model for drainage water salinity. The results show that because the water is low in gypsum, carbonates, and silicate minerals at leaching fractions higher than 0.10 the water draining from the root zone would contain salt dissolved from the soil profile and at leaching fractions lower than 0.10 salt would precipitate in the soil. This means that if the leaching fraction for the South Delta is based upon the ratio EC_i/EC_d the leaching fraction would be slightly lower than it really is because some of the salts in the drainage water would be from dissolution of salts in the soil.

I also asked Dr. Jim Oster, emeritus professor from the University of California, Riverside, to analyze the same data set. He also used the WATSUIT model but based his analysis on the average root zone salinity rather than drainage water salinity. The results are also shown in Figure 3.15. The results by Oster predict that salts would tend to dissolve from the soil profile at all leaching fractions.

Both analyses indicate that at a leaching fraction of 0.15, salinity would be increased about 5%. Considering all of the other factors that influence crop response to salinity, the effect of salt precipitation/dissolution would be minimal at leaching fractions near 0.15.

Figure 3.15. The relationship between leaching fraction and salt precipitation or dissolution in the soil when using water from the San Joaquin River (Don Suarez, 2008 personal communication and Jim Oster, 2009, personal communication).



3.12. Shallow Groundwater

3.12.1. State of Knowledge

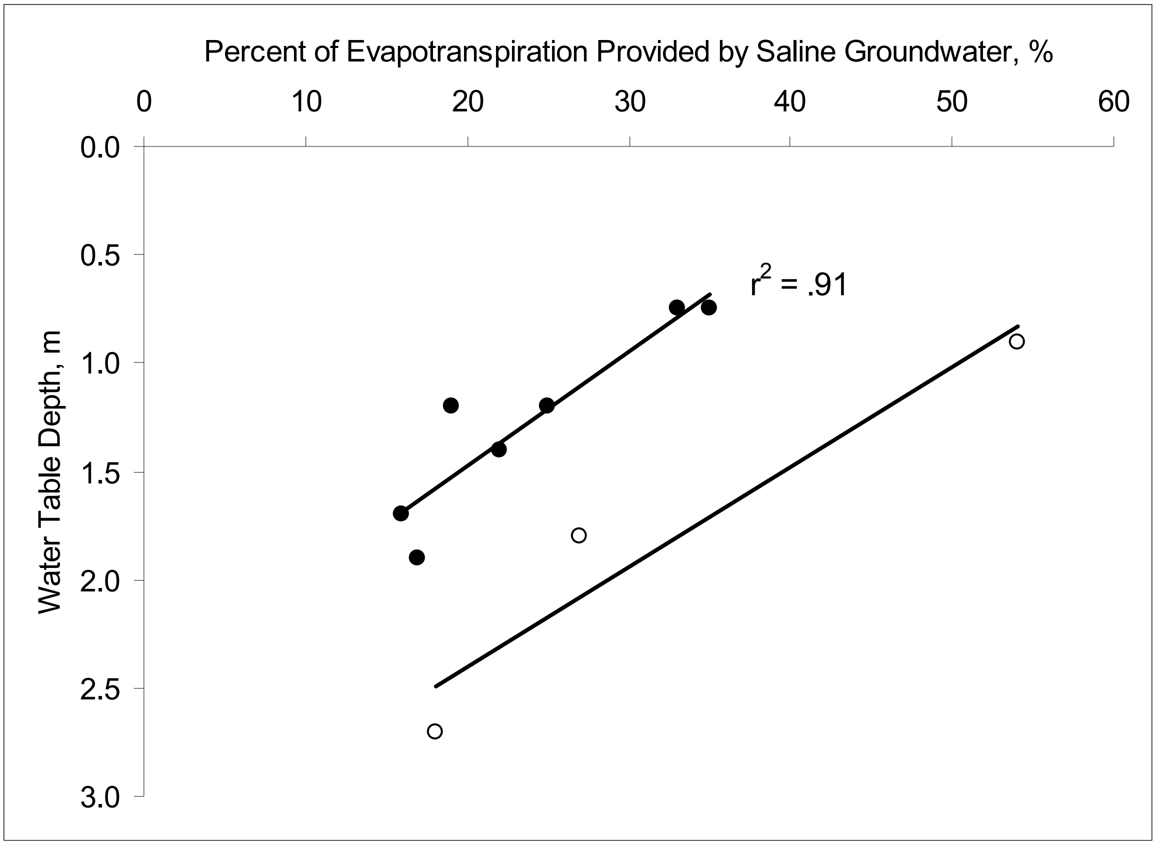
An important mechanism leading to salination of soils is the upward movement of saline groundwater into the crop root zone. To minimize upward movement and thus reduce the salinity hazard, attempts are usually made to lower the water table by drainage. The impact of the water table depth and soil properties on the rate of upward movement must be known to evaluate what water table depth should be maintained. This information is also desirable when estimating the amount of water available to plants due to upward movement of groundwater, thereby reducing the irrigation requirement.

The depth at which a water table should be maintained to minimize upward flow can be determined from an analysis like that published by Gardner (1958). Lowering the water table from the soil surface to a depth of about 3 feet would be of little value in most irrigated soils in a semi-arid or arid climate where groundwater is saline. Upward flow at these shallow depths could be in excess of 0.1 in. per day for clay soils and greater for coarser textured soils (Gardner and Fireman, 1958). As the water table is lowered below 3 ft. the upward flow becomes limited by the hydraulic properties of the soil and decreases markedly with increasing soil depth. Lowering the water table from 4 to 10 ft. in Pachappa sandy loam would decrease upward flow by a factor of 10 (Gardner and Fireman, 1958). When the water table is at 8 ft., further lowering reduces upward flow only slightly. Upward movement and evaporation of water from the soil surface is possible even with the water table at a depth of 13 ft., and, although the rate will be slow, accumulation of harmful amounts of soluble salts is possible if the groundwater is sufficiently saline, if sufficient time is allowed, and if rainfall and irrigation amounts are low. These results, verified by field observations, and the increased cost of drain installation at deeper soil depths have lead to most subsurface drainage systems being installed at depths of 5 to 8 ft. where salinity is a hazard.

Water supplied to a crop by capillary rise from shallow groundwater can be an important resource. Benefits of using shallow groundwater include reduced irrigation, lower production costs, moderation of groundwater moving to deeper aquifers, and minimization of groundwater requiring disposal through subsurface drainage systems. As an example, cotton, grown on a loam soil in the San Joaquin Valley of California with a water table 6 to 8 ft. below the soil surface, obtained 60 % or more of its water requirements from the shallow groundwater that had an EC of 6 dS/m (Wallender et al., 1979). As less water was applied by irrigation, the groundwater contribution to ET increased, but lint yields were reduced.

The relationships between crop water use and the depth and salt content of groundwater are not well understood. Several experiments have been conducted, but generalizations are difficult to make based upon these results. Some of the most consistent data have been obtained with cotton (see Figure 3.16). The relationship between cotton water use from the groundwater and water table depth for soils ranging from clay to clay loam is from field experiments on the west side of the San Joaquin Valley. The data points presented are from three independent studies (Grimes et al., 1984; Hanson and Kite, 1984; and Ayars and Schoneman, 1986). The relationship in Figure 3.16 for sandy loam soil is from a lysimeter study in Texas (Namken et al., 1969). Results indicate uptake of groundwater by cotton is not reduced measurably until the EC of the groundwater exceeds at least 12 dS/m. Groundwater use by alfalfa and corn varies from 15 to 60 % of the total seasonal water use, but the data are not consistent enough to establish a relationship. As an example, groundwater use by alfalfa from a water table 0.6 m deep relative to the total seasonal use in the Grand Valley of Colorado (Kruse et al., 1986) varied among years by more than double; 46 % vs. 94 % in two separate years when the salinity of the groundwater was 0.7 dS/m and 23 % vs. 91 % when the groundwater EC was 6 dS/m.

Figure 3.16. Contribution of shallow, saline groundwater to the evapo-transpiration of cotton as a function of depth to the water table and soil type.



3.12.2. South Delta Situation

Three sources of information on the depth of the water table in the South Delta were located. One source is the NRCS-SSURGO database (NRCS, 2009); a second source is data from ten wells throughout the South Delta as monitored by Department of Water Resources (DWR, 2009); and the third source is the salinity status report of Meyer et al. (1976).

The depths to ground water for each soil series in the south Delta were determined using the NRCS-SSURGO database and are given in Table 2.1, and mapped in Figure 3.17. The depth to the water table is at least 3 feet for all soils (with the exception of miscellaneous areas totaling about 300 acres along the San Joaquin and Old Rivers). The shallowest depths tend to be along the northern boundaries of the South Delta. About 32% of the SDWA has a water table greater than 5 feet deep.

The locations of 10 shallow wells are also shown in Figure 3.17. The depth to the water table measured in the wells over the past 30 years varies with time of year but the average depth is 5 feet or more as shown in Table 3.9. A depth of 5 feet will minimize upward flow of water from the water table and except for deep rooted crops like alfalfa and cotton the crops are probably not taking up significant amounts of water from the groundwater. Furthermore, the more salt sensitive crops in the South Delta are shallow rooted. In a few areas the water table is on the order of 3 to 4 feet deep. On these soils, crops could extract water from the groundwater but if irrigation management prevents crop water stress, insignificant amounts of water will be taken up from the groundwater.

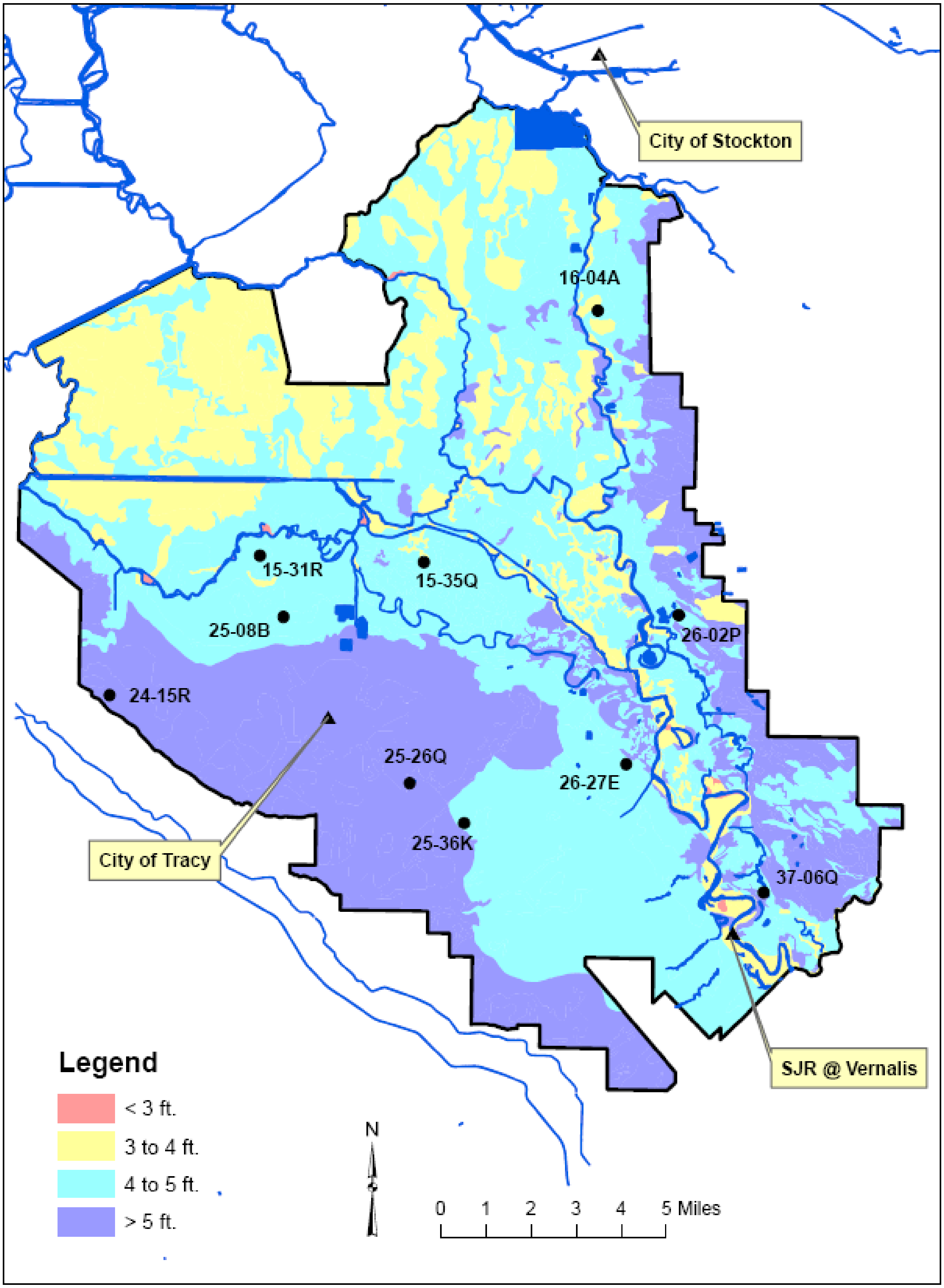
Table 3.9. Depth to groundwater at 10 wells located within the SDWA per Department of Water Resources monitoring network (DWR, 2009).

