Final Report

DETAW

DELTA EVAPOTRANSPIRATION OF APPLIED WATER

Version 1.0

California Land and Water Use, Department of Water Resources and Department of Air, Land and Water Resources, University of California, Davis

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Software Recommendations:

Minimum Platform:

IBM PC compatible Pentium-equivalent or higher, 16MB RAM, Windows 95/98, NT 4.0, Windows 2000, Windows XP

Recommended Platform:

32 MB RAM, or greater

Spreadsheet:

Windows Excel 97, Excel 2000, Excel XP

OVERVIEW

The DETAW computer application program was written in Borland Professional C^{++} to provide a tool for estimating evapotranspiration of applied water (ET_{aw}), which is a seasonal estimate of the water requirement for evapotranspiration of a crop minus any water supplied by effective rainfall. ET_{aw} information is needed to determine the demand side of water requirements. The application is specifically designed to estimate ET_{aw} within the Sacramento-San Joaquin River Delta. It does not account for the additional water needed for irrigation efficiency or for salinity. It does include the contribution from rainfall and ground water seepage from the rivers and canals

DESCRIPTION AND METHODS

DETAW versus SIMETAW

A major goal of this project was to develop a computer application program to estimate daily soil water balances for surfaces within the Sacramento-San Joaquin River Delta region that account for evapotranspiration losses and water contributions from rainfall, seepage of ground water, and irrigation. The water balance model is similar to that used in the Simulation of ET of Applied Water (SIMETAW) application program, which was also developed as a cooperative effort between the University of California (UC) and the Department of Water Resources (DWR). The main differences between the SIMETAW and DETAW application programs are: (1) SIMETAW simulates daily weather data from monthly means for use where daily data are unavailable and DETAW does not do simulation, (2) SIMETAW is used to determine the daily water balance of individual fields of crops within a region, whereas DETAW is designed to use batch files of input data to compute daily water balance for all 15 land use categories over the period of record for each of 168 sub-areas having a range of evaporative demand and rainfall. With some modification, SIMETAW could be used to compute the same results as DETAW;

however, considerable time would be required for direct entry of the input data. Therefore, DETAW was mainly designed to reduce the time needed for data input.

Creating the 168 DICU Sub-areas

A scanned image, of the original 142 DICU Model sub-areas, was geo-referenced and digitized using ESRI's ArcView software – creating a GIS shape file (Fig. 1). See Table A.1 for a listing of sub-areas with their original numbers.

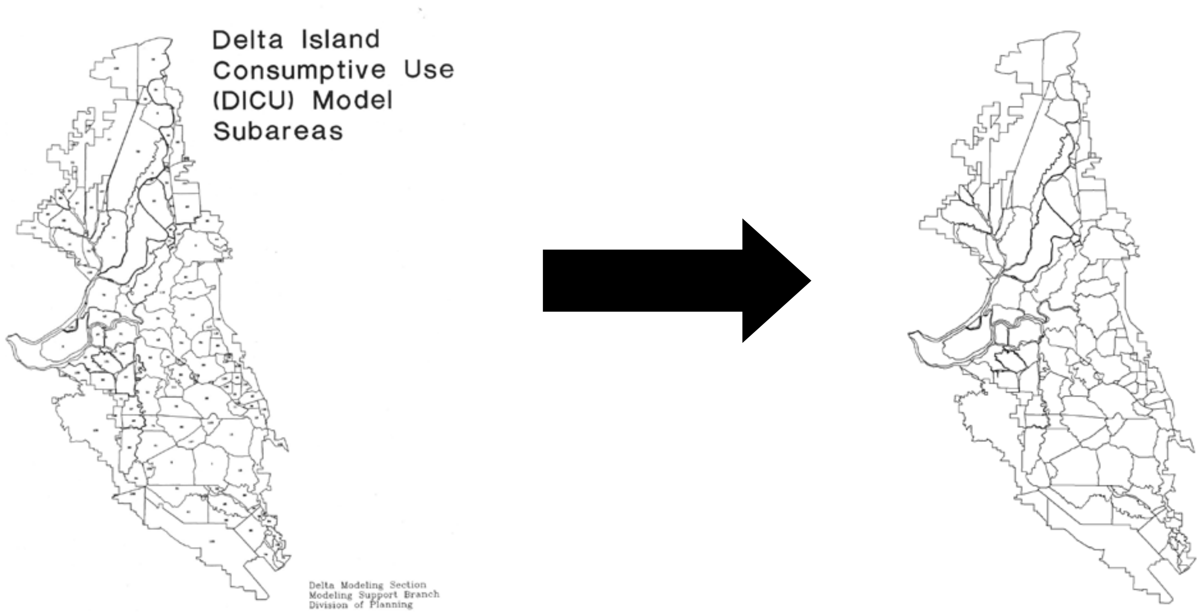


Figure 1. Consumptive Use (DICU) Model Sub-areas and the scanned GIS shape file results (maps from Mary Serato)

Eleven of the 142 DICU Model sub-areas contain multiple areas within an individual sub-area. To give each area its own identification, the additional areas were reclassified into 26 new DICU sub-areas for a total of 168 DICU Model sub-areas. See Table A.1 for a listing of the new sub-area numbers, the surface area (acres), precipitation stations used to estimate rainfall for that sub-area, correction factors for estimating ETo, and whether the sub-area is in the Delta uplands or lowlands. The final GIS map with 168 sub-areas is shown in Fig. 2 with the 26 new sub-areas highlighted in color.

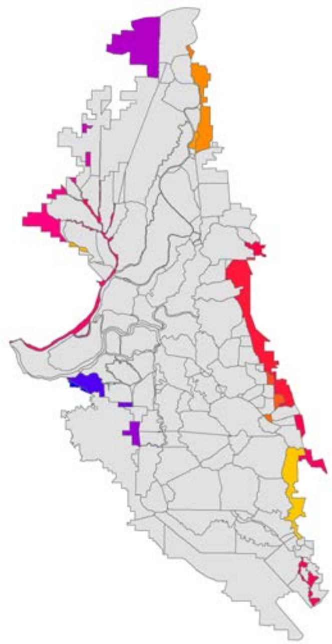


Figure 2. Delta sub-area GIS map with the 26 newly identified sub-areas highlighted in color (map from Mary Serato).

Historical Delta Land-Use Area Calculation

Delta historical land use from 1992 through 2003 was obtained from current CU model input files for both DSA54 and DSA55. A snapshot of GIS land use during the1990's was used to derive the land use distribution over the 168 sub-areas with a distinction between low land and upland sub-areas. Attempts to apply the developed GIS distribution to the historical land-use records have resulted in erroneous results such as assigning more land use than the actual surface area of a particular sub-area. Therefore, the following procedures were followed to reasonably mimic the GIS distribution and to insure that the results were bounded by both the year-to-year historic land-use and the physical delta surface area. The analysis was completed by Mary Serato from the DWR Bay-Delta Office staff.

1) Calculate a correction factor for the urban, crops, dry grain, riparian vegetation and water surface. The total GIS area of the land-use category was divided by the corresponding average of 1992-2000 historical record of that category.
2) Adjust the CU historical land use records from 1922 to 2003 using the factors calculated in step 1. Any remaining DSA areas were assigned as Native Vegetation.

3) Calculate the intra-distribution of crops including the dry grain for each historical year in the record.
4) Calculate another intra-distribution for NV, RV and surface water for each historical year.
5) Develop three distributions from the available GIS snapshot, one for urban use, one for agriculture land including the dry grain and the third for NV, RV and surface water.
6) Assign the historical urban land use to each of the 168 sub-areas according to GIS distribution developed in step 5.
7) Assign the total agriculture land for each sub-area using GIS distribution from step 5. Later and to distribution that assigned agriculture land among different crops, the intra crop distribution calculated in step 3 was used.
8) Assign and distribute the remaining area, if any left unassigned, among NV, RV and surface water according to the corresponding intra distribution calculated in step 4.

The resulting land-use distribution was saved in an Excel application with 168 worksheets corresponding to the sub-areas and the acres listed under the 15 land-use categories in columns by the 82 years in rows. Another Excel file was created with 82 worksheets, corresponding to the study period years, and acres listed under the 15 land-use categories in columns by the 168 sub-areas in rows.

The Excel file having 168 worksheets of sub-areas was modified for use with the DETAW application. The surface areas were converted to hectares and the data were archived in 168 individual comma delimited text files having the land-use categories in columns and the surface areas (hectares) in rows corresponding to the 1922-2003 water years. The land-use data files were saved using the filenames SA0001.csv, SA0002, … , SA0168.csv to identify the sub-area. A sample data file for SA0001 is shown in Appendix A in Table A.2. In the data file, the first column identifies the water year and the second column identifies the type of water year. Years with the symbol ‘C’ or ‘D’ in the second column are critical (dry) water years and all other symbols are for non-critical water years. The remaining columns contain the areas (hectares) for each of the 15 land-use categories. The land-use category is identified in row 1 of the files and the land-use categories are numbered in row 2. The 168 files are stored in a folder named “Historical” in the DETAW analysis folder. Note that in the historical files, there are smooth changes in the surface areas of the land-use categories over time (Table A.2).