State Well No.	Identifier on Figure 3.16	Years of Data	Average Depth (ft.)	Depth per NRCS-SURRGO
02S05E26Q001M	25-26Q	1960 to 1995	14.5	6.6
02S06E02P001M	26-02P	1973 to 2005	10.6	5.0
02S06E27E001M	26-27E	1960 to 2008	9.9	5.0
01S05E31R002M	15-31R	1962 to 2008	3.4	5.0
02S05E08B001M	25-08B	1960 to 2008	6.6	5.0
01S05E35Q002M	15-35Q	1963 to 2002	6.8	4.0
03S07E06Q001M	37-06Q	1966 to 2008	7.8	6.6
01S06E04A002M	16-04A	1963 to 2003	6.7	5.0
02S05E36K001M	25-36K	1960 to 1993	7.7	5.0
02S04E15R002M	24-15R	1958 to 2008	3.3	6.6

In 1976, Meyer and colleagues (Meyer et al., 1976) studied the salinity status at nine locations in the South Delta. The depth of the water table was found to be from 4-5 feet to as deep as 12 feet. Unfortunately, this study only included nine locations and thus no generalizations can be inferred.

Although there are relatively few observations of water table depth at various times over the past thirty years, the depth of the water table appears to be at least 3 to 4 feet throughout the South Delta. The installation of subsurface tile drains in the central and western potions of the South Delta (see discussion of agricultural drains in section 3.13.2) would indicate that any problems of shallow groundwater have been rectified by subsurface tile drains.

Figure 3.17. Depth to the water table in the south Delta from NRCS SURRGO database, and location of 10 groundwater wells listed in Table 3.9.



3.13. Leaching Fraction

3.13.1. State of Knowledge

The amount of applied water needed to satisfy the crop's water requirement can be estimated from water and salt balances within the crop root zone. The major flows of water into the root zone are irrigation, rainfall, and upward flow from the groundwater. Water flows out by evaporation, transpiration, and drainage. Under steady-state conditions, the change in the amount of water and salt stored in the root zone is essentially zero. If the total water inflow is less than evaporation plus transpiration, water is extracted from soil storage and drainage is reduced, with time, the difference between inflows and outflows becomes zero. In the absence of net downward flow beyond the root zone, salt will accumulate, crop growth will be suppressed, and transpiration will be reduced.

In the presence of a shallow water table, deficiencies in the irrigation and rainfall amounts may be offset by upward flow from the groundwater. Upward flow will carry salts into the root zone. If upward flow continues and sufficient leaching does not occur, soil salinity will ultimately reduce crop growth and water consumption. Over the long term, a net downward flow of water is required to control salination and sustain crop productivity.

Rarely do conditions controlling the water that flows into and out of the root zone prevail long enough for a true steady state to exist. However, it is instructive to consider a simple form of the steady-state equation to understand the relationship between drainage and salinity. If it is assumed that the upward movement of salt is negligible, the quantities of salt dissolved from the soil minerals plus salt added as fertilizer or amendments is essentially equal to the sum of precipitated salts plus salt removed in the harvested crop, and the change in salt storage is zero under steady-state conditions, the leaching fraction (L) can be written as:

$$L = D_d / D_a = C_a / C_d = EC_a / EC_d \qquad \text{(Eqn. 3.5)}$$

where D refers to depth of water, C is salt concentration, and EC is the electrical conductivity and the subscripts d and a designate drainage and applied water (irrigation plus rainfall). This equation applies only to salt constituents that remained dissolved.

The minimum leaching fraction that a crop can endure without yield reduction is termed the leaching requirement, L_r, which can be expressed as follows:

$$L_r = D_d^* / D_a = C_a / C_d^* = EC_a / EC_d^*. \qquad \text{(Eqn. 3.6)}$$

The notation in Equation 3.6 is the same as in Equation 3.5 except the superscript (*) distinguishes required from actual values.

3.13.2. South Delta Situation

The leaching fraction in the South Delta is difficult to estimate because measurements of soil salinity or salt concentration of drainage water are not measured routinely. However, there are several areas where subsurface drains have been installed and the electrical conductivity of the drainage water measured for short periods of time. In addition, the study by Meyer and colleagues (Meyer et al., 1976) on soil salinity through the crop root zone in nine locations in the South Delta on different soils and crops was used to estimate the leaching fraction.

Chilcott and co-workers (1988) sampled tile drain discharge in the San Joaquin River Basin and Delta from Contra Costa County in the north to Fresno County in the south. Only the drains in Zone C from their report are discussed here. The subsurface drains in Zone C are located in the western portion of San Joaquin County principally from the Delta Mendota pumping plant to just east of the City of Tracy (see Figure 3.18). The majority of the drains lie along a line approximately 1 to 3 miles upslope of the San Joaquin River. Fourteen discharge sites within this zone were sampled in June, 1986 and again in June, 1987. The drain waters were analyzed for many properties including minerals and trace elements; only the electrical conductivity measurements are reported in Table 3.10.

The data in Table 3.10 are relatively consistent from one year to the next with values from different drains ranging from 1.9 to 4.2 dS/m with an overall average of 3.1 dS/m. The drains are located in clay and clay loam soils and are in or near the soils mapped as saline (compare Figures 3.7 and 3.17). If the applied water (irrigation and rainfall) averaged 0.7 dS/m then the leaching fraction for the fields drained by the systems reported in Table 3.10 was LF = 0.7 / 3.1 = 0.23. If the applied water was 1.0 dS/m then the LF would be 1.0/3.1 = 0.32. Regardless of the applied water quality, the leaching fractions are relatively high and indicative of surface irrigation systems managed to prevent crop water stress.

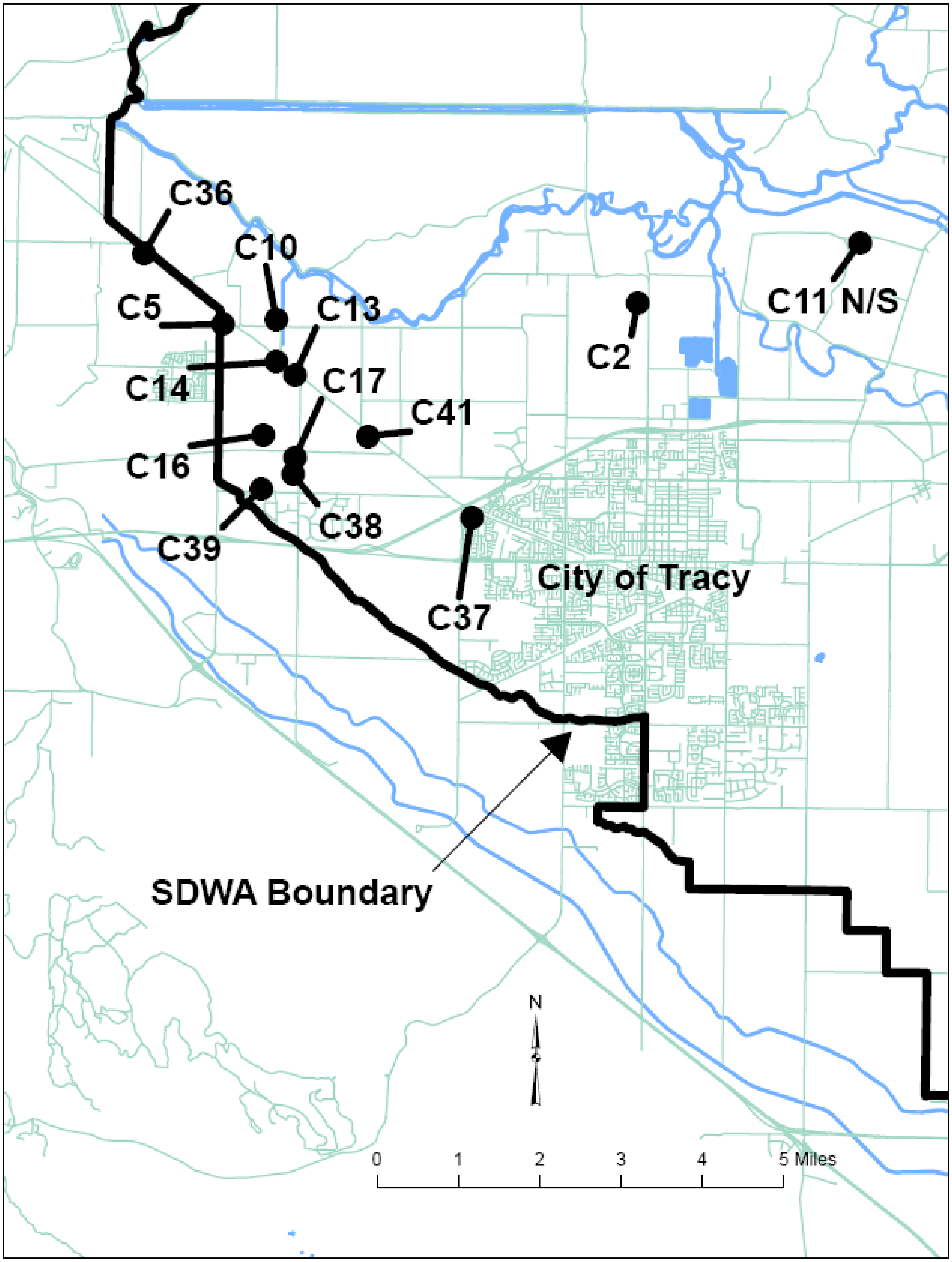
Montoya (2007) summarized the sources of salinity in the South Sacramento-San Joaquin Delta. Of the approximately 74 discharge sites to waterways in the South Delta, he reported that the vast majority of the discharge sites were agricultural. The report gives the electrical conductivity of 26 agricultural drains in the South Delta taken from several DWR reports. The drain discharges monitored included 8 drains discharging into the Grant Line Canal, 7 into Paradise Cut, 9 into South Old River, and 2 into Tom Paine Slough. The average electrical conductivity of the 26 outlets was 1.5 dS/m. If the salinity of the applied water was 0.7 dS/m then the leaching fraction would be 0.7/1.5 = 0.47. This is a very high leaching fraction and based on these data one would surmise that the irrigation efficiency, on average, is low and/or a great deal of low salinity water was entering the drain without passing through the crop root zone. If the main drains were open surface drains then it is possible that much of the discharge from these drains was irrigation return flow rather than subsurface drainage.

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

	Electrical Conductivity, dS/m		
Site Location	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

The other source of information located for the South Delta is the study by Meyer and colleagues (1976). They measured soil salinity at nine locations in April or May, 1976 and again in August or September, 1976. The locations represented a variety of crops, soil types, and irrigation water sources. They estimated the leaching fraction based upon the irrigation water quality in 1976 and the maximum soil salinity in the lower reaches of the crop root zone. Of the nine locations studied, six had leaching fractions of 0.15 or greater. At three locations the leaching fraction was estimated at 0.10 or less; one location had an apparent leaching fraction of less than 0.05. The highest soil salinities and lowest apparent leaching fractions occurred at locations where water quality was the best in this study, seasonal average of about 0.7 dS/m. High leaching and low salt accumulations were found at the locations where more saline irrigation water was available, 1.1 dS/m or more. Their concluding remark was “Given the wide variety of soils in the South Delta, good yields and diversity of crops appear to be related to water quality and levels of farm management”.

Figure 3.18. Location of subsurface tile drains sampled on the west side of the SDWA (Chilcott, et al., 1988).



4. Steady State vs. Transient Models for Soil Salinity

4.1. Steady-State Models

Steady-state analyses are simpler than transient-state analyses. The common assumption is that with time, a transient system will converge into a steady-state case and provide justification for steady-state analyses. This convergence never truly exists in the upper soil profile but investigators have found that steady-state analyses are excellent first approximations and over long time periods, if rainfall is taken into account, provide acceptable results and do not require the vast amount of information on irrigation amount and frequency, soil physical and chemical properties, and crop evapotranspiration that are typically required for transient models.

At least five different steady-state models have been developed and published over the past half century. These models are typically applied over a period of a year or a number of years, assuming the storage of soil water and salt does not change over the period of time in question; thus, steady-state is assumed. All of the steady-state models considered here have been directed at solving for the leaching requirement. The leaching requirement (L_r) is the smallest fraction of applied water (irrigation plus rainfall) that must drain below the crop root zone to prevent any loss in crop productivity from an excess of soluble salts. The amount of leaching necessary to satisfy the L_r depends primarily upon the salinity of the applied water and the salt tolerance of the crop. As the leaching fraction decreases, the salt concentration of the soil solution increases as crop roots extract nearly pure soil water leaving most of the salts behind. If the salt concentration in the soil exceeds the crop's salt tolerance threshold level (refer to Table 3.1), leaching is required to restore full crop productivity. Depending on the degree of salinity control required, leaching may occur continuously or intermittently at intervals of a few months to a few years. If leaching is insufficient, losses will become severe and reclamation will be required before crops can be grown economically.

All steady-state models are based upon mass balance of water and salt. Thus for a unit surface area of a soil profile over a given time interval, inflow depths of irrigation (D_i) and effective precipitation (P_e) minus outflows of crop evapotranspiration (ET_c) and drainage (D_d) must equal changes in soil water storage (ΔD_s). That is

$$\Delta D_s = D_i + P_e - ET_c - D_d = 0. \qquad \text{(Eqn. 4.1)}$$

The amount of salt leaving the soil by evapotranspiration and that applied in precipitation are negligible. Thus, the change in mass of salt stored per unit area within the root zone (ΔM_s) is given by

$$\Delta M_s = (C_i \text{ x } D_i) - (C_d \text{ x } D_d) = 0. \qquad \text{(Eqn. 4.2)}$$

The salt concentration in the irrigation water is noted as C_i and the salt concentration in the drain water is represented by C_d. Under steady-state conditions ΔD_s and ΔM_s are zero. Therefore, the leaching fraction (L) at steady-state, defined as the ratio of water leaving the root zone as drainage to that applied, $D_a = D_i + P_e$, or the ratio of salt applied to salt drained, can be expressed as was given in Equation 3.5. The leaching requirement (L_r) can be expressed as presented in Equation 3.6.

Steady-state models have been proposed to relate EC_d* to some readily available value of soil salinity that is indicative of the crop's leaching requirement. Bernstein (1964) assumed EC_d* to be the electrical conductivity of the soil saturation extract (EC_e) at which yield in salt tolerance experiments was reduced by 50 % (EC_{e50} in Figure 4.1). Bernstein and Francois (1973b) and van Schilfgaarde et al. (1974) contended that the value of EC_d* could be increased to the EC of soil water at which roots can no longer extract water. Assuming the soil water content in the field to be half of the water content of a saturated soil sample, the value of EC_d* was proposed to be twice EC_e extrapolated to zero yield from salt tolerance data ($2EC_{e0}$ in Figure 4.1). Concurrently, Rhoades (1974) proposed that EC_d* could be estimated from $EC_d^* = 5EC_{et} – EC_i$ in which EC_{et} is the salt tolerance threshold ($5EC_{et} – EC_i$ in Table 4.1). A fourth model, proposed by Rhoades and Merrill (1976) and Rhoades (1982), differentiates between infrequent and high-frequency irrigations. The model calculates soil salinity based upon a 40-30-20-10 soil water extraction pattern by successively deeper quarter-fractions of the root zone. The average soil salinity for conventional (infrequent) irrigations is taken as the linear-average of the quarter-fraction values. This is the model utilized by Ayers and Westcot (1976 and 1989). For high frequency irrigation, Rhoades assumed soil salinity is weighted by crop water-uptake.

Hoffman and van Genuchten (1983) determined the crop water-uptake weighted salinity by solving the continuity equation for one dimensional vertical flow of water through the soil assuming an exponential soil water uptake function (Exponential in Table 4.1). Their equation given as the crop water-uptake weighted salt concentration of the saturated extract (C) is given by:

$$C/C_a = 1/L + (\delta/Z \times L) \times \ln [L + (1 – L) \times \exp^{(-Z/\delta)}]. \qquad \text{(Eqn. 4.3)}$$

C_a is the salt concentration of the applied water, L is the leaching fraction, Z is the depth of the crop root zone, and δ is an empirical constant set to 0.2xZ.

The resultant mean root zone salinity (C) for any given L was reduced by the mean root zone salinity at an L of 0.5 because salt tolerance experiments were conducted at leaching fractions near to 0.5. The amount of soil salinity at a crop's salt tolerance threshold does not have to be leached. This correction results in a reasonable relationship between any given crop's salt tolerance threshold, determined at an L of about 0.5, and the salinity of the applied water as a function of L_r. The L_r based on the Hoffman and van Genuchten model can be determined from Figure 4.2 for any given EC of the applied water and the crop's salt tolerance threshold.

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

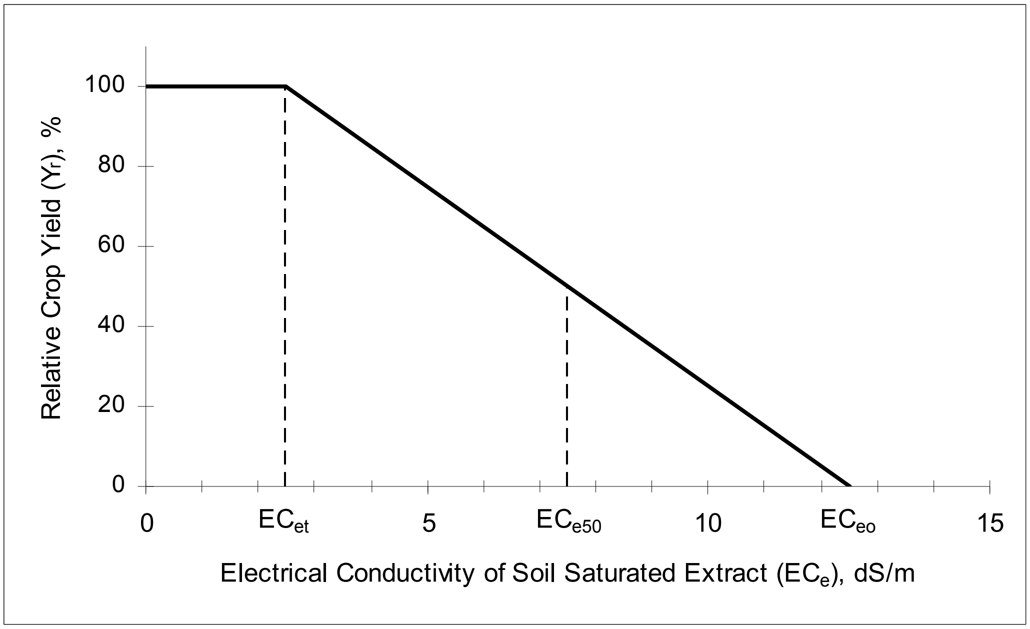
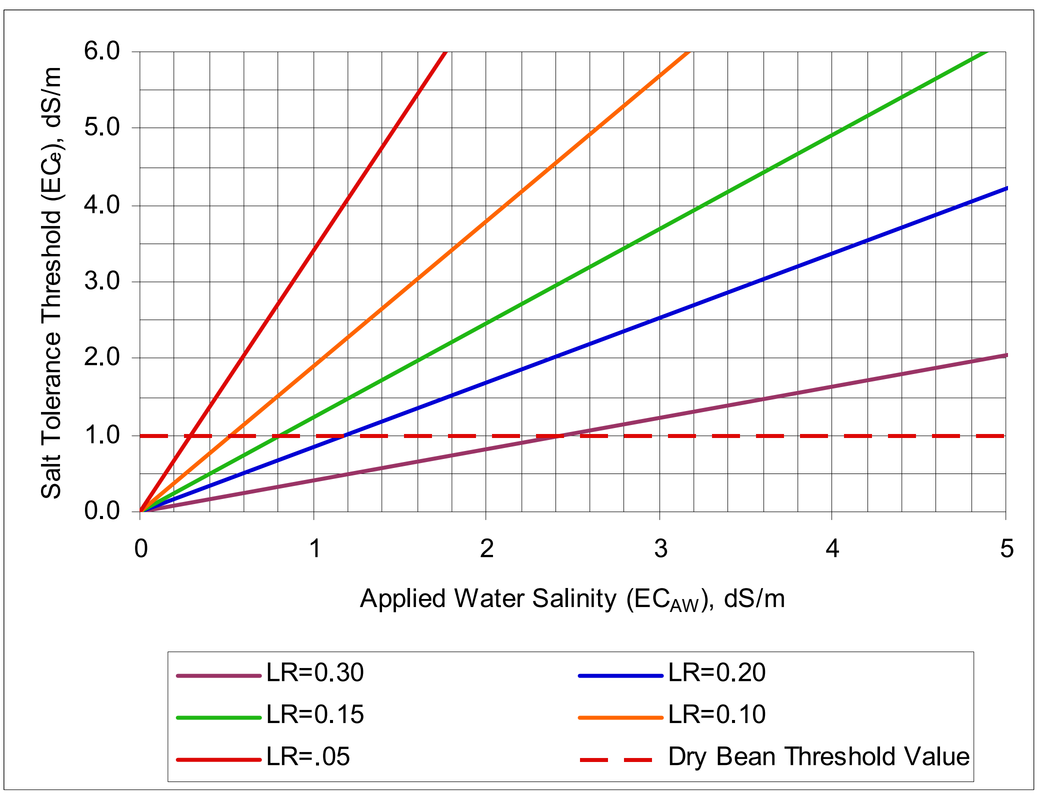


Figure 4.2. Graphical solution (using exponential plant water uptake model) for crop salt tolerance threshold (EC_e) as a function of applied water salinity (EC_{AW}) for different leaching requirements (Hoffman and Van Genuchten, 1983).



4.2. Transient Models

Transient models are designed to account for the time dependent variables encountered in the field. These variables include switching crops with different salt tolerances, variable irrigation water salinity, rainfall, timing and amount of irrigation, multiple soil layers, crop ET, initial soil salinity conditions, and other time dependent variables. Some basic concepts concerning transient models are as follows. The water flow and salt transport equations are the basic components of transient models. Water flow, which takes into account water uptake by roots, is quantified by the Darcy-Richards equation. Salt transport is calculated using the convection-dispersion equation for a non-reactive, non-interacting solute. Solving the nonlinearity of these two equations is typically accomplished by numerical methods that require high-speed computers. Beyond these two basic equations, differences among models exist to account for soil-water-plant-salinity interactions, such as water stress, bypass flow, salt precipitation/dissolution, water uptake distribution, and evapotranspiration as a function of plant size and soil salinity.

Letey and Feng (2007) listed the following factors that need to be considered when evaluating transient models for managing irrigation under saline conditions. (1) Is the appropriate water-uptake function for crops utilized? (2) Is there a feedback mechanism between the soil-water status, plant growth, and transpiration? (3) Does the model allow for extra water uptake from the non-stressed portion of the root zone to compensate for reduced water uptake from the stressed portion of the root zone? (4) Does the model account for possible salt precipitation or dissolution? (5) Have model simulations been compared to field experimental results? The inclusion of these factors in each transient model is given in the following discussion of each model.

In recent years, a number of transient models have been developed using complex computer programs for managing irrigation where salinity is a hazard. These models do not assume steady-state and frequently use daily values of applied water, drainage, and crop evapotranspiration. Four of these models, called the Grattan, Corwin, Simunek, and Letey models for short, will be discussed in terms of the principles employed, the assumptions made, the factors considered, and the conclusions drawn. Other transient models that have been proposed recently include: SALTMED (Ragab et al., 2005a,b), SWAGMAN (Khan et al., 2003), SDB (Sahni et al., 2007). These models are not considered in this report.

Grattan Model

Isidoro-Ramirez et al. (2004) and Grattan and Isidoro-Ramirez (2006) developed a model based upon the steady-state approach used by Ayers and Westcot (1976 and 1989) and it relates EC_i to the seasonal average root zone salinity. The approach assumes a leaching fraction of 0.15 to 0.2 and that the following relationships hold:

$$EC_{sw} = 3 \times EC_i$$
$$EC_e = 1.5 \times EC_i$$
$$EC_{sw} = 2 \times EC_e.$$

The model proposed by Grattan and co-workers considers the timing and quantity of applied irrigation water, the quantity and distribution of rainfall, and various soil water factors based on soil texture. Like Ayers and Westcot (1976 and 1989), they assumed a water uptake pattern of 40-30-20-10 % by quarter fractions down through the crop root zone and that the average root zone salinity could be calculated by averaging the soil-water salinity at the soil surface and at the bottom of each quarter of the root zone. A daily mass balance (water and salt) is calculated for each layer. The inputs for the first layer are applied irrigation and rainfall and the outputs are the drainage from layer 1 to layer 2 and evapotranspiration (ET) from the layer. For the underlying layers, the only input is drainage from the overlying layer and the outputs are the drainage to the underlying layer and ET from the layer. For the fourth and deepest layer, the drainage represents the total drainage from the crop root zone. Important soil properties in the model are the wilting point (WP), field capacity (FC), and total available water (TAW) for the crop (TAW = FC – WP). The evapotranspitation of the crop (ET_c) is calculated for each soil layer using appropriate crop coefficient values (K_c) and historical reference evapotranspiration (ET_o) data from Goldhamer and Snyder (1989). The achievable ET_c is calculated as $ET_c = K_c \times ET_o$. Between cropping seasons all ET (or evaporation (E) since there is no crop) is assumed to take place from the upper soil layer and bare soil surface evaporation (E_S) is assumed to be relatively constant at 0.024 in./day or 0.7 in./month(MacGillivray and Jones, 1989).

The model can be used to either quantify the extent by which an irrigation supply with a given salinity would decrease the crop yield potential under site-specific conditions or determine the maximum EC of an irrigation supply, which if used as the sole source of irrigation water over the long term, is fully protective of crop production. This model was used to evaluate site-specific conditions near Davis, CA. The specific goal was to determine the maximum EC value for Putah Creek that would protect downstream agricultural uses of the water. Bean was chosen for the analysis because it is potentially grown in the downstream area and bean is salt sensitive, having a salt tolerance threshold of EC_e = 1.0 dS/m. They concluded that protecting bean would, in turn, protect all other crops commonly grown in the area.

Isidoro-Rameriz and co-workers (2004) considered three scenarios:

1. No rainfall and an irrigation water having an EC_i of 0.7 dS/m. Without rainfall, the situation considered is similar to that of Ayers and Westcot (1989), no off-season ET was assumed.
2. Calculate the maximum EC_i to maintain EC_e less than or equal to 1 dS/m using daily rainfall for periods of record representing a five year period of low rainfall and a five year period of average rainfall.
3. Irrigation water with an EC_i of 1.1 dS/m and 1.2 dS/m over an entire 53-year record of rainfall.

The purpose of the first scenario was to compare their model with results obtained using the approach of Ayers and Westcot by assuming no rainfall. The Grattan model predicted that an EC_i of 0.7 dS/m would result in an average seasonal soil salinity (EC_e) of 0.95 dS/m compared to 1.0 dS/m by Ayers and Westcot.