Projected Delta Land Use Areas

Two snap shots of GIS land use were utilized to develop the projected land use estimates. One projection used the year 1976, which represents critical and dry water years and the other projection used the 1990’s representing the wet, below normal and above normal water years. Using GIS, land distribution for each sub-area was determined from the two snapshots. Land use for a particular year for a particular sub-area was simply a replication of the corresponding GIS land use based on the water year type. Again, the results were presented in two formats using Excel software with land use by year in worksheets identified by sub-area or with land use by sub-area in worksheets identified by year.

As with the historical data, the Excel file with worksheets identified by sub-area and acreages by year within each worksheet was modified to a format useable by DETAW. The acres were converted to hectares and 168 individual comma-delimited ASCII data files were created with the hectares listed under the land-use categories in columns and the years in rows. The filenames SA0001.csv, SA0002, …, SA0168.csv were again used to correspond with the sub-areas. The projected data files were stored in a subfolder of the DETAW analysis folder named “Projected” to avoid mixing with the historical data files that were stored in the “Historical” subfolder. A sample data set for SA0001 is presented in Appendix A in Table A.3. In the projected data, the surface areas change between critical and non-critical years and there is no smooth change in surface areas over time.

Study Period

The historical period of record for the DETAW analysis is from 1 October 1921 through 30 September 2003.

Critical and Non-Critical Years

DETAW uses historical records of land usage and adjusts the land-use crop coefficients for differences between non-critical years (i.e., with no shortage of water) and critical years (i.e., when there is a water shortage). Whether a year is critical or non-critical affects cropping patterns and, therefore, how the crop coefficient curves are computed.

Land Use Categories

The DETAW application uses 15 land-use categories that can include one or more crops or other surfaces. The land-use categories and what they include vary depending on the source of the information (Table 1). In the DETAW application, the GIS survey components were used to sub-divide the land-use categories. Two GIS land-use surveys were used to determine crop acreages for each of the 168 sub-areas. One was the Critical Land Use or 1976 Level Delta 1976 survey that was provided by Tom Hawkins from the DWR Division of Planning and Local Assistance. The other was the Non-Critical Land Use or Current Level from the Delta 1993 (Alameda), Solano 1994, Contra Costa 1995, San Joaquin 1996, Yolo 1997, and Sacramento 2000 surveys. The data were provided by Tom Hawkins from the DWR Division of Planning and Local Assistance.

Table 1. Components of the 15 land-use categories for the GIS survey, DICU model, and CU model.

Crop	GIS Survey	DICU Model	CU Model
Urban	Urban, Commercial, Industrial, Landscape, Residential, Vacant, Semi-Agricultural	Urban	Urban
Pasture	Pasture	Pasture	Pasture
Alfalfa	Part of Pasture	Alfalfa, Non-Irrigated Pasture	Alfalfa
Field Crops	Field, Safflower, Corn	Field, Safflower, Corn	Field
Sugar Beets	Part of Field Crop	Sugar Beets	Sugar Beets
Grain	Grain & Hay	Grain	Grain
Rice	Rice	Rice	Rice
Truck	Truck,	Truck	Truck
Tomato	Part of Truck Crop	Tomato	Tomato
Orchards	Citrus & Subtropical, Deciduous Fruits & Nuts	Orchards, Non-Irrigated Orchards	Orchards
Vineyards	Vineyards	Vineyards, Non-Irrigated Vineyards	Vineyards
Native Riparian	Riparian Vegetation	Riparian Vegetation	Riparian Vegetation
Water Surface	Water Surface	Water Surface	Water Surface
Non-Irrigated Grain	---	Non-Irrigated Grain	Non-Irrigated Grain
Native Vegetation	Native Vegetation, Native Classes Unsegregated, Idle, Barren Wasteland	Native Vegetation	Native Vegetation

Land Use Categories and Crop Percentages

Information was not available on the acreage planted to most individual crops during the study period, but there were estimates of the area allocated to each of 15 general land-use categories (Table 1). Percentages of the total surface area attributed to each crop or other surface within a land-use category were known, and the percentages were used to determine weighted mean annual crop coefficient curves for each land-use category. Because the cropping patterns were different, separate sets of weighted mean crop coefficient curves were derived for critical and non-critical years.

Data on land-use was available for the 15 land-use categories by sub-area for the 82 year study period, but information on the individual crop (sub-category) acreages within the land-use categories were only available for a few years when surveys were conducted. Using data from the survey years, the percentages of each land-use category areas covered by sub-categories were calculated. Land-use categories that represent individual crops have seasonal crop coefficient (Kc) curves, but categories containing multiple crops or other surfaces do not have seasonal Kc curves. These multiple surface sub-categories, however, generally have one or two dominant surfaces. Therefore, it was possible to determine a weighted mean seasonal Kc curve using the percentages of the entire land-use category corresponding to the sub-category crops and surfaces. In some of the surveys, there was a “blank” or “**” for the crop name, so the small acreages were added to the crop with the largest acreage in the land-use category. A summary of the sub-category percentages for each land-use category is shown in Table 2.

Table 2. Land-use categories and percentages of the total area covered by sub-category crops or other surfaces.

UR – Urban	**Percentages**	
	Non-Critical	**Critical**
Urban Hard Tops	37.67	41.46
Urban Vacant Lots	39.66	40.47
Urban Lawns	22.67	18.08
TOTAL Percentage	**100**	**100**
PA - Pasture	**Percentages**	
	Non-Critical	**Critical**
2. Clover	0.75	0.29
3. Mixed Pasture	78.84	99.20
4. Native Pasture	14.17	0.51
6. Misc. Grasses (normally grown for seed)	3.30	
7. Turf Farms	2.94	
TOTAL Percentage	**100**	**100**
AL - Alfalfa	**Percentages**	
	Non-Critical	**Critical**
1. Alfalfa & Alfalfa Mixtures	100	100
TOTAL Percentage	**100**	**100**

FL – Field Crops	**Percentages**	
	Non-Critical	**Critical**
10. Beans (dry)	5.14	3.00
12. Sunflowers	1.15	
2. Safflower	26.31	4.04
6. Corn (field & Sweet)	64.44	81.36
7. Grain Sorghum	1.02	6.79
8. Sudan	1.94	3.70
Misc. Field Crops		1.08
Castor Beans		0.03
TOTAL Percentage	**100**	**100**
SB - Sugar Beets	**Percentages**	
	Non-Critical	**Critical**
5. Sugar Beets	100	100
TOTAL Percentage	**100**	**100**
GR – Grain	**Percentages**	
	Non-Critical	**Critical**
1. Barley	0.11	
2. Wheat	1.88	
6. Misc. & Mixed Grain & Hay	98.01	100
TOTAL Percentage	**100**	**100**
RI – Rice	**Percentages**	
	Non-Critical	**Critical**
Rice	100	100
TOTAL Percentage	**100**	**100**
TR – Truck	**Percentages**	
	Non-Critical	**Critical**
1. Artichokes	0.06	
10. Onions & Garlic	1.48	0.99
12. Potatoes	11.66	9.24
16. Flowers, Nursery, & Christmas Tree Farms	0.28	2.26
17. Mixed (four or more)	0.38	
18. Misc. truck	0.28	2.89
2. Asparagus	66.74	74.95
20. Strawberries	0.08	
21. Peppers (chilli, bell, etc.)	1.93	0.58
23. Cabbage	0.11	
3. Beans (green)	0.95	0.86
4. Cole Crops	0.07	0.92
6. Carrots	0.63	0.18
7. Celery	0.04	
Lettuce		1.19
9. Melons, Squash, & Cucumbers (all types)	15.32	5.92
Bushberries		0.02
TOTAL Percentage	**100**	**100**
TO – Tomatos	**Percentages**	
	Non-Critical	**Critical**

15. Tomatoes	100	100
TOTAL Percentage	**100**	**100**
OR – Orchards	**Percentages**	
	Non-Critical	**Critical**
1. Grapefruit	0.02	
8. Kiwis	0.14	
Oranges		0.04
10. Eucalyptus	0.22	
1. Apples	11.96	0.13
10. Misc Deciduius	1.46	
12. Almonds	9.30	
13. Walnuts	24.66	0.37
14. Pistachios	0.41	
2. Apricots	9.71	
3. Cherries	3.88	
5. Peaches & Nectarines	1.54	1.28
6. Pears	36.08	98.17
7. Plums	0.33	0.01
9. Figs	0.31	
TOTAL Percentage	**100**	**100**
VI – Vineyards	**Percentages**	
	Non-Critical	**Critical**
Vineyards	100	100
TOTAL Percentage	**100**	**100**
RV - Riparian Vegetation	**Percentages**	
	Non-Critical	**Critical**
1. Marsh Lands, Tules, & Sedges	60.30	97.72
3. Trees, Scrubs, & Other Larger Stream Side or Watercourse Vegetation	27.18	2.24
4. Seasonal Duck Marsh, dry or only partially wet during summer	11.68	
5. Permanent Duck Marsh, flooded during summer	0.84	
Brush		0.04
TOTAL Percentage	**100**	**100**
WS - Water Surface	**Percentages**	
	Non-Critical	**Critical**
Water	100	100
TOTAL Percentage	**100**	**100**
DG - Non-Irrigated Grain	**Percentages**	
	Non-Critical	**Critical**
Dry Grain	100	100
TOTAL Percentage	**100**	**100**
NV - Native Vegetation	**Percentages**	
	Non-Critical	**Critical**
Idle - 1. Land not cropped the current or previous crop season, but cropped within past 3 years	10.60	2.00
Idle – 2. Ne lands being prepared for crop production		0.55
NB - Barren & Wasteland	0.08	