The second scenario introduced rainfall while keeping all other factors and assumptions the same as for scenario 1. The dry period (1953-1957) and an average rainfall period (1963-1967) gave essentially the same results; namely that an EC_i of 1.2 dS/m gave an average seasonal soil salinity of 1.0 dS/m. They concluded that the results suggest rainfall distribution plays a significant role in determining seasonal soil salinity.

In the third scenario when an EC_i of 1.1 dS/m is considered over 53 years of rainfall record (1951 to 2003), the Grattan model predicts a seasonal mean EC_e of 0.94 dS/m. Over the 53 years of record, bean yield is predicted to be reduced during only 3 years with an EC_i of 1.1 dS/m. Yield reductions would be 2, 4, and 6 % for the 3 years. These predicted yield reductions are probably less than the error associated with the yield threshold itself. With an EC_i of 1.2 dS/m, the seasonal mean soil salinity was 1.02 dS/m, while the range in seasonal EC_e for individual years varied from 0.88 to 1.42 dS/m. For the year with an average EC_e of 1.42 dS/m, the yield reduction for bean would be 8 %.

Given these results, Grattan and co-workers concluded that an EC_i of 1.1 dS/m would be protective for bean, and thus would be protective for all other crops in the Davis area. When considering if the Grattan model satisfies the five factors given above from Letey and Feng (2007) for transient models, the model does not perform well. There does not appear to be a feedback mechanism between soil-water status, plant growth, and transpiration and the model does not consider any changes in the 40-30-20-10 pattern to compensate for changes in water availability. Furthermore, the model does not account for salt precipitation or dissolution and no field verification of the model results are presented.

Corwin Model

The TETrans model proposed by Corwin and colleagues (Corwin et al., 1991) is a functional, transient, layer-equilibrium model that predicts incremental changes over time in amounts of solute and water content occurring within the crop root zone. Transport through the root zone is modeled as a series of events or processes within a finite collection of discrete depth intervals. The sequential events or processes include infiltration of water, drainage to field capacity, plant water uptake resulting from transpiration, and/or evaporative losses from the soil surface. Each process is assumed to occur in sequence within a given depth interval as opposed to reality where transport is an integration of simultaneous processes. Other assumptions include: (1) the soil is composed of a finite series of discrete depth intervals with each depth interval having homogeneous properties, (2) drainage occurs through the profile to a depth-variable field capacity water content, (3) the depletion of stored water by evapotranspiration within each depth increment does not go below a minimum water content that will stress the plant, (4) dispersion is either negligible or part of the phenomenon of bypass flow, and (5) upward or lateral water flow does not occur.

Included within the Corwin model is a simple mechanism to account for bypass (preferential) flow of applied water. Bypass is approximated using a simple mass-balance approach by assuming that any deviation from piston flow for the transport of a conservative solute is due to bypass flow (Corwin et al., 1991).

With respect to satisfying the five factors proposed by Letey and Feng (2007), this model performs well. The soil profile is divided into many depth intervals so ET can be considered for many soil depth intervals. There is a feedback mechanism to prevent transpiration to go below a water content that would stress the plant. The model does not account for salt precipitation/dissolution but it does consider bypass flow. The model was tested using data from the Imperial Valley of California.

Simunek Model

Simunek and co-workers developed a sophisticated mechanistic, numerical model called UNSATCHEM. This model simulates the flow of water in unsaturated soils, along with transport and chemical reactions of solutes, and crop response to salinity (Simunek and Suarez, 1994). The model has submodels accounting for major ion chemistry, crop response to salinity, carbon dioxide (CO_2) production and transport, time-varying concentration in irrigated root zones, and the presence of shallow groundwater. The variably-saturated water flow is described using the Richard's equation and the transport of solutes and CO_2 is described using the convection-dispersion equation. Root growth is estimated by using the logistic growth function and root distribution can be made user-specific. Precipitation, evapotranspiration, and irrigation fluxes can be specified at any user-defined time interval.

While the model was not developed to determine the L_r, it can be altered to do so by determining the minimum L that can be used under a specified set of soil, crop, and management conditions while preventing losses in crop yield. The UNSATCHEM model does not account for bypass flow but the complex transient chemical processes included are salt precipitation and/or dissolution, cation exchange, and complexation reactions as influenced by the CO_2 composition of the soil air, which largely controls the soil pH, as well as sulfate ion association, which affects the solubility of gypsum.

The Simunek model satisfies the first and fourth factor listed by Letey and Feng (2007), but it does not adjust the potential ET to account for reduced plant growth in response to water stress, nor does it provide increased water uptake from non-stressed portions of the root zone to compensate for decreased water uptake from stressed portions. Comparisons between model-simulated crop yield and experimentally measured crop yield has been reported for California's Imperial Valley.

Letey Model

Letey and co-worker developed a transient model called ENVIRO-GRO (Pang and Letey, 1998). The Letey model uses the Darcy-Richards equation to account for water flow. This equation has a term to quantify water uptake by roots. In comparing water uptake functions, Cardon and Letey (1992) concluded that the equation

$$S = S_{max} / 1 + [(ah + \pi) / \pi 50]^3 \qquad \text{(Eqn. 4.4)}$$

was the best water uptake function to use in their model. The factors in equation 4.4 are: S is the root water uptake, S_{max} is the maximum water uptake by a plant that is not stressed (potential transpiration), a accounts for the differential response of the crop to matrix and osmotic pressure head influences and is equal to the ratio of π50 and h50 where 50 represents the values at which S_{max} is reduced by 50 %, h is the soil-water pressure head, and π is the osmotic pressure head. This model satisfies all of the factors listed by Letey and Feng (2007) except it does not account for salt precipitation/dissolution. Model simulations on corn yield agreed well with experimental data from an extensive field experiment conducted in Israel (Feng et al., 2003). The model has recently been converted from a combination of several computer programs to the C++ program.

4.3. Comparison of Leaching Requirement Models

Hoffman (1985) compared the five steady-state models described above with results from seven independent experiments conducted to measure the leaching requirement of 14 crops with irrigation waters of different salt concentrations. Bower, Ogata, and Tucker (1969 and 1970) studied alfalfa, tall fescue, and sudan grass. Hoffman and colleagues experimented on barley, cowpea, and celery (Hoffman and Jobes, 1983); oat, tomato, and cauliflower (Jobes, Hoffman, and Wood, 1981); and wheat, sorghum, and lettuce (Hoffman, et al., 1979). Bernstein and Francois (1973b) studied alfalfa and Lonkerd, Donovan, and Williams (1976, unpublished report) experimented on wheat and lettuce. Comparisons between measured and predicted leaching requirements by these five steady-state models are given in Table 4.1.

The EC_{e50} model consistently over estimated the L_r while the $2EC_{e0}$ model consistently under estimated. The $5EC_{et}$-EC_i model gave reasonable estimates at low leaching requirements, but over estimated severely at high leaching requirements. The exponential model correlated best with measured values of L_r but under estimated high measured values of the L_r.

One of the main conclusions of Letey and Feng (2007) was that steady-state analyses generally over predict the negative consequences of irrigating with saline waters. In other words, the L_r is lower than that predicted by steady-state models. Letey (2007) made a comparison among steady-state models and concluded that the highest L_r was calculated with linear averaged soil salt concentrations, intermediate L_r values occurred with the $5EC_{et}$-EC_i model, and the lowest L_r was found with the water-uptake weighted soil salt concentrations, the exponential model. This is confirmation that if a steady model is to be used to evaluate a water quality standard, the exponential model is the closest to the results from a transient model like the ENVIRO-GRO transient model proposed by Letey (2007).

Table 4.1. Comparisons of leaching requirement (L_r) predicted by five steady-state models with experimentally measured leaching requirements for 14 crops with various saline irrigation waters (Hoffman, 1985).

	Data		L_r Prediction Using				
Crop	L_r	EC_i	EC_{e50}	$2EC_{e0}$	$5EC_{et}$-EC_i	40-30-20-10	Exp.
CEREALS							
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
VEGETABLES							
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
FORAGES							
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

Corwin and coworkers compared the Corwin and Simunek transient models along with the $5EC_{et}$-ECi and the WATSUIT steady-state computer models (Corwin et al., in press). For their comparative analysis they selected a set of realistic conditions representative of California's Imperial Valley. Details describing the development of the data set from available data sources can be found in Corwin et al. (2007). To estimate the L_r for the entire Imperial Valley they choose a single crop rotation that would be representative of the Valley. From available records, it was found that the dominant crops grown in the Valley during the period 1989-1996 were field crops with alfalfa as the most dominant followed by wheat. Lettuce was the most dominant truck crop. Thus, they choose a 6-year crop rotation of four years of alfalfa, followed by one year of wheat and one year of lettuce. The EC of the irrigation water was taken as 1.23 dS/m (Colorado River water). ET_c values for alfalfa, wheat, and lettuce were assumed to be 5273 (4-year total), 668, and 233 mm, respectively. Additional irrigation water was added to compensate for E during the fallow periods and for the depletion of soil water that occurred during cropping. Table 4.2 summarizes the L_r predicted by the four methods.

Table 4.2. Summary of leaching requirements (L_r) for California's Imperial Valley 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.*

Using the area of every crop and an estimate of the L_r for each crop by the $5EC_{et}$-EC_i model to obtain a valley-wide L_r based on the weighted average of the crop areas and the leaching requirements, Jensen and Walter (1998) obtained a L_r value of 0.14 for the Imperial Valley. In comparison, field studies by Oster et al. (1986) showed a similar steady-state estimate of L_r of 0.12. The L_r value obtained from Corwin et al. (2007) as described above was 0.13. The three results are essentially the same.

The conclusions drawn by Corwin et al. (2007) are summarized in this paragraph. Based on the results presented in Table 4.2, they noted that steady-state models over-estimated L_r compared to transient models, but only to a minor extent. The estimates of L_r were significantly reduced when the effect of salt precipitation with Colorado River water was included in the salt-balance calculations, regardless of whether the model was steady-state (WATSUIT) or transient (UNSATCHEM). The small differences in the estimated L_r between WATSUIT and UNSATCHEM shows that accounting for salt precipitation under the conditions of the Imperial Valley was more important than whether the model was a steady-state or transient model. This comparison suggests that there are instances where steady-state models can be used as long as the steady-state model accounts for all the dominant mechanisms such as bypass flow, salt precipitation/dissolution reactions, plant water uptake, and perhaps other factors that are affecting the leaching of salts and that few or no perturbations have occurred over a long time period that would prevent essentially steady-state conditions. For instance, in situations where salt precipitation/dissolution reactions are dominant and temporal dynamic effects are minimal, L_r could be adequately estimated using WATSUIT. Or, in situations where irrigation water quality and amount minimizes the temporal dynamic effects of plant water uptake, L_r could be adequately estimated by the exponential model.

Letey and Feng (2007) compared the $5EC_{et}$-EC_i steady-state model and the ENVIRO-GRO model using inputs from an Israeli field experiment on corn (Feng et al., 2003) for yields of 85, 90, 95, and 100%. Only the results for 100 % yield are given in Table 4.3. The transient model estimates a lower L_r than the steady-state model. The primary reason for the over estimate of the L_r is that the $5EC_{et}$-EC_i model assumes that the plants response to the linear average root zone salinity.

Table 4.3. Comparison of the calculated leaching requirement for a steady-state model and the ENVIRO-GRO model based on the Israeli field experiment on corn (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

Strong evidence that the water quality standard could be raised was presented by Letey (2007) based upon his comparisons between steady-state and transient models. The following is nearly a direct quote from his publication. The reasons that the transient-state analysis simulated a much lower irrigation amount than the steady-state approach for a given yield (see Table 4.3) are as follows: The steady-state approach assumed that the plant responded to the average root zone salinity that increased greatly as the L decreased. However the major amount of water is extracted by plant roots from the upper part of the root zone. Furthermore, the salt concentration at a given depth in the field does not remain constant with time, but is continually changing. The salts become concentrated by water extraction, but the irrigation water "flushes" the salts downward thus reducing the concentration to a lower value at a given depth after irrigation. The concentration immediately after irrigation near the soil surface would be close to the concentration in the irrigation water. For most soils, the volumetric soil-water content would be reduced by less than half between irrigations. (The practice of irrigating when half of the soil water available to the plant has been extracted is a very typical irrigation practice.) Thus the salts would concentrate by less than two between irrigations. Therefore as a general guideline, a water with a salt concentration equal to the Maas and Hoffman threshold value (see Table 3.1) can be used and irrigated with a relatively low L. This conclusion is based on the fact that the Maas and Hoffman coefficients are on the basis of EC_e which is about $EC_{sw}/2$. The soil-water can therefore be concentrated by a factor of two without exceeding the threshold value.

Based upon Letey's reasoning, the water quality standard could be raised to 1.0 dS/m. This is predicated on the salt tolerance of bean being selected to protect all crops in the South Delta. Since the salt tolerance threshold for bean is 1.0 dS/m the water quality standard could be 1.0 dS/m.

5. Steady-State Modeling for South Delta

5.1. Model Description

5.1.1. Steady-State Assumptions

The model, developed specifically for the South Delta, begins with the steady-state equations presented in Section 4.1. At steady state the inputs of irrigation (I) and precipitation (P) must equal crop evapotranspiration (ET_c) plus drainage (D) (see Equation 4.1 presented as depths of water). Furthermore, the amount of salt entering the crop root zone must equal the amount leaving (refer to Equation 4.2). The time frame chosen for the model is yearly and the inputs and outputs are annual (water year, October 1st through September 30th) amounts. Being a steady-state model, changes in soil water storage and salt mass are assumed to not change from one year to the next. Also the model is not capable of determining intra-seasonal salinity or double or inter-row cropping. These modeling deficiencies, however, can be addressed by using transient models.

5.1.2. Cropping Assumptions

Bean is the most salt sensitive crop grown in the South Delta. Thus, bean was used as the indicator crop in the model. The salt tolerance threshold for bean is an EC_e of 1.0 dS/m (refer to Table 3.1). In the model the salinity of the soil water (EC_{sw}) is used. Thus, for ease in comparison, the threshold value for bean is an EC_{sw} of 2.0 dS/m. This assumes the relationship $EC_{sw} = 2 \times EC_e$.

Based upon the publication of Goldhamer and Snyder (1989), beans in the San Joaquin Valley are planted from April 1 until as late as mid-June and harvested as early as the end of July until the end of September. For modeling purposes in this report, it is assumed that beans are planted the first of April and harvested at the end of July. If desired, other planting and harvesting dates could be modeled. For ease in calculations in the model it is assumed that there is no double cropping and that the soil surface is bare from August 1 until April 1. The model could be used to evaluate a multi-year crop rotation if desired.

5.1.3. Crop Evapotranspiration

Crop water requirements are normally expressed as the rate of evapotranspiration (ET_c). The level of ET_c is related to the evaporative demand of the air above the crop canopy. The evaporative demand can be expressed as the reference evapotranspiration (ET_o) which predicts the effect of climate on the level of crop evapotranspiration of an extended surface of a 4 to 6 inch-tall cool season grass, actively growing, completely shading the ground, and not short of water.

One of the more simple and accurate equations to estimate ET_o is the Hargreaves equation (Hargreaves and Allen, 2003). The equation can be written as

$$ET_o = 0.0023 \times R_a \times (TC + 17.8) \times TR^{0.50} \qquad \text{(Eqn. 5.1)}$$

Where R_a is the extraterrestrial radiation, TR is the difference between the mean maximum and minimum daily temperatures in degrees Celsius, and TC is the temperature in degrees Celsius for a 5-day time step.

Values of ET_o are calculated with the Hargreaves equation using temperature data from the National Climate Data Center (NCDC) station #8999 (Tracy-Carbona) and then compared with ET_o calculated by the Penman-Montheith equation based upon data collected at the California Irrigation Management Information System (CIMIS) station #70 near Manteca in Figure 5.1. The Penman-Montheith equation is generally considered the most comprehensive and accurate equation to estimate ET_o. However, the CIMIS station has a short historical record compared to the 56 years of temperature and precipitation data at the NCDC Tracy-Carbona station. The longer historical record is used in our steady-state analysis; thus, the Hargreaves equation was employed in the model for the years 1952 to 2008. The data in Figure 5.1 shows excellent agreement between the Hargreaves and the Penman-Montheith equations. This excellent comparison validates the use of the Hargreaves equation. Figure 5.2 shows the location of the NCDC #8999, Tracy-Carbona and CIMIS #70 Manteca stations.

Figure 5.1. Monthly reference evapotranspiration (ET_O) calculated with the Hargreaves equation plotted against CIMIS ET_O calculations with the Penman-Montheith equation; using Manteca CIMIS #70 climate data from January 1988 through September 2008.

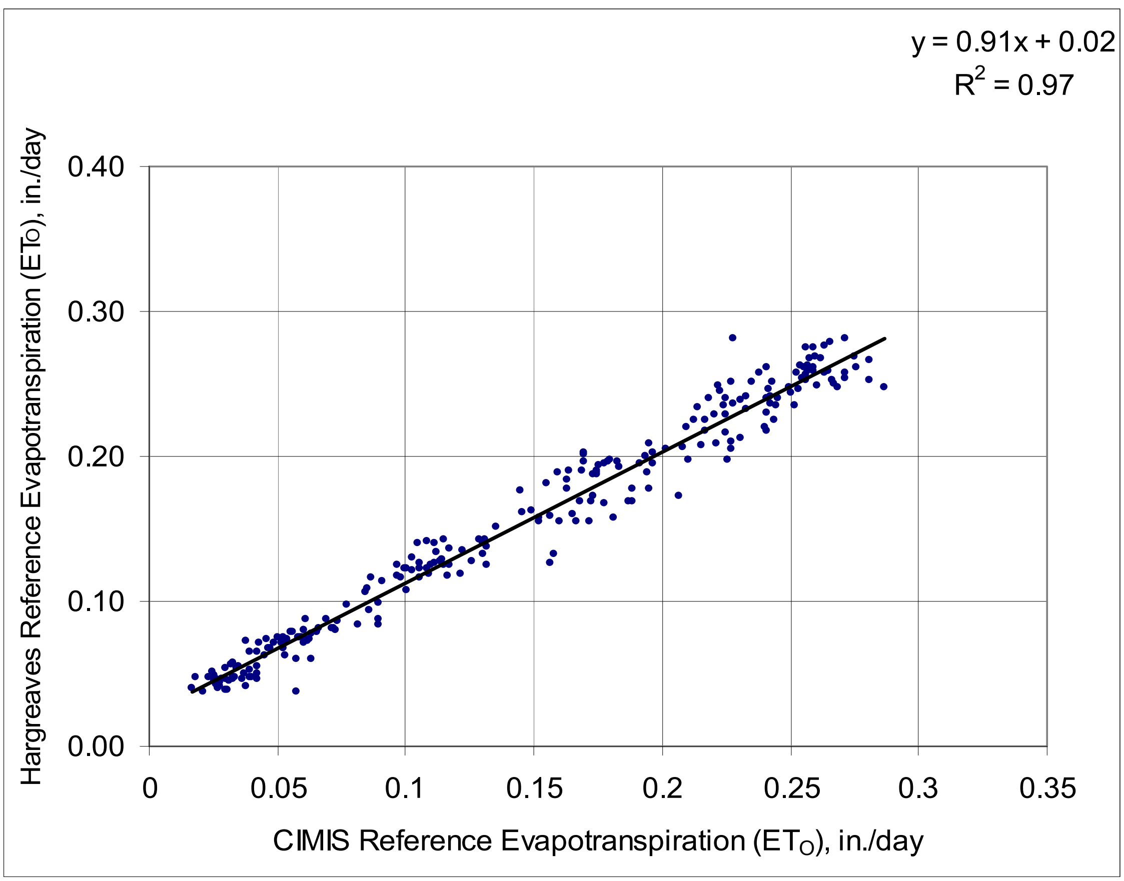
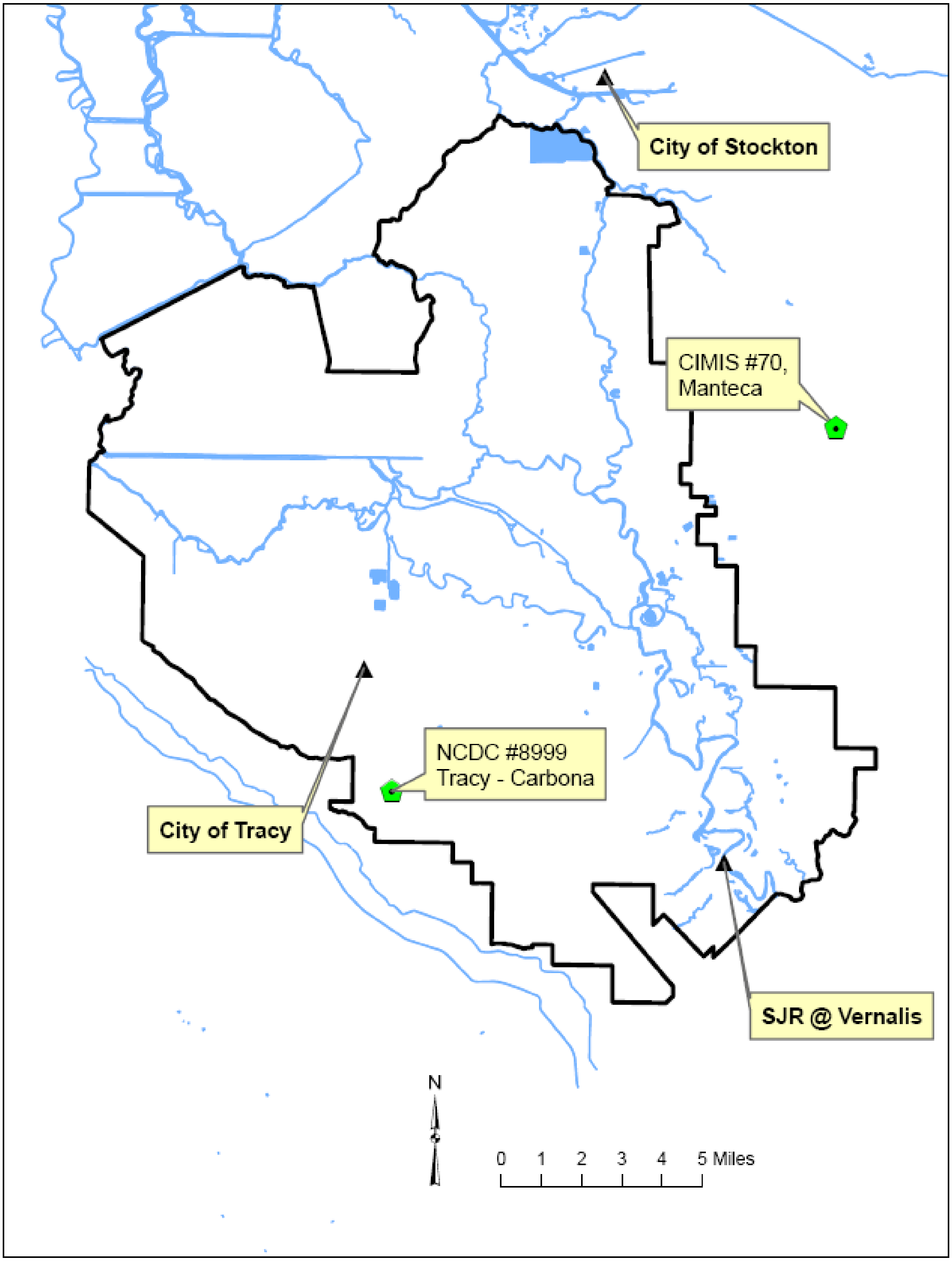


Figure 5.2. Location map for NCDC #8999, Tracy-Carbona and CIMIS #70 Manteca weather stations.

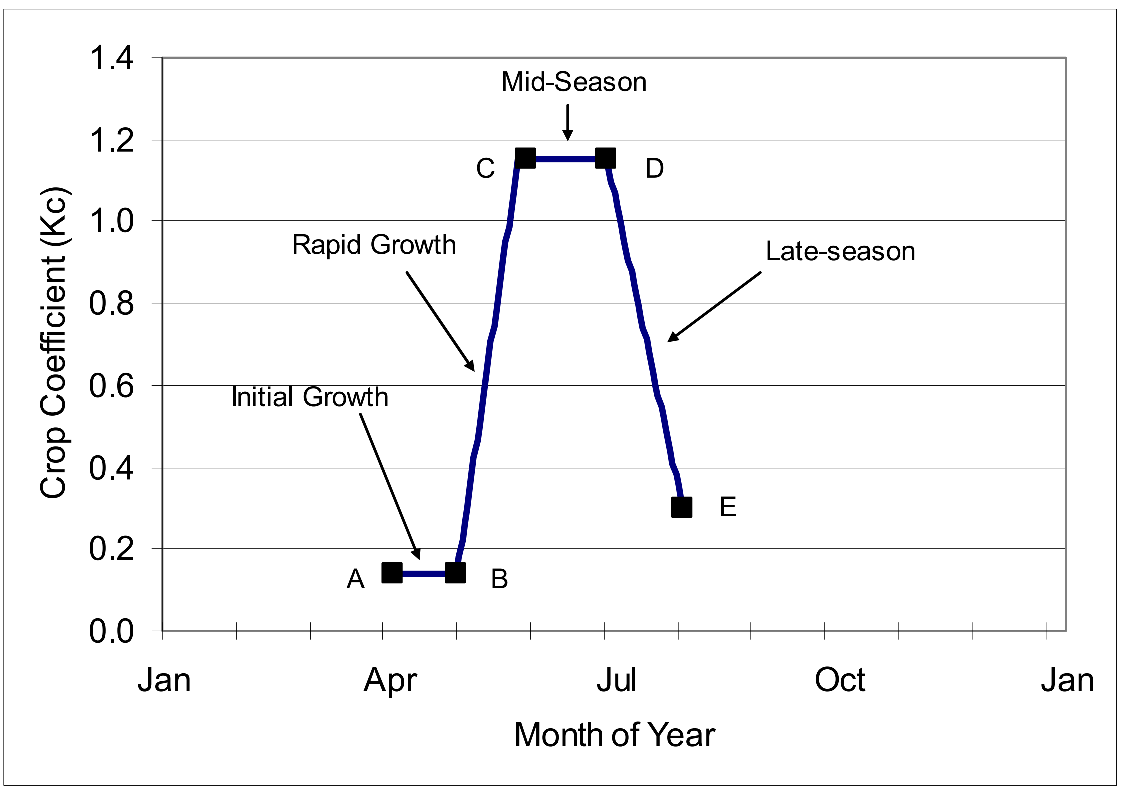


The evapotranspiration of a crop (ET_c) can be estimated by multiplying the ET_o value by a crop coefficient (K_c) that accounts for the difference between the crop and cool-season grass. A crop coefficient actually varies from day to day depending on many factors, but it is mainly a function of crop growth and development. Thus, K_c values change as foliage develops and as the crop ages. Crop growth and development rates change somewhat from year to year, but the crop coefficient corresponding to a particular growth stage is assumed to be constant from season to season. Daily variations in ET_c reflect changes in ET_o in response to evaporative demand. The equation to calculate crop evapotranspiration is

$$ET_c = K_c \times ET_o. \qquad \text{(Eqn. 5.2)}$$

The crop coefficient is typically divided into four growth periods as shown in Figure 5.3 (Goldhamer and Snyder, 1989). The four growth periods for annual crops are initial growth, rapid growth, midseason, and late season. Growth is reflected by the percentage of the ground surface shaded by the crop at midday. For annual crops, the K_c dates correspond to: A, planting; B, 10 % ground shading; C, 75 % or peak ground shading; D, leaf aging effects on transpiration; and E, end of season. Figure 5.3 shows the K_c values for bean and the dates when each growth stage changes. Table 5.1 shows ET_C for bean based on ET_O calculated by the Hargreaves equation using temperature data from NCDC station #8999, Tracy-Carbona along with precipitation data from water years 1952 to 2008.