NC - Native Classes Unsegregated	0.73	
Native	88.58	97.46
TOTAL Percentage	**100**	**100**

Reference Evapotranspiration Equations

Reference evapotranspiration (ETo) is an estimate of the evapotranspiration is technically defined as the ET from a short 12 cm tall vegetation of large extent and not lacking for water. In practice, ETo is approximately equal to the ET of a 12 cm tall, cool-season pasture grass. The DETAW program uses ETo and crop coefficients to estimate the ET of various crops. To estimate ETo, DETAW uses the Hargreaves-Samani (HS) equation and daily maximum and minimum temperatures from the Lodi NCDC climate station for the period of record. The spatial variation across the Delta was assessed by calculating ETo using the standardized Penman-Monteith (PM) daily (24-hour) reference evapotranspiration equation (ASCE-EWRI, 2005) and daily solar radiation, maximum and minimum temperature, the daily mean dew point temperature, and the wind speed from several California Irrigation Management Information System (CIMIS) stations located around the Delta. The ETo calculation methods are explained in Appendix B, and the procedure to spatially estimate ETo across the Delta is explained below.

Spatial ETo Estimation

A fundamental problem with estimating ETo in the Delta is the lack of sufficient long-term climate data. Currently, Twitchell Island has the only CIMIS station located within the Delta, and that station has only existed for about seven years. There are, however, other CIMIS stations around the Delta, but most them have also only existed for 20 years or less. Prior to 1986, there were no CIMIS stations and only temperature data were available for estimating ETo. Conventional weather stations with long periods of record are located on the east side of the Delta near Lodi and Stockton. The weather conditions change dramatically from west to east, however, and this presents a problem for spatially estimating ETo across the Delta. To resolve this problem, data from the nine CIMIS stations around the Delta were used to compute ETo using the standardized PM equation (ASCE-EWRI, 2005). Daily ETo was also calculated using temperature data from the Lodi NCDC station and the HS equation. Location information for all stations used in the analysis is shown in Table 3.

Table 3. CIMIS and NCDC weather stations and the time period used for the spatial estimation of ETo.

Location	CIMIS No.	Begin Date	End Date	Lat.	Long.	Elevation (m)
Lodi NCDC		01-Oct-21	31-Dec-04	38º07’12”	121º18’00”	12.2
Brentwood	47	04-Jan-86	31-Dec-04	37º55’43”	121º39’31”	13.7
Bryte	155	12-Mar-89	31-Dec-04	38º35’38”	121º32’25”	12.2
Davis	6	05-Jan-83	31-Dec-04	38º32’09”	121º46’32”	18.3
Hastings Tract	122	28-Mar-95	31-Dec-04	38º16’57”	121º47’24”	3.0
Lodi	42	05-Jan-83	17-Jan-98	38º06’34”	121º20’46”	7.0
Lodi West	166	14-Sep-00	31-Dec-04	38º07’48”	121º22’57”	7.6
Manteca	70	12-Nov-87	31-Dec-04	37º50’05”	121º13’22”	10.1
Tracy	167	02-Sep-01	31-Dec-04	37º43’34”	121o28’26”	25.0
Twitchell Island	140	15-Oct-97	31-Dec-04	38º07’00”	121º39’29”	-0.3

Lodi NCDC Temperature Data

While the Lodi NCDC climate station has a long record, daily data were not available for the entire 82 year period. Daily climate data were available from July 1948 through December 2004. Before July 1948, the daily weather data were estimated using monthly mean maximum and minimum temperatures from Lodi (1931-1948) and Stockton (1922-1931). The monthly data came from a DWR spreadsheet that was previously used by DWR for another project. Daily maximum and minimum temperature variations prior to 1948 were estimated using the corresponding daily temperature variations about the monthly means from Davis and the monthly means from Lodi and Stockton. A small sample of the Lodi NCDC temperature data in the ASCII format is shown in Appendix A in Table A.5.

Determining ETo Correction Factors

The daily ETo estimates from the Lodi NCDC station were matched with daily data from each of the CIMIS stations over the maximum possible time period and least squares regression of the CIMIS station ETo versus the Lodi ETo data was computed for each CIMIS station to determine the slope of the linear regressions through the origin. Then the PM-ETo on any day at any CIMIS station could be estimated as the product of the Lodi HS-ETo and the slope. Therefore, the derived slopes can be used as correction factors to estimate PM ETo at the CIMIS stations using the HS ETo from the Lodi NCDC station. The derived slopes by month and annually are presented in Table 4 and the standard error of the estimates for each month and annually are given in Table 5. Because the standard errors of the regressions (Table 5) were similar and relatively small in magnitude for the annual regression analysis and the slopes on an annual basis were similar to those in the peak ETo months (Table 4), the annual slopes were adopted for use as the correction factors in all months.

Table 4. Slopes of the regression of PM ETo versus HS ETo from Lodi.

Location	Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Brentwood	0.95	0.79	0.89	0.94	0.96	0.96	0.97	0.94	0.95	0.96	0.95	0.91	0.81
Bryte	0.88	0.68	0.75	0.82	0.87	0.90	0.91	0.92	0.90	0.84	0.81	0.68	0.69
Davis	1.04	0.88	0.94	0.97	1.02	1.02	1.06	1.02	1.03	1.07	1.14	1.14	0.96
Hastings Trt	1.06	0.81	0.87	0.93	0.94	0.98	1.05	1.11	1.14	1.16	1.16	0.87	0.86
Lodi	0.90	0.70	0.79	0.88	0.94	0.93	0.92	0.90	0.89	0.88	0.82	0.75	0.66
Lodi West	0.78	0.64	0.72	0.77	0.79	0.81	0.79	0.78	0.78	0.76	0.73	0.64	0.61
Manteca	0.93	0.81	0.86	0.93	0.93	0.94	0.96	0.96	0.93	0.90	0.85	0.82	0.85
Tracy	1.06	0.76	0.89	0.97	1.00	1.07	1.15	1.06	1.03	1.08	1.08	0.87	0.84
Twitchell Is.	1.08	0.81	0.91	1.01	1.01	1.11	1.11	1.08	1.15	1.14	0.90	0.94	0.94

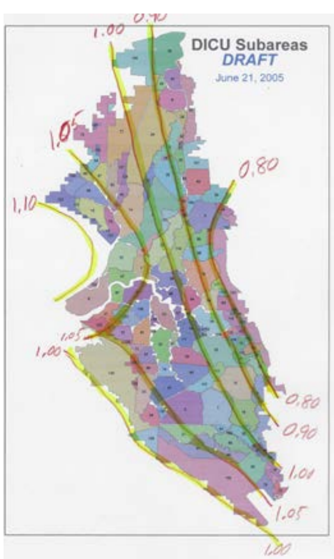
Table 5. Standard error of the estimate for PM ETo versus HS ETo from Lodi.

Location	Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Brentwood	0.80	0.48	0.66	0.87	1.05	1.07	0.98	0.74	0.71	0.78	0.86	0.64	0.50
Bryte	0.60	0.26	0.36	0.57	0.71	0.74	0.65	0.47	0.66	0.68	0.69	0.32	0.28
Davis	1.05	0.61	0.84	1.07	1.27	1.32	1.20	0.77	0.80	1.09	1.38	1.00	0.73
Hastings Trt	0.99	0.55	0.67	0.91	1.08	1.13	1.12	0.83	1.04	0.93	1.29	0.63	0.58
Lodi	0.72	0.32	0.52	0.80	1.08	1.18	0.80	0.56	0.60	0.54	0.58	0.46	0.33
Lodi West	0.52	0.18	0.28	0.51	0.55	0.61	0.80	0.69	0.41	0.42	0.46	0.22	0.19
Manteca	0.88	0.56	0.55	1.19	0.99	1.06	1.12	0.89	0.59	0.87	0.61	0.74	0.81
Tracy	0.87	0.40	0.57	0.81	0.94	1.03	1.08	1.04	0.80	0.92	0.81	0.51	0.41
Twitchell Is.	0.88	0.42	0.56	0.91	0.89	1.01	1.04	0.88	1.08	0.88	1.13	0.52	0.49

Reference Evapotranspiraiton Correction Isolines

Using the annual slopes as correction factors for each CIMIS station (Table 4), correction factor isolines were drawn by hand on a Delta map (Fig. 3.a). A scanned image, of the isolines, was geo-referenced and digitized into a GIS shape file (Fig. 3.b). Then, the isolines were digitized by Mary Serato using ESRI's ArcGIS Spatial Analyst software, and the isoline values were used to generate a continuous surface that covered the 168 DICU Model sub-areas. A weighted average/correction factor value, for each of the sub-areas, was derived by overlaying the sub-area GIS shape file on the continuous surface and using Spatial Analyst's Zonal Statistic tool to extract the values. See Table A.6 for list of the correction factors by sub-area.