Figure 5.3. Relationship between crop coefficients (K_C) and growth and development periods for dry bean (Goldhammer and Snyder, 1989).

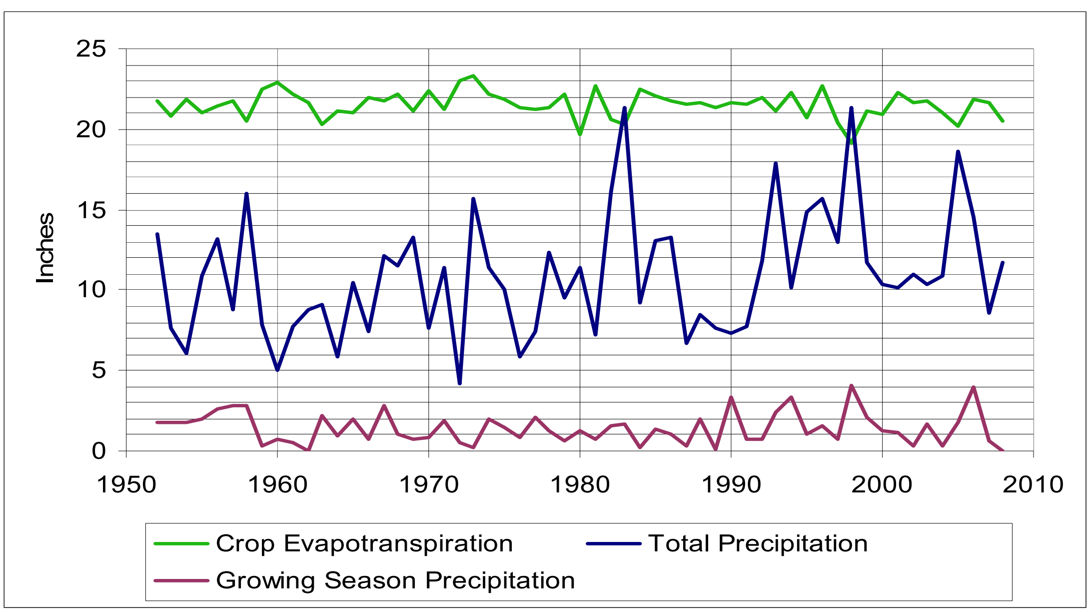


5.1.4. Precipitation

To maximize the time period for the model, precipitation records were taken from the NDCD at the Tracy-Carbona Station. Rainfall records are presented by water years (October of previous year through September of the stated water year) from 1952 through 2008. The rainfall amounts were divided between the amount during the growing season from April 1 to August 1 (P_{GS}) and the remainder of the year (P_{NG}). It was assumed that all rainfall occurring during the growing season was consumed by evapotranspiration. The reasons for this assumption are given in Section 3.5.2. The amount of rainfall during the growing season (P_{GS}) never exceeded 4.1 inches and the median was only 1.2 inches over the 56 years of rainfall record. Thus, if some runoff occurred it would generally be insignificant.

During the non-growing season the rate of surface evaporation (E_s) was taken as 0.7 inches per month as discussed in Section 3.5.2. This value was also used in the Grattan model for the watershed near Davis, CA. For bean with a 4-month growing season, surface evaporation (E_S) would total 5.6 inches for the 8 months of the year without a crop. On a yearly basis, the evapotranspiration for bean was added to the 5.6 inches of E_s to obtain one of the outputs from the root zone. The values for ET_C, P_{GS}, and P_T are plotted in Figure 5.4 and listed in Table 5.1 for water years 1952 to 2008. P_{EFF} is P_{GS} + (P_{NG} - E_S) and is also listed in Table 5.1. P_{GS} is taken as contributing to ET_C and P_{NG} is reduced annually by E_S or 5.6 inches per year. As reported in Table 5.1, and shown earlier in Figure 3.11, in only 2 years of the 56 years of record was P_{EFF} negative (1960 and 1972) which means that stored water had to be used to satisfy E_S. Surface runoff was assumed to be zero for the reasons stated in Section 3.5.2. Thus, all of the precipitation and irrigation is assumed to infiltrate the soil surface and be available for surface evaporation, crop evapotranspiration, or leaching.

Figure 5.4. Comparison of total precipitation (P_T) and growing season precipitation (P_{GS}) with crop evapotranspiration (ET_C) based on precipitation data from NCDC station no. 8999, Tracy-Carbona for water years 1952 through 2008.



As discussed in Sections 3.9 and 4.1, there are two crop water uptake distributions that appear to be appropriate to calculate the average soil salinity. One distribution assumes a 40-30-20-10 uptake distribution by quarter fractions of the root zone and the other assumes an exponential uptake distribution. These patterns are described in detail in Section 3.9. Although the exponential pattern agrees the best with experimental results (see Section 4.1), both are used in this model because the 40-30-20-10 pattern is used in several models.

The equations used in the model to calculate the average EC_{SW} for both water uptake distributions are given in Table 5.2. Both equations use EC_i when precipitation is ignored and EC_{AW} when rainfall is considered.

5.2. Model Results

An example of the calculated irrigation amounts and the soil water salinity values for 56 water years is given in Table 5.1. Values are presented for both water uptake distributions with and without precipitation. The example is for model input variables of EC_i = 1.0 dS/m and LF = 0.15. The input values for total, growing season, and nongrowing season precipitation, off season evaporation, and crop evapotranspiration for the 56 water years are also given in Table 5.1. The model was run over a range of EC_i values from 0.5 to 2.0 dS/m, with LF = 0.15 and 0.20. The corresponding results are shown in Figures 5.5 and 5.6. Other combinations of ECi and LF can be calculated as desired.

Results from the model for both water uptake distributions at leaching fractions of 0.15 and 0.20 are shown in Figure 5.5. First, the average of the lines for LF=0.15 and 0.20 the 40-30-20-10 approach without precipitation shows that an ECi of about 0.7 dS/m could be used without bean yield loss. This is in agreement with the analysis of Ayers and Westcott (1977). When considering precipitation with the 40-30-20-10 approach, EC_i increases to 0.77 dS/m at LF=0.15 and 0.92 dS/m for a LF of 0.2 as the threshold.

The model results for the exponential water uptake distribution gives a permissible EC_i of 0.80 dS/m at a LF of 0.15 ignoring precipitation without bean yield loss. Considering precipitation at a LF of 0.15, EC_i at the bean threshold is 1.0 dS/m. EC_i using the exponential model could be increased even further if the leaching fraction is increased to 0.2 without loss of bean yield.

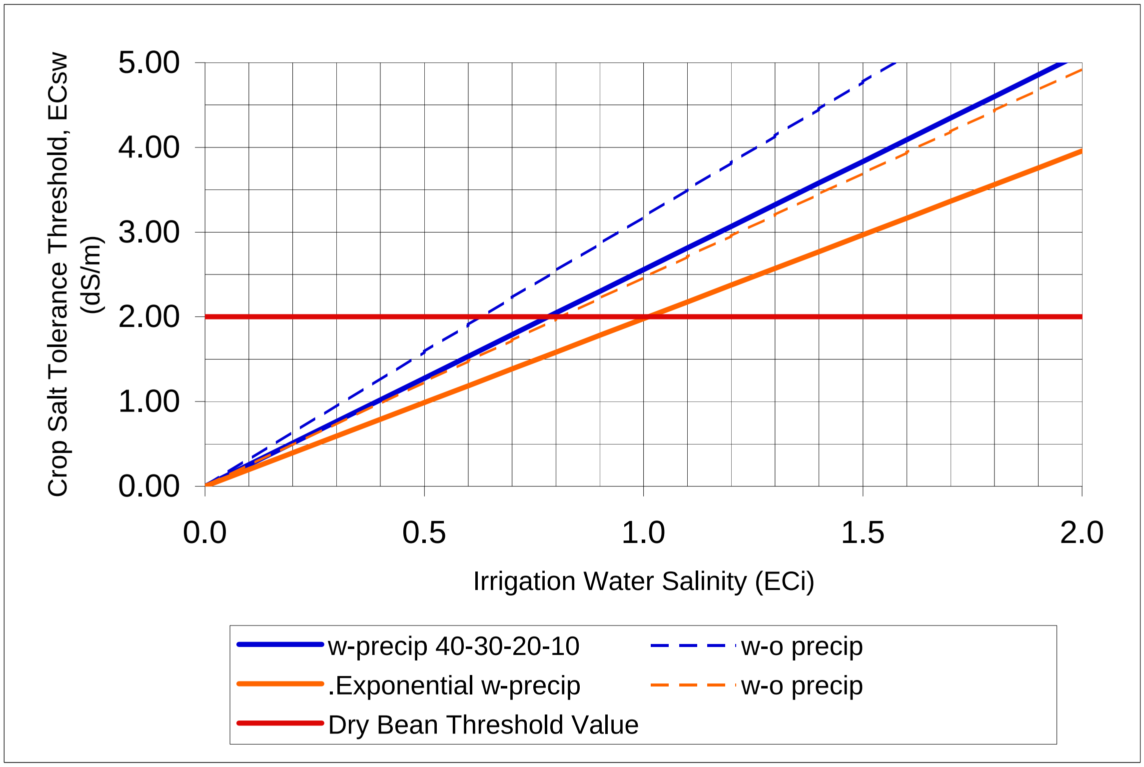
These results are shown in a different manner in Figure 5.6. In this figure bean yield on a relative basis is shown as a function of irrigation water salinity. The dashed lines assume no precipitation and the solid lines include average precipitation. The values of EC_i at the yield threshold are the same as in Figure 5.5 but as EC_i increases beyond the threshold the rate of yield decline is shown. Values are given for LF values of 0.15 and 0.20.

Table 5.1. Input variables (precipitation data from NCDC Tracy-Carbona Station #8999, estimates of surface evaporaton, and crop evapotranspiration assuming dry beans), and output from the steady-state model both 1) without precipitation, and 2) including precipitation (all equations defined in Table 5.2).

Input Variables							Model Output						
							EC_i = 1.0			LF = 0.15			
							1) without precipitation			2) with precipitation			
Water Year	P_T (in.)	P_{NG} (in.)	E_S (in.)	P_{GS} (in.)	P_{EFF} (in.)	ET_C (in.)	I_1 (in.)	EC_{SWa-1} (dS/m)	EC_{SWb-1} (dS/m)	I_2 (in.)	EC_{AW-2} (dS/m)	EC_{SWa-2} (dS/m)	EC_{SWb-2} (dS/m)
1952	13.5	11.7	5.6	1.8	7.9	21.8	25.6	3.18	2.46	17.7	0.69	2.20	1.70
1953	7.6	5.8	5.6	1.8	2.0	20.8	24.5	3.18	2.46	22.5	0.92	2.92	2.26
1954	6.1	4.3	5.6	1.8	0.5	21.9	25.7	3.18	2.46	25.3	0.98	3.12	2.42
1955	10.9	8.9	5.6	2.0	5.3	21.0	24.8	3.18	2.46	19.5	0.79	2.50	1.94
1956	13.2	10.6	5.6	2.6	7.5	21.4	25.2	3.18	2.46	17.7	0.70	2.23	1.73
1957	8.8	6.0	5.6	2.8	3.2	21.8	25.6	3.18	2.46	22.4	0.87	2.78	2.15
1958	16.0	13.2	5.6	2.8	10.4	20.5	24.2	3.18	2.46	13.7	0.57	1.81	1.40
1959	7.9	7.5	5.6	0.3	2.3	22.5	26.5	3.18	2.46	24.2	0.91	2.91	2.25
1960	5.1	4.4	5.6	0.7	-0.5	22.9	26.9	3.18	2.46	27.5	1.02	3.25	2.51
1961	7.8	7.2	5.6	0.5	2.2	22.2	26.1	3.18	2.46	24.0	0.92	2.92	2.26
1962	8.7	8.7	5.6	0.0	3.1	21.6	25.5	3.18	2.46	22.3	0.88	2.79	2.16
1963	9.1	6.8	5.6	2.2	3.5	20.3	23.9	3.18	2.46	20.4	0.85	2.72	2.10
1964	5.9	5.0	5.6	0.9	0.3	21.1	24.8	3.18	2.46	24.5	0.99	3.15	2.43
1965	10.5	8.4	5.6	2.0	4.9	21.1	24.8	3.18	2.46	19.9	0.80	2.56	1.98
1966	7.5	6.7	5.6	0.8	1.9	22.0	25.8	3.18	2.46	24.0	0.93	2.95	2.28
1967	12.2	9.4	5.6	2.8	6.6	21.8	25.6	3.18	2.46	19.1	0.74	2.37	1.83
1968	11.5	10.5	5.6	1.0	5.9	22.2	26.1	3.18	2.46	20.2	0.77	2.47	1.91
1969	13.2	12.5	5.6	0.7	7.6	21.1	24.9	3.18	2.46	17.2	0.69	2.20	1.70
1970	7.6	6.8	5.6	0.8	2.0	22.3	26.3	3.18	2.46	24.3	0.92	2.94	2.27
1971	11.4	9.6	5.6	1.8	5.8	21.3	25.0	3.18	2.46	19.2	0.77	2.44	1.89
1972	4.2	3.7	5.6	0.6	-1.4	23.0	27.1	3.18	2.46	28.5	1.05	3.35	2.59
1973	15.7	15.5	5.6	0.2	10.1	23.4	27.5	3.18	2.46	17.3	0.63	2.01	1.55
1974	11.4	9.4	5.6	2.0	5.8	22.2	26.1	3.18	2.46	20.3	0.78	2.47	1.91
1975	10.0	8.5	5.6	1.5	4.4	21.9	25.8	3.18	2.46	21.4	0.83	2.64	2.04
1976	5.8	5.0	5.6	0.8	0.2	21.4	25.1	3.18	2.46	24.9	0.99	3.15	2.44
1977	7.4	5.3	5.6	2.1	1.8	21.3	25.0	3.18	2.46	23.2	0.93	2.95	2.29
1978	12.3	11.1	5.6	1.2	6.7	21.3	25.0	3.18	2.46	18.3	0.73	2.33	1.80
1979	9.6	8.9	5.6	0.6	4.0	22.1	26.1	3.18	2.46	22.1	0.85	2.70	2.09
1980	11.4	10.1	5.6	1.2	5.8	19.7	23.2	3.18	2.46	17.4	0.75	2.39	1.85
1981	7.2	6.5	5.6	0.7	1.6	22.7	26.7	3.18	2.46	25.1	0.94	2.99	2.31
1982	16.2	14.5	5.6	1.6	10.6	20.6	24.3	3.18	2.46	13.7	0.57	1.80	1.39
1983	21.3	19.6	5.6	1.7	15.7	20.3	23.9	3.18	2.46	8.2	0.34	1.09	0.84
1984	9.2	9.0	5.6	0.2	3.6	22.5	26.5	3.18	2.46	22.9	0.86	2.75	2.13
1985	13.1	11.7	5.6	1.4	7.5	22.1	25.9	3.18	2.46	18.5	0.71	2.27	1.75
1986	13.3	12.2	5.6	1.0	7.7	21.8	25.6	3.18	2.46	18.0	0.70	2.23	1.73
1987	6.7	6.4	5.6	0.3	1.1	21.5	25.3	3.18	2.46	24.2	0.96	3.04	2.36
1988	8.4	6.5	5.6	2.0	2.8	21.7	25.5	3.18	2.46	22.7	0.89	2.83	2.19
1989	7.7	7.6	5.6	0.1	2.1	21.4	25.1	3.18	2.46	23.1	0.92	2.92	2.26
1990	7.3	4.0	5.6	3.3	1.7	21.6	25.5	3.18	2.46	23.7	0.93	2.97	2.29
1991	7.7	7.0	5.6	0.7	2.1	21.6	25.4	3.18	2.46	23.3	0.92	2.92	2.26
1992	11.8	11.1	5.6	0.7	6.2	22.0	25.9	3.18	2.46	19.7	0.76	2.42	1.87
1993	17.9	15.5	5.6	2.4	12.3	21.2	24.9	3.18	2.46	12.6	0.50	1.61	1.24
1994	10.1	6.8	5.6	3.3	4.5	22.3	26.2	3.18	2.46	21.7	0.83	2.63	2.04
1995	14.9	13.8	5.6	1.1	9.3	20.7	24.3	3.18	2.46	15.0	0.62	1.97	1.52
1996	15.7	14.1	5.6	1.6	10.1	22.7	26.8	3.18	2.46	16.7	0.62	1.98	1.53
1997	12.9	12.2	5.6	0.7	7.3	20.4	24.0	3.18	2.46	16.7	0.69	2.21	1.71
1998	21.4	17.3	5.6	4.1	15.8	19.2	22.6	3.18	2.46	6.8	0.30	0.95	0.74
1999	11.7	9.6	5.6	2.1	6.1	21.1	24.8	3.18	2.46	18.7	0.75	2.40	1.86
2000	10.4	9.2	5.6	1.2	4.8	21.0	24.7	3.18	2.46	19.9	0.81	2.56	1.98
2001	10.1	9.0	5.6	1.1	4.5	22.3	26.2	3.18	2.46	21.7	0.83	2.63	2.04
2002	11.0	10.7	5.6	0.3	5.4	21.6	25.5	3.18	2.46	20.1	0.79	2.51	1.94
2003	10.3	8.7	5.6	1.6	4.7	21.8	25.6	3.18	2.46	20.9	0.82	2.59	2.01
2004	10.9	10.5	5.6	0.3	5.3	21.1	24.8	3.18	2.46	19.5	0.79	2.51	1.94
2005	18.6	16.8	5.6	1.8	13.0	20.2	23.7	3.18	2.46	10.7	0.45	1.43	1.11
2006	14.6	10.6	5.6	4.0	9.0	21.9	25.7	3.18	2.46	16.8	0.65	2.07	1.60
2007	8.6	7.9	5.6	0.6	3.0	21.7	25.5	3.18	2.46	22.6	0.88	2.81	2.18
2008	11.7	11.7	5.3	0.0	6.4	20.5	24.1	3.18	2.46	17.8	0.74	2.34	1.81
Median:	10.5	9.0	5.6	1.2	4.9	21.6	25.5	3.18	2.46	20.2	0.80	2.56	1.98

Figure 5.5. Crop salt tolerance threshold as a function of irrigation water salinity (EC_i) using exponential and 40-30-20-10 water uptake functions with a) LF = 0.15 and b) LF = 0.20 assuming median effective precipitation from NCDC station no. 8999, Tracy-Carbona - water years 1952 through 2008 (solid lines) and no precipitation (dashed lines).

a) LF = 0.15



b) LF = 0.20

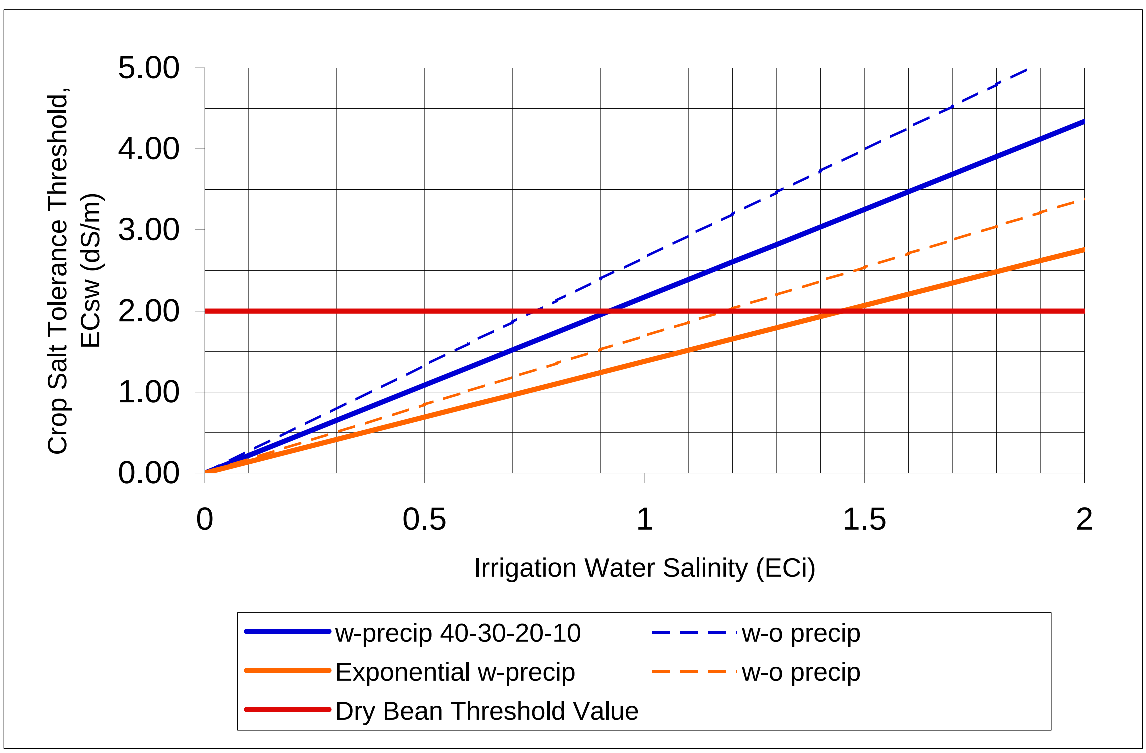
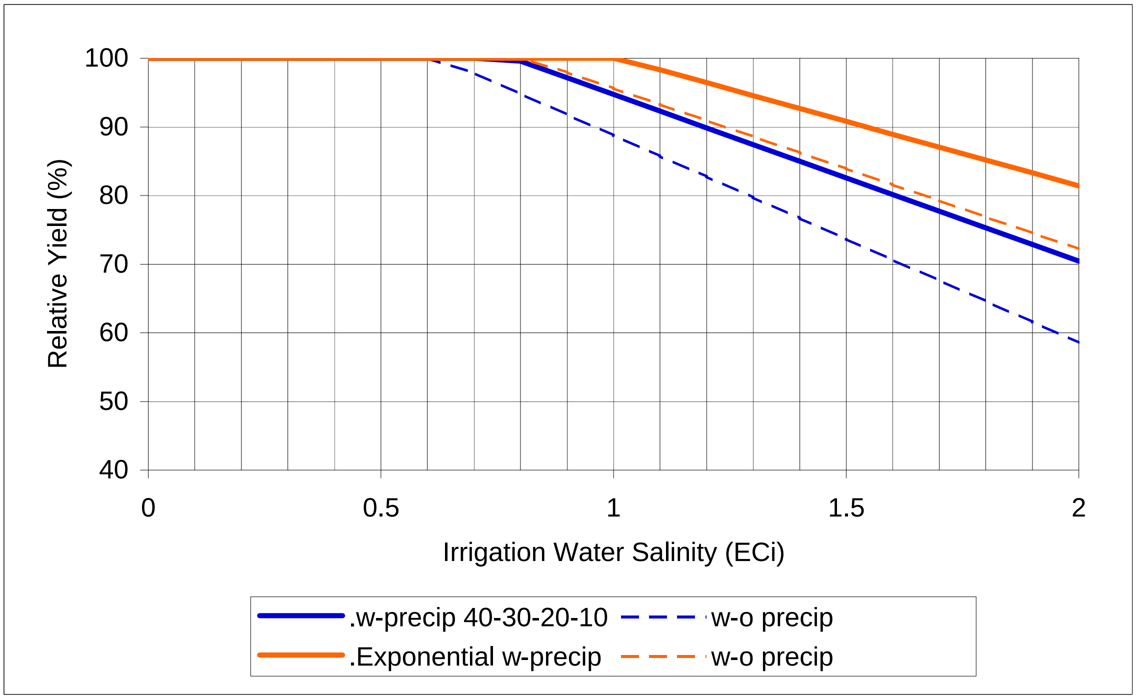


Figure 5.6. Relative crop yield (percent) as a function of irrigation water salinity (ECi) with a) LF = 0.15 and b) LF = 0.20 assuming median effective precipitation from NCDC station no. 8999, Tracy-Carbona - water years 1952 through 2008 (solid lines) and no precipitation (dashed lines).

a) LF = 0.15



b) LF = 0.20

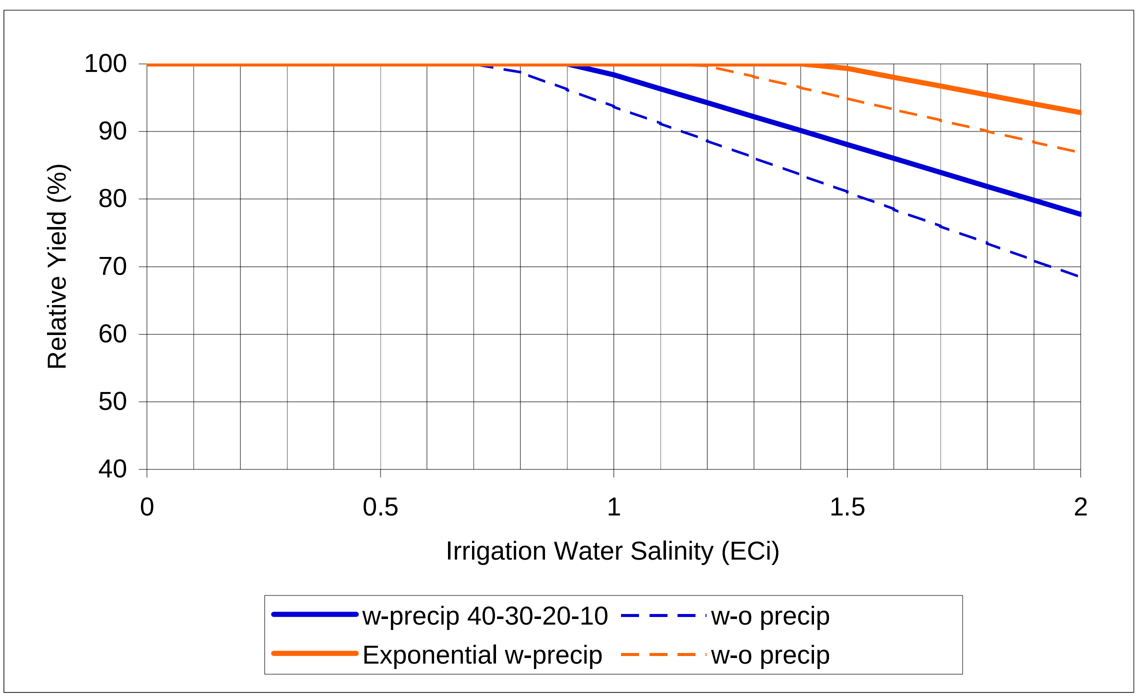


Table 5.2. Definition of input variables and equations for the steady-state model.