(a)



(b)

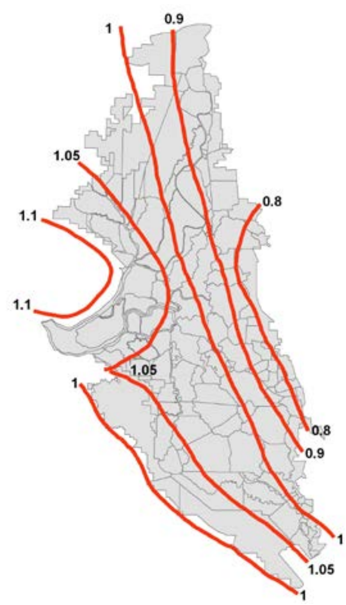


Figure 3. The Delta with hand-drawn isolines of ETo correction factors (a) and GIS digitized isolines of ETo correction factors (b).

Spatial Rainfall Estimation in the Delta

Rainfall data were unavailable for most of the Delta sub-areas. Therefore, a spatial relationship between rainfall data from key stations was developed and used to estimate rainfall in each of the 168 sub-areas. Monthly and daily data were obtained from either the NCDC or data used in the DWR Consumptive use model for seven stations: Davis, Stockton, Lodi, Tracy-Carbona, Rio Vista, Brentwood and Galt. Except for a few months, the Davis station had a complete record of daily and monthly data from 1922 to present. The daily distribution of rainfall about the monthly means was calculated for Davis and the daily fluctuations were used to calculate daily precipitation for missing data at the other stations. A daily distribution was estimated based on surrounding time periods in cases where Davis total monthly precipitation was zero or missing and monthly precipitation was recorded at another station. Galt rainfall data are highly correlated with Lodi, so, when available, the daily rainfall distribution of Lodi was used to estimate Galt daily data. Similarly, Brentwood is highly correlated to Tracy-Carbona and the daily Tracy rainfall distribution, when available, was used to calculate Brentwood daily data.

Daily precipitation data were compiled by Mahmoud Mabrouk, of the Bay-Delta Office. See Table 6 for precipitation station locations.

Table 6. Precipitation station locations

Precipitation Stations	Data Source	Data Record
Brentwood	DWR's Central District	Oct. 1921 – Jan. 1987
	Correlation with Tracy Carbona (1.37)	Feb. 1987 – Dec. 2003
Galt	COMP.IN file (B03301)	Oct. 1921 – Sept. 1988
	Correlation with Lodi (1.01)	Oct. 1988 – Dec. 2003
Lodi	COMP.IN file	Oct. 1921 – June 1994
	NCDC CD (B05032)	July 1994 – Dec. 2003
Rio Vista	NCDC CD (B97446)	July 1948 – May 1977
	Correlation with Davis (0.98)	June 1977 – Dec. 2003
Stockton	California Daily Exchange Center	1905 – June 1948
	NCDC CD	July 1948 – Dec. 2003
Davis	NCDC CD (#2294)	Jan. 1917 – Dec. 2003
Tracy-Carbona	Correlation with Tracy SP & COMP.IN file	Oct. 1921 – Sept. 1949
	NCDC CD	Oct. 1949 – Dec. 2003

A set of rainfall contribution percentages from each station was developed for each of the 168 sub-areas using GIS, and they were used to develop the daily time series for each sub-area.

Thiessen Polygons were created around the precipitation stations using “Create Thiessen Polygon” – an ArcGIS script – to determine which precipitation stations can be used to estimate sub-area rainfall. Any sub-area that was completely within a Thiessen Polygon (Fig. 4) is represented by a single precipitation station. Sub-areas that fall in more than one Thiessen Polygon use more than one station to estimate the rainfall. In this situation, rainfall was estimated as the sum of the percentage of the rainfall recorded at each of the contributing weather stations corresponding to Thiessen Polygons that intersect the sub-area. See Figure 4 for Thiessen Polygon boundaries and Table A.6 for the precipitation by station.

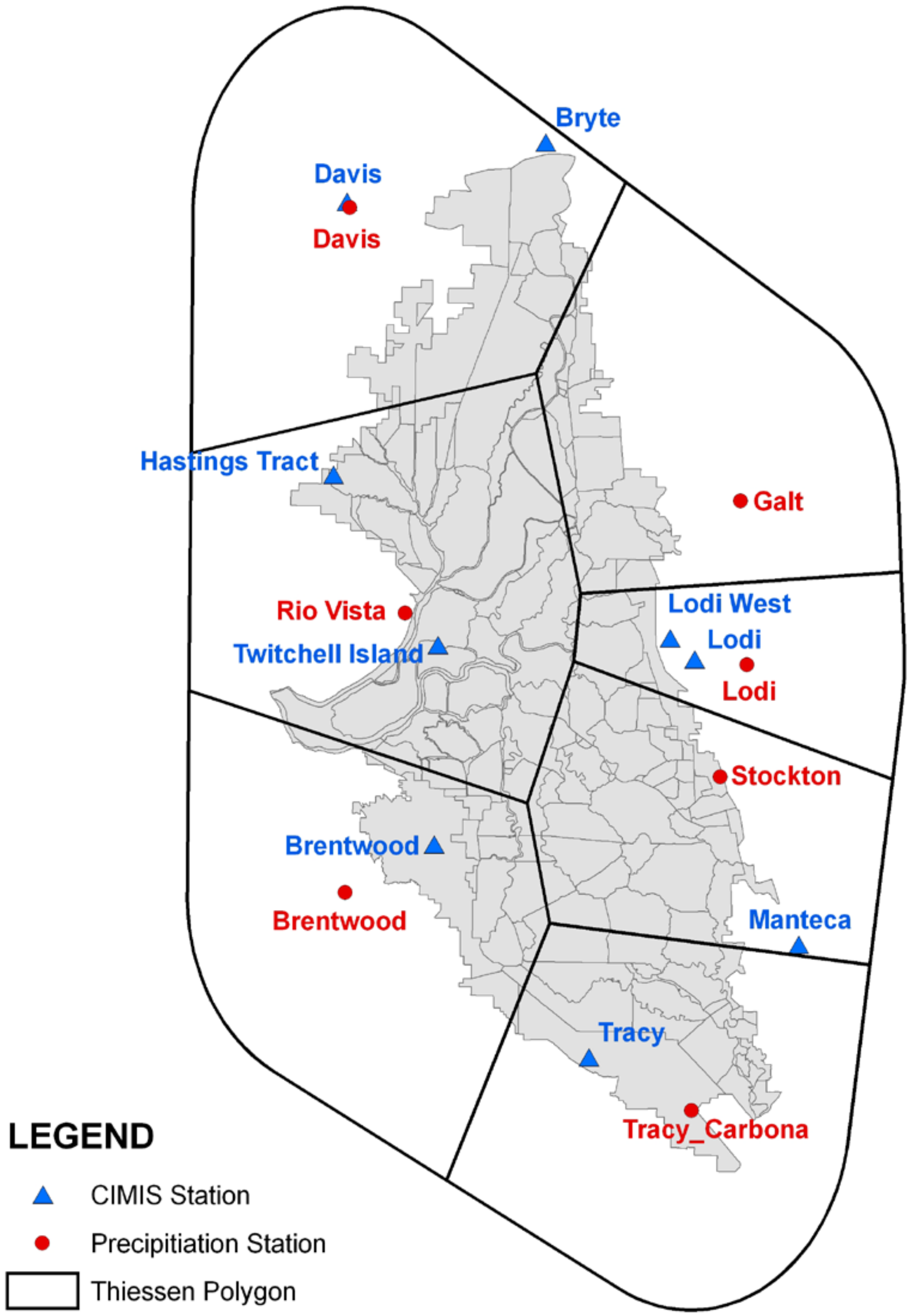


Figure 4. Thiessen Polygons for determining spatial distribution of precipitation.

Land-use Category Kc Curves

The basic concept of crop coefficient (Kc) factors is explained in Appendix C. In DETAW, seasonal Kc curves are used to estimate evapotranspiration for the 15 various land-use surfaces. There are actually two sets of Kc factor curves of 15 general land-use categories. One set is for non-critical years and the other is for critical (dry) years. The land-use categories include combinations of various surfaces that generally have similar characteristics. Most of the categories are associated with crop types, but a few categories do not included crops (e.g., riparian vegetation and urban landscape). Therefore, the use of "crop" with coefficient is strictly incorrect. While the Kc values are used to estimate the evapotranspiration rates of land-use categories in a similar manner as crop evapotranspiration, from this point forward, we will simply use the symbol Kc rather than the name "crop coefficient" for the factors that are multiplied by reference evapotranspiration (ETo) to estimate the ET of a particular land-use category. We will use the symbol ETc, which is commonly used for crop evapotranspiration, as the symbol for evapotranspiration by the land-use category. Therefore, the land-use category evapotranspiration rate on any given day is calculated as:

$$\mathrm{ETc} = \mathrm{ETo} \times \mathrm{Kc} \qquad (1)$$

where Kc is a factor to convert ETo to ETc. The methodology to determine the Kc curves for crops is explained in Appendix C and the derivation of Kc factors for various land-use categories is described Appendix D.

One set of 15 Kc curves (Fig. 4) is used for ET calculations during non-critical water years and the other set of 15 Kc curves (Fig. 5) is used during critical water years. Critical water years are those when irrigation water supply was identified as "short in supply" by the US Bureau of Reclamation and DWR. Whether or not a particular year is critical or non-critical is identified in the second column of the files (SA0001.csv – SA0168.csv) that provide information on the surface areas covered by the 15 land-use categories. Using the developed crop coefficients in Figs. 1 and 2, monthly mean in-season Kc values were computed for each of the 15 land-use categories (Table 7).

Table 7. Monthly mean crop coefficient (Kc) factors for the 15 surfaces ignoring off-season soil evaporation contributions.

Mon	OR	SB	FL	GR	DG	RV	NV	WS	AL	PA	RI	TO	TR	VI	UR
1				0.87	0.70	0.82	0.90	1.10		0.95					0.59
2				1.10	0.90	0.86	0.70	1.10		0.95			0.43		0.51
3	0.57	0.20		1.10	0.90	0.90	0.51	1.10		0.95			0.46		0.43
4	0.66	0.28	0.20	0.95	0.78	0.95	0.30	1.10	1.00	0.95		0.30	0.74	0.54	0.36
5	0.79	0.73	0.27	0.42	0.36	0.97	0.20	1.10	1.00	0.95	1.33	0.47	0.99	0.74	0.32
6	0.93	1.12	0.85			0.97	0.20	1.10	1.00	0.95	1.12	1.02	1.00	0.80	0.32
7	1.03	1.15	1.02			0.97	0.20	1.10	1.00	0.95	1.03	1.10	1.00	0.80	0.32
8	1.04	1.14	0.84			0.97	0.20	1.10	1.00	0.95	1.03	0.86	1.00	0.80	0.32
9	1.02	1.02	0.52			0.95	0.30	1.10	1.00	0.95	0.92		1.00	0.73	0.35
10	0.86					0.90	0.50	1.10	1.00	0.95			1.00	0.48	0.43
11	0.76			0.45	0.33	0.86	0.70	1.10		0.95			0.69	0.35	0.51
12				0.52	0.39	0.82	0.91	1.10		0.95					0.59

The Kc curves for the 15 land-use categories were determined as weighted means of the crop or other surface Kc curves within each category based on percentages that were observed in the land-use surveys. The growth dates and Kc values for individual crops and other surfaces are given in Appendix A in Table A.1 for non-critical years and in Table A.2 for critical years. The Kc method used in the DETAW program is the same as that used in the SIMETAW program, which follows a modified version of the method presented in Doorenbos and Pruitt (1977). The Kc method, crop types, etc. are explained in Appendix B of this document.

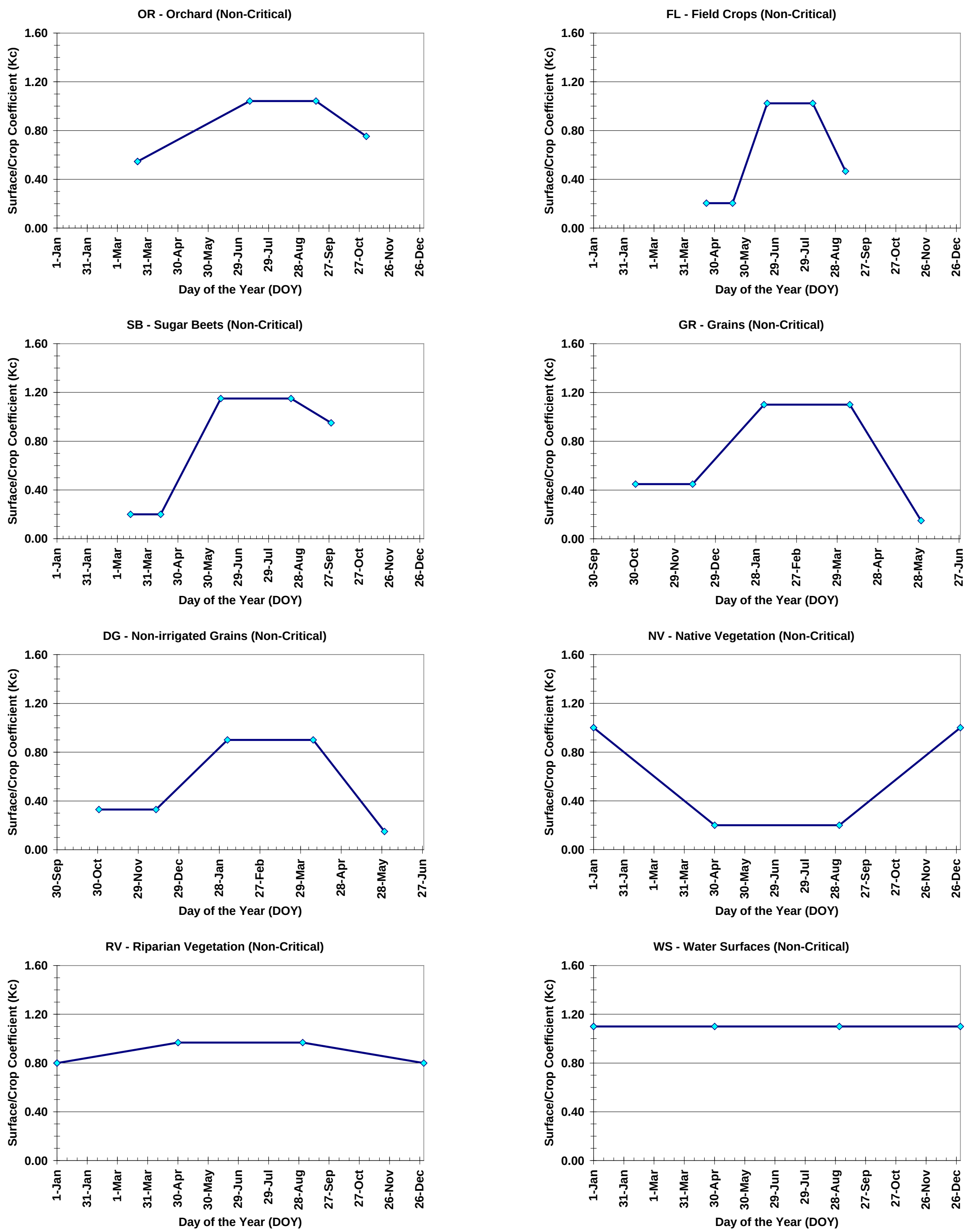


Figure 5. A set of eight charts show the surface land-use category crop coefficient curves for non-critical years ignoring the influence of off-season bare soil evaporation.