<u>Input Variables</u>

LF = leaching fraction (input assumption)
EC_i = irrigation water salinity (input assumption)
P_T = total annual precipitation
P_{NG} = total precipitation during the non-growing season (dates determined by Goldhamer & Snyder, 1989)
E_S = total off-season surface evaporation (0.7 in/mo. from end of previous to beginning of stated water year's growing season)
P_{GS} = total precipitation during the growing season (dates determined by Goldhamer & Snyder, 1989)
P_{EFF} = total effective precipitation where: $P_{EFF} = P_{GS} + (P_{NG} - E_S)$
ET_C = total crop evapotranspiration as calculated per Goldhamer & Snyder 1989 (total for growing season of stated water year)

<u>Steady-State Equations (without consideration of precipitation)</u>

For a particular water year:

I_1 = irrigation required to satisfy assumed LF given total ET_C (excluding precipitation): $I_1 = ET_C / (1\text{-}LF)$

$$EC_{SWa-1} = \left[ECi + \frac{EC_i * I_1}{I_1 - (0.4 * ET_C)} + \frac{EC_i * I_1}{I_1 - (0.7 * ET_C)} + \frac{EC_i * I_1}{I_1 - (0.9 * ET_C)} + \frac{EC_i * I_1}{I_1 - ET_C} \right] \div 5$$

$$EC_{SWb-1} = \left[\left(\frac{1}{LF}\right) + \left(\frac{0.2}{LF}\right) * \ln\left[LF + (1 - LF) * \exp(-5)\right] \right] * EC_i$$

<u>Steady-State Equations (including consideration of precipitation)</u>

For a particular water year:

I_2 = amount of irrigation required to maintain LF (accounting for precipitation): $I_2 = [ET_C / (1\text{-}LF)] - P_{EFF}$

EC_{AW} = salinity of applied water (combined $P_{EFF} + I_2$): $EC_{AW} = I_2 \times EC_i / (P_{EFF} + I_2)$.

$$EC_{SWa-2} = \left[EC_{AW} + \frac{EC_{AW} * (I_2 + P_{EFF})}{(I_2 + P_{EFF}) - (0.4 * ET_C)} + \frac{EC_{AW} * (I_2 + P_{EFF})}{(I_2 + P_{EFF}) - (0.7 * ET_C)} + \frac{EC_{AW} * (I_2 + P_{EFF})}{(I_2 + P_{EFF}) - (0.9 * ET_C)} + \frac{EC_{AW} * (I_2 + P_{EFF})}{(I_2 + P_{EFF}) - ET_C} \right] \div 5$$

$$EC_{SWb-2} = \left[\left(\frac{1}{LF}\right) + \left(\frac{0.2}{LF}\right) * \ln\left[LF + (1 - LF) * \exp(-5)\right] \right] * EC_{AW}$$

6. Summary & Conclusions

This portion of the report is divided into two sections. The first section summarizes the information on irrigation water quality, soil types and location of saline and shrink/swell soils, crop surveys, salt tolerance of crops, effective rainfall, irrigation methods and their efficiency, crop water uptake distribution, climate, salt precipitation/dissolution in soil, shallow groundwater, and leaching fraction. The second section draws conclusions on published steady-state and transient models, compares model results with experimental or field results, and draws conclusions from the results of the steady-state model developed in Section 5 using data applicable to the South Delta.

6.1. Factors Influencing a Water Quality Standard

The quality of water in the San Joaquin River from 1990 to 2006 as measured at Vernalis and the quality in South Old River at Tracy Bridge over the same time period averages around 0.7 dS/m and ranges from 0.1 to 1.4 dS/m. The average level of salinity in the irrigation water is suitable for all agricultural crops. Based on analyses of these waters for various salt constituents, neither sodicity nor toxicity should be a concern for irrigated agriculture.

Review of the 1992 SCS Soil Survey indicates that clay and clay loam soils are predominant in the southwestern portion of the South Delta, organic soils are minimal in area and are restricted to the northern section, and loam soils are dominate in the remainder of the South Delta. Saline soils were identified in 1992 on about 5 % of the irrigated land. Sodic soils were not reported. The Soil Survey also identified a number of soils that have a high potential to shrink and swell. These shrink/swell soils occupy nearly 50 % of the irrigated area. However, based on a study of soils in the Imperial Valley of similar texture, it does not appear that bypass flow of applied water should cause a salinity management problem.

Data taken from Crop Surveys over the past three decades indicate that tree and vine crops occupy about 8 % of the irrigated land in the South Delta, field crops about 24 %, truck crops about 22 %, grain and hay nearly 13 %, and hay and pasture about 31 % . Of the predominant crops identified in the Crop Surveys the salt sensitive crops are almond, apricot, bean, and walnut with bean being the most sensitive with a salt tolerance threshold of EC_e =1.0 dS/m. Thus, to protect the productivity of all crops, bean yield must be protected against loss from excess salinity. It is unfortunate that the published results on the salt tolerance of bean are taken from five laboratory experiments conducted more than 30 years ago. In addition, there are no data to indicate how the salt tolerance of bean changes with growth stage. With such an important decision as the water quality standard to protect all crops in the South Delta, it is unfortunate that a definitive answer can not be based on a field trial with modern bean varieties.

One of the shortcomings of some leaching requirement models is the failure to account for effective rainfall to satisfy a portion of a crop's evapotranspiration. The DWR study in the Central Valley makes it possible to estimate effective rainfall from winter rains. This information is used in the steady-state model prepared for the South Delta in Section 5.

Based upon estimates by Dr. Pritchard of the UC Cooperative Extension, it appears that about 40 % of the South Delta is irrigated by borders which have an average irrigation efficiency of about 78 %, 55 % is irrigated by furrows with an average efficiency of 70 %, and 5 % is irrigated by sprinklers (75 % efficiency) and/or microirrigation (87 % efficiency). Thus, on average, the overall irrigation efficiency in the South Delta is about 75 %. With so little irrigation by sprinkling it is reasonable to assume that foliar damage is not a concern.

One of the important inputs to most steady-state and transient models is the crop water uptake distribution through the root zone. The distribution used in most models is the 40-30-20-10 uptake distribution but the exponential distribution has also been used. In comparisons of steady-state model outputs with experimentally measured leaching requirements, both distributions worked satisfactorily but the exponential distribution agreed a little better with the experimental results. In the model developed for the South Delta (see Section 5) both distributions were used.

It has been shown experimentally that hot, dry conditions cause more salt stress in plants than cool, humid conditions. A comparison of temperature and humidity between the South Delta and Riverside, CA, where most salt tolerance experiments have been conducted, showed the South Delta to be slightly cooler and more humid than Riverside. Thus, the tolerance of crops to salinity may be slightly higher in the South Delta than many published results.

Two analyses of the waters reported in Section 2.2 would result in an additional 5 % being added to the salt load from salts being weathered out of the soil profile at leaching fractions of about 0.15. Therefore, the salt load in the soil profile and in the drains would be higher than expected from the irrigation water alone. This may cause L estimates to be a little lower than might be expected in the absence of salt dissolution from the soil profile.

The depth to the water table in the South Delta appears to be at least 3 feet with much of the area having a groundwater depth of at least 5 feet. Subsurface tile drains have been installed in the western portion of the South Delta to maintain the water table at an acceptable depth for crop production. With the water table at these depths, any significant water uptake by crop roots would be restricted to deep-rooted and more salt tolerant crops like cotton and alfalfa.

Estimates of leaching fraction were made based upon the salinity of tile drain discharge and a few soil samples taken at various locations in the South Delta. From drain discharge measurements the leaching fraction varied from 0.23 to 0.47. Based on soil samples the leaching fraction varied from less than 0.05 at one site to more than 0.15 at six locations.

6.2. Using Models to Determine Water Quality Standards

A number of steady-state and transient models have been developed to calculate the leaching requirement which can also be used to estimate a water quality standard. At least five different steady-state models have been published. When the steady-state models are compared with experimentally measured leaching requirements for 14 crops, the exponential model agreed most closely with the measured values. This conclusion is supported by the comparisons made between steady-state and transient models by Letey (2007) and Corwin et al. (in press).

If the steady-state model based on an exponential crop water uptake pattern is applied considering rainfall, the water quality standard could be 1.0 dS/m at a leaching fraction of 0.15 and 1.4 dS/m at a leaching fraction of 0.20. If the steady-state model using the 40-30-20-10 crop water uptake distribution and rainfall is taken into account, the water quality standard could be 0.8 dS/m at a leaching fraction of 0.15 and 0.9 dS/m at a leaching fraction of 0.20. The limited information on leaching fraction in the South Delta based upon drain discharge and soil sampling, with perhaps a few exceptions, is above 0.15. Antidotal evidence of relatively high leaching fractions are the irrigation efficiencies estimated to be 70 % for furrow irrigated beans and an overall irrigation efficiency of 75 % for the South Delta.

Four transient models were reviewed. The Grattan model which uses a 40-30-20-10 water uptake distribution was applied to a watershed near Davis, CA. No verification of this model has been done. The Corwin model, called TETrans, is a functional, layer-equilibrium model. The model was tested using data from the Imperial Valley, CA. The Simunek model, called UNSATCHEM, is a sophisticated, mechanistic, numerical model. Although not developed to determine the LR, it can be altered to do so. This model was also tested on data from the Imperial Valley. Letey and co-workers developed the ENVIRO-GRO model. This model contains a sophisticated equation to compute crop water uptake. Letey's model was tested on a corn experiment conducted in Israel.

Results from the Grattan model indicated that the water quality standard could be 1.1 dS/m for the watershed near Davis, CA. Using information from the Imperial Valley, Corwin and co-workers noted that steady-state models over-estimated the L_r compared to transient models, but only to a minor extent. Based upon the conclusion of Letey comparing steady-state and transient models, the water quality standard could be raised to 1.0 dS/m. This assumes that the salt tolerance of bean is to be used to protect irrigated agriculture.

All of the models presented in this report predict that the water quality standard could be increased to as high as 0.9 to 1.1 dS/m and all of the crops normally grown in the South Delta would be protected. This finding is substantiated by the observation that bean is furrow irrigated with an irrigation efficiency of about 70 % which results in a high leaching fraction.

7. Recommendations

1. If the salt tolerance of bean is to be used to set the water quality standard for the South Delta, it is recommended that a field experiment be conducted to ensure that the salt tolerance of bean is established for local conditions. The published data for bean is based on five laboratory experiments; one in soil, three in sand, and one water-culture. All five laboratory experiments were conducted more than 30 years ago. There may well be new varieties grown that under local conditions might have a different salt tolerance than the one published.

2. If the water quality standard is to be changed throughout the year then the salt tolerance of bean at different growth stages (time of year) needs to be determined. No published results were found on the effect of salinity on bean at different stages of growth. This type of experiment can best be conducted at the U. S. Salinity Laboratory at Riverside, CA where the experimental apparatus and previous experience on studying salt tolerance at different stages resides.

3. If a steady-state model is to be used to determine the water quality standard, it is recommended that either the exponential or the 40-30-20-10 model be used with the inclusion of effective rainfall as part of the applied water. As reported in Section 5, the 40-30-20-10 model gives a more conservative water quality standard than the exponential model (1.0 dS/m for the exponential versus 0.8 dS/m for the 40-30-20-10 model at a leaching fraction of 0.15.)

4. Transient models have a number of advantages over steady-state models. Of course the major advantage is that transient models account for time dependent variables. These variables include considering crop rotations, double cropping, and intercropping; changes in irrigation water quality and quantity and rainfall. The major disadvantage is that far more data are required. Transient models are currently under development but very few checks of their validity against field data have been accomplished. It is recommended that support be given to the testing of one or more of these models using data from the South Delta.

5. In an attempt to determine the leaching fraction in the South Delta, data from agricultural drains were used. It was not clear from the reports whether the drain discharge was a combination of irrigation return flow and subsurface drainage or subsurface drainage alone. To make the collected data useful for calculating leaching fraction, it is recommended that the source of the drain discharge be identified. It would also be helpful to know the area drained by the various systems.

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