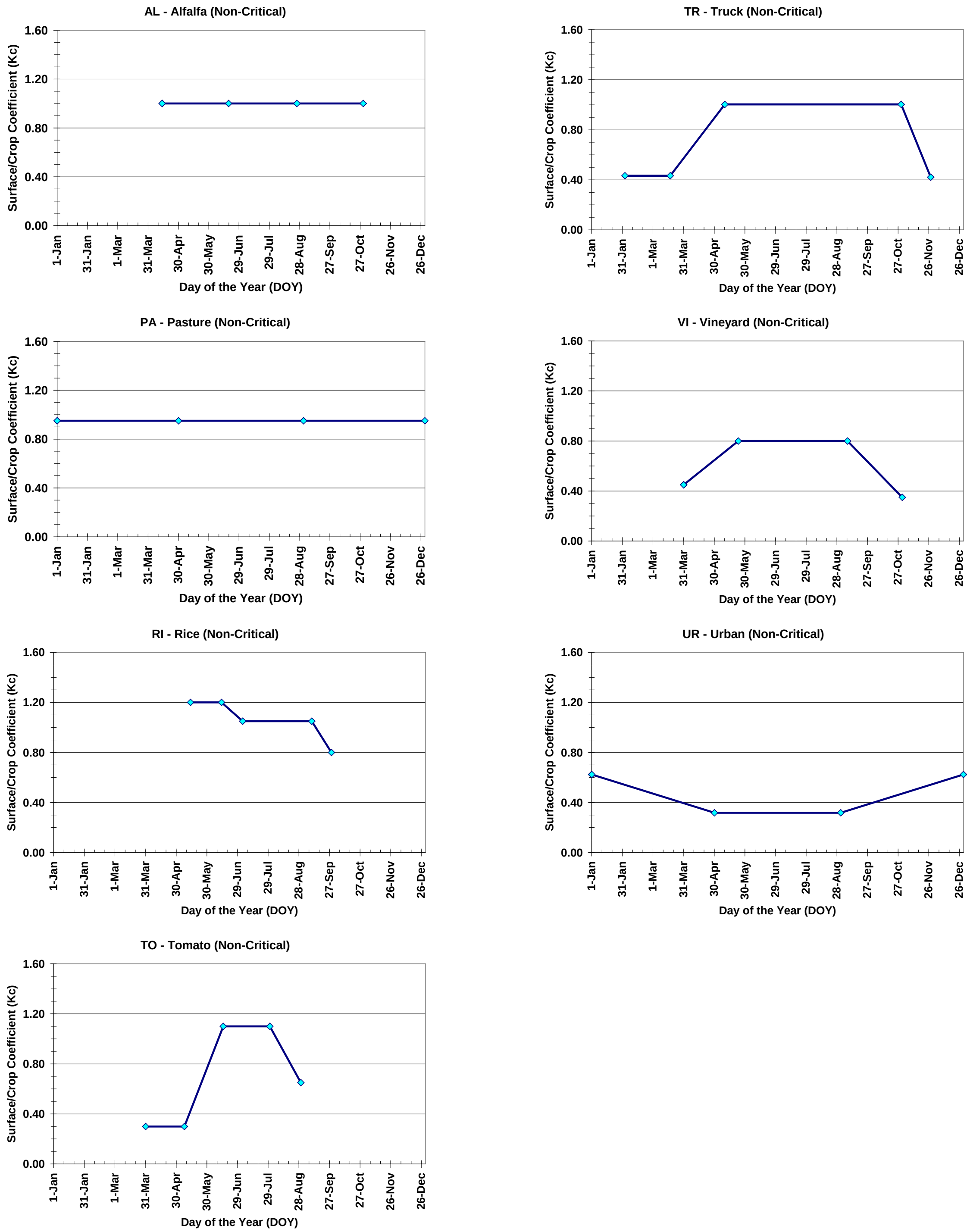


Figure 5. Continued - A set of seven charts show the surface land-use category crop coefficient curves for non-critical years ignoring the influence of off-season bare soil evaporation.

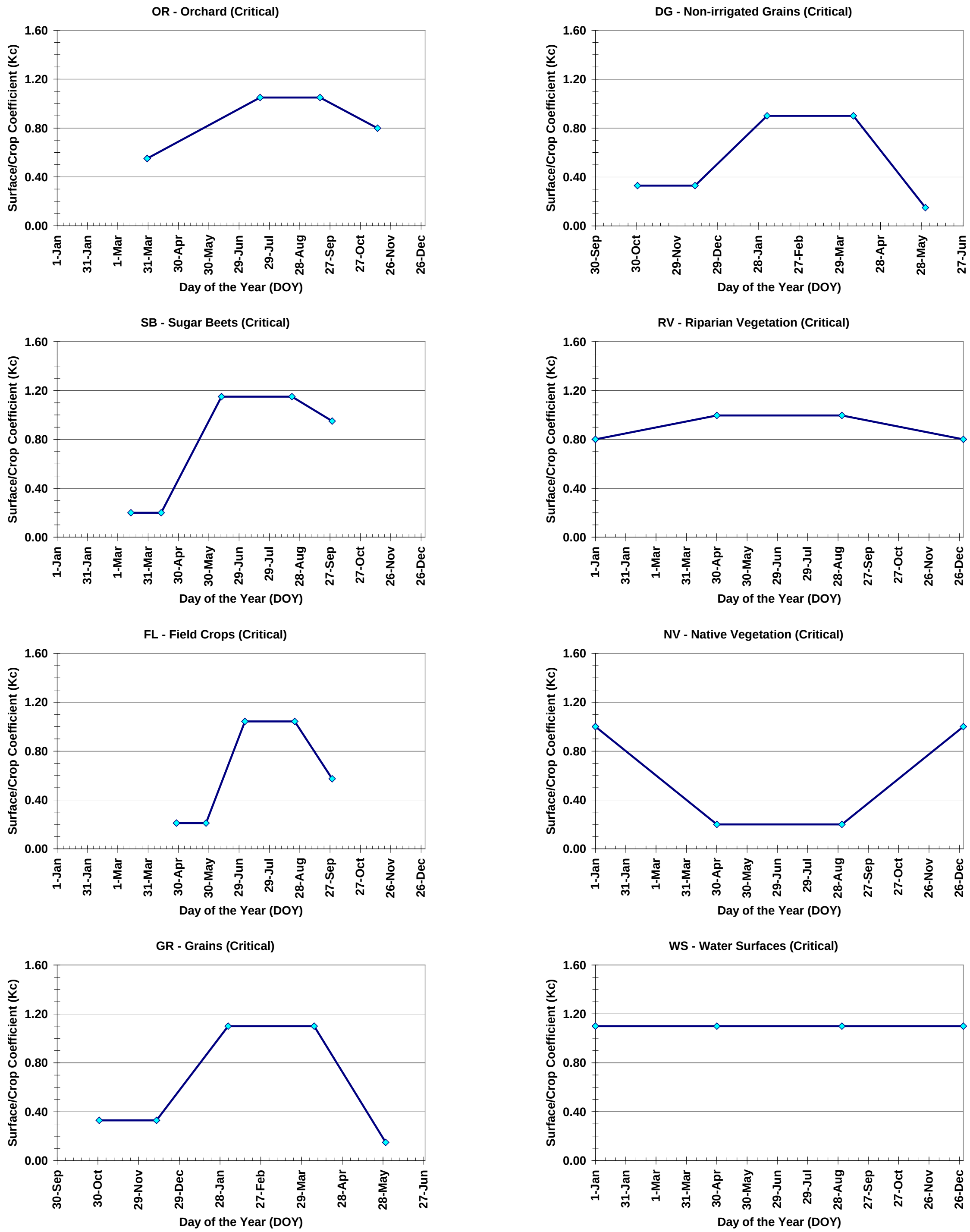


Figure 6. A set of eight charts show the surface land-use category crop coefficient curves for critical years ignoring the influence of off-season bare soil evaporation.

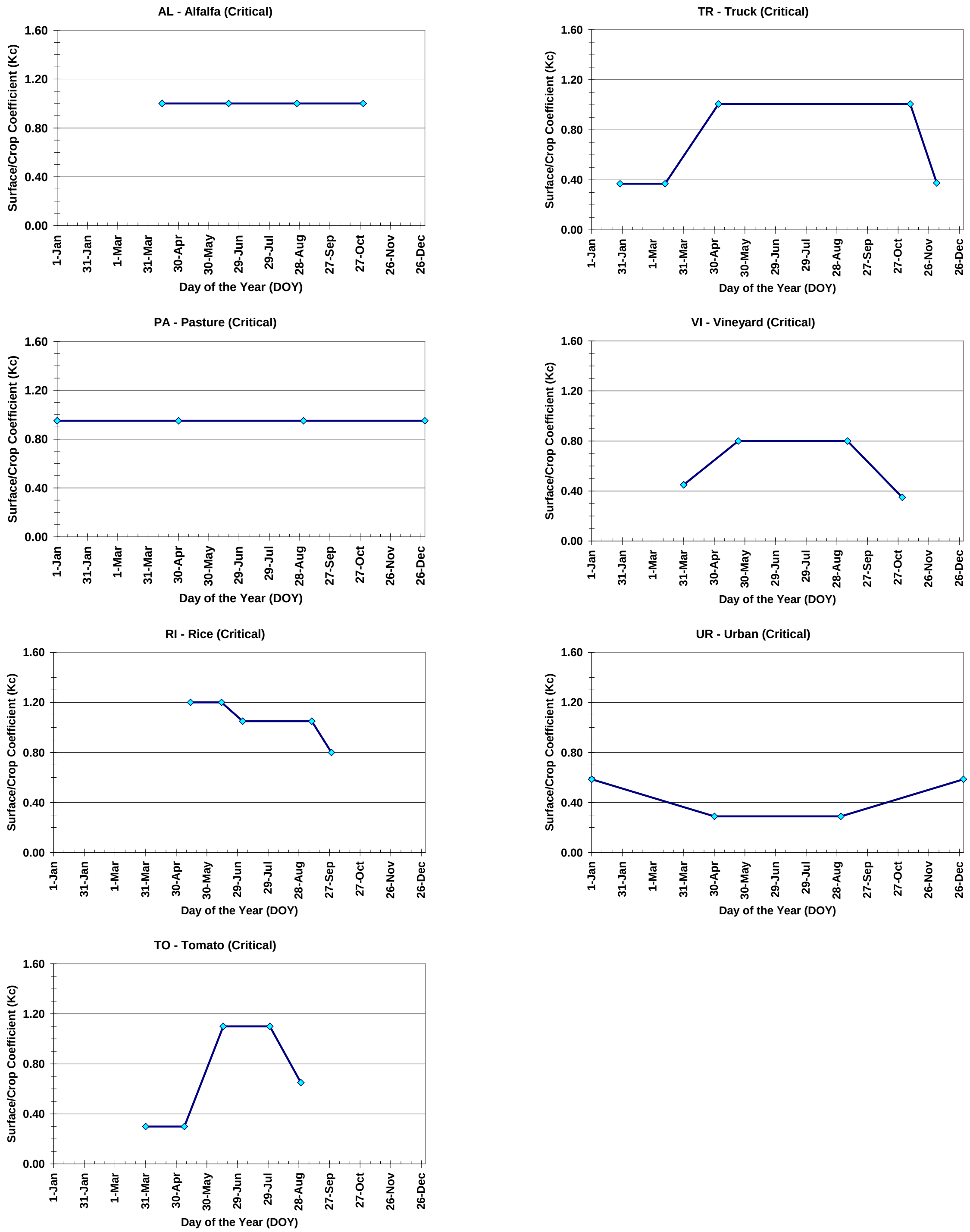


Figure 6.- Continued - A set of seven charts show the surface land-use category crop coefficient curves for critical years ignoring the influence of off-season bare soil evaporation.

ET of Applied Water

Definition and Calculations

ETaw is the sum of the net irrigation applications to a crop during its growing season, where each net irrigation application (NA) is equal to the product of the gross application (GA) and an application efficiency fraction (AE), i.e., NA = GA × AE. The gross application is equivalent to the applied water, and the application efficiency is the percentage of GA that contributes to crop evapotranspiration (ETc). Three possible methods to determine ETaw are explained below using the example of a tomato crop grown in Sub-area 104 in the Sacramento – San Joaquin River Delta. The ETo, ETc and Kc values for two sample years are shown in Figure 7.

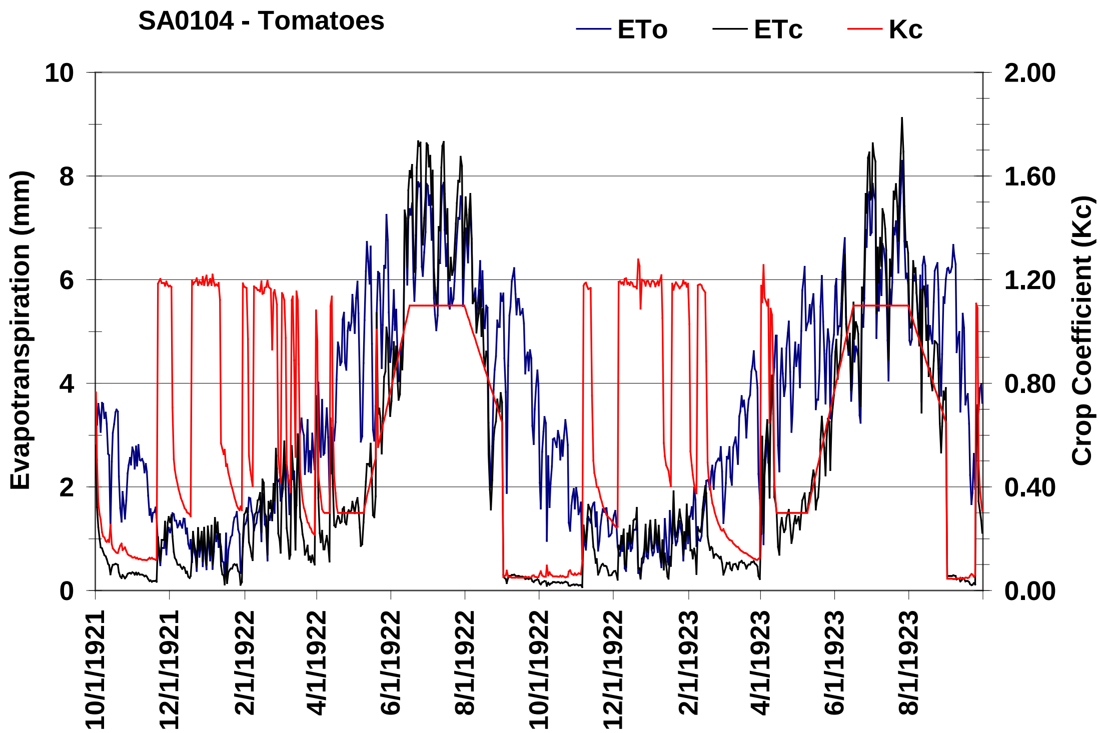


Figure 7. Crop (ETc) and reference (ETo) evapotranspiration and crop coefficient factors for 1921 – 1922 water years for a tomato crop grown in Sub-area 104 of the Delta.

Daily water balance calculations start with the soil water content on the previous day (SWC_i). Then the water losses to ETc are subtracted ($SWC_{i+1}=SWC_i - ETc$) to obtain the soil water content based only on ETc. The effective seepage (S_e) contribution to the water balance is computed by adding the seepage (S) contribution to the soil water content. If the sum is negative then S_e = S, otherwise $S_e = SWC_i - ET_c$. Then the soil water content based on ETc and effective seepage is given by $SWC_{i+1} = SWC_i - ETc + Se$. Next the precipitation (P) is added to the result to account for rainfall. If the sum is negative, then the effective rainfall is $R_e = P$, otherwise $R_e = SWC_i - ET_c + S_e$. Then, the final estimate of soil water content is given by:

$$SWC_{i+1} = SWC_i - ET_c + S_e + R_e$$

Irrigation is applied whenever the soil water content on a given day would fall below the management allowable depletion (MAD) set for that date. The net application (NA) amount is the depth of water needed to raise the soil water content (SWC_{i+1}) back to field capacity (FC) on the irrigation date. By definition, ETaw is the total applied water that contributes to ETc. Therefore, ETaw equals the sum of the net irrigation applications during a cropping season, and the ETaw for n irrigation events is calculated as:

$$ET_{aw} = NA_1 + NA_2 + \cdots + NA_n .$$

Alternatively, ETaw can be calculated as the seasonal total evapotranspiration (CETc) minus the cumulative effective seepage contribution (CS_e) minus the cumulative effective rainfall contribution (CR_e) minus the drop in soil water content (ΔWC) from the beginning to the end of the season (Figure 2). Ignoring irrigation contributions to the water balance, the daily drop in soil water content (dsw) from day *i* to *i*+1 is calculated as:

$$dsw = SWC_{i+1} - SWC_i = ET_c - S_e - R_e$$

where ETc is the crop evapotranspiration, S_e is the effective seepage contribution, and R_e is the effective rainfall. Therefore, the cumulative dsw curve (Cdsw) is the running total of the dsw values.

Figure 8 illustrates how one can calculate ETaw from CETc, CSe, CRe, Cdsw, and ΔSW. The Cdsw on any date, the cumulative change in daily soil water content is calculated as: $Cdsw = CET_c - C_{se} - C_{re}$. The ETaw is calculated at the end of the season as:

ETaw = Cdsw - ΔSW.

The ΔSW is unknown until the end of the season, however, so it cannot be computed until the end of a cropping season using this method. The ETaw can be computed from the net applications after the last NA is applied.

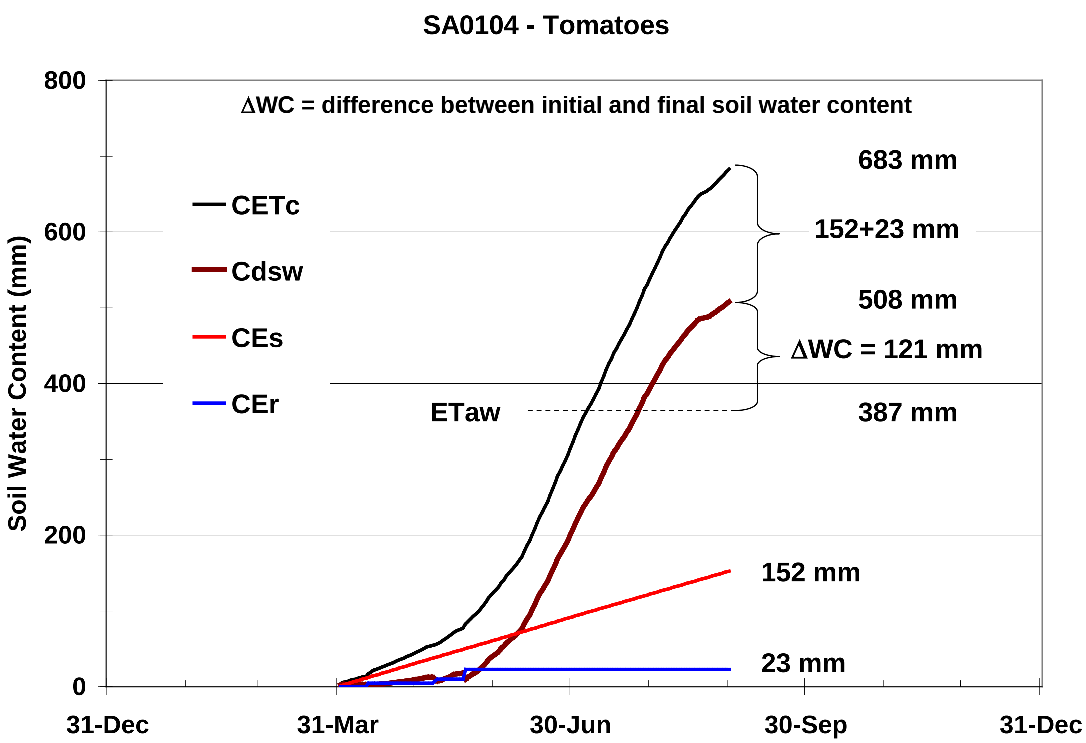


Figure 8. A plot of CET_c, CS_e, CR_e, and Cdsw versus time for the tomato crop using data from the 1921-22 water-year.

To obtain an estimate of the ETaw, one must also subtract the difference between the initial and final soil water content (ΔSW). Therefore,

$$\mathrm{ETaw} = \mathrm{Cdsw} - \Delta\mathrm{WC} = \mathrm{CETc} - \mathrm{CEs} - \mathrm{CEr} - \Delta\mathrm{WC} = \sum_{i=1}^{n} \mathrm{NA}_i$$

Thus, ETaw can be determined by (1) computing the season accumulation of daily changes in soil water content and subtracting ΔWC, (2) calculating the seasonal cumulative ETc and subtracting the cumulative Es and Er and the ΔWC, or (3) summing the net irrigation applications that occur during the season (Figure 3).

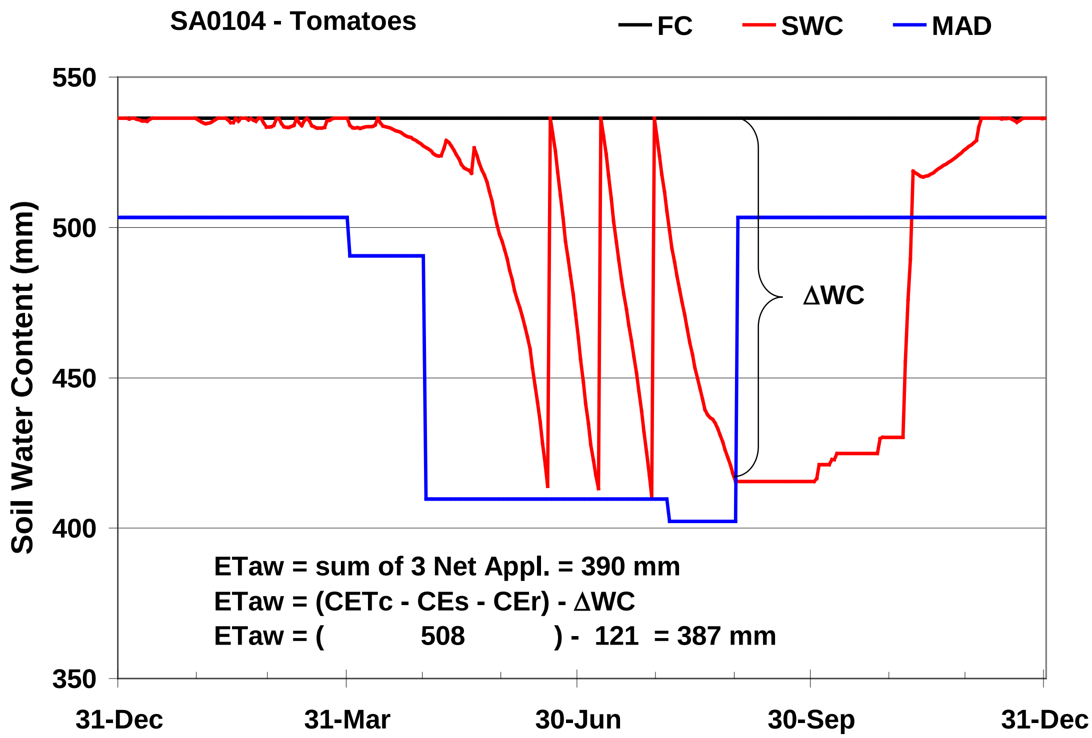


Figure 3. Water balance for tomatoes during the 1921-22 water-year on Sub-area 104 illustrating two ETaw calculation methods

The seasonal diversion of irrigation water needed to produce a crop is calculated as:

$$D = \frac{NA_1}{AE_1} + \frac{NA_2}{AE_2} + \cdots + \frac{NA_n}{AE_n}$$

where NA_i and AE_i are the net applications and application efficiencies on the i^{th} date of the season. Assuming a representative, seasonal application efficiency for the season, then the seasonal irrigation water diversion can be calculated as:

$$D = \frac{ETaw}{\overline{AE}}$$

where $\overline{AE}$ is the representative application efficiency fraction for the season.

Entering crop and soil information

Crop and soil information are read from a ‘.csv’ comma-delimited data file. The symbols used in the file are defined in Table 3 and sample ‘.csv’ files are shown for non-critical and critical years in Tables 4 and 5, respectively. The input data include the land-use category name, planting and ending dates, soil water holding characteristics, maximum soil and rooting depths, etc. Each row of data in the file contains a unique combination of the crop, soil and irrigation information. Unlike the SIMETAW model, DETAW is currently not designed to account for initial growth irrigation frequency, pre-irrigation information, immaturity factors, and presence of cover crops. This feature was not included because the data base of information is unavailable. The ability to account for these factors can be easily added to the application program.

Table 8. Symbols used in Tables 9 and 10.

Symbol	Variable
BD	Beginning calendar date for the in-season period
ED	Ending calendar date for the in-season period
BD	Beginning day of the year for the in-season period
ED	Ending day of the year for the in-season period. Subtract 365 for bigger numbers.
F	Frequency of irrigation during initial growth of type 1 crops (default =30 days)
Kc1	Crop coefficient on date B and between dates A and B
Kc2	Crop coefficient between dates C and D
Kc3	Crop coefficient on date E
a-b	Percentage of the season from date A to B
a-c	Percentage of the season from date A to C
a-d	Percentage of the season from date A to D
SDx	Maximum soil depth (mm)
RDx_Lo	Maximum crop root depth in Delta lowlands (mm)
RDx_Up	Maximum crop root depth in Delta uplands (mm)
AW_Lo	Available water content in Delta lowland soil (mm)
AW_Up	Available water content in Delta upland soils (mm)
AD %	Allowable depletion of available water (%)

Table 9. The first 28 rows of the file containing the non-critical year information including: the crop type number, the begin (BD) and end (ED) calendar dates and day of the year, the Kc values from dates a-b (Kc1), dates c-d (Kc2), and date E (Kc3), the percentages of the season from dates a-b, a-c, and a-d, the maximum soil depth (SDx), the maximum root depth for the lowlands (RDx_Lo) and uplands (RDx_Up) Delta regions, the available water for the lowlands (AW_Lo) and uplands (AW_Up), and the allowable depletion (50%). Row 5 contains the sub-area number, uplands or lowlands indicator, surface area in hectares and the type number that identifies uplands or lowlands. Table 5 contains symbol definitions.

Acreage	Planted by crop and year			BD = begin date ED = end date; IF = irrig. freq. init. growth; Kc1 = init. Growth Kc; Kc2 = midseason Kc; Kc3 = end season Kc												
A x 0.404687																
Sub-Area	TYPE	Sfc Area	TYPE #													
4	Uplands	403	2													
DICU Crop		Urban	Irrig Pasture	Alfalfa	Field	Sugarbeet	Irrig Grains	Rice	Truck Crops	Tomato	Orchard	Vineyard	Riparian Vegetation	Water Surfaces	Non-irrig Grain	Native Vegetation
Code	Type	UR	PA	AL	FI	SB	GR	RI	TR	TO	OR	VI	RV	WS	DGR	NV
Number	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Type		3	2	2	1	1	1	1	1	1	3	3	3	2	1	3
BD		1-Jan	1-Jan	14-Apr	22-Apr	14-Mar	31-Oct	14-May	3-Feb	31-Mar	21-Mar	31-Mar	1-Jan	1-Jan	31-Oct	1-Jan
ED		31-Dec	31-Dec	30-Oct	7-Sep	29-Sep	30-May	29-Sep	28-Nov	30-Aug	3-Nov	31-Oct	31-Dec	31-Dec	30-May	31-Dec
BD		1	1	105	113	74	305	135	34	91	81	91	1	1	305	1
ED		366	366	304	251	273	516	273	333	243	308	305	366	366	516	366
F		30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Kc1		0.62	0.95	1	0.2	0.2	0.45	1.2	0.43	0.3	0.55	0.45	0.8	1.1	0.33	1
Kc2		0.32	0.95	1	1.02	1.15	1.1	1.05	1	1.1	1.04	0.8	0.97	1.1	0.9	0.05
Kc3		0.62	0.95	1	0.47	0.95	0.15	0.8	0.42	0.65	0.75	0.35	0.8	1.1	0.15	1
a-b		0	0	0	19	15	20	22	15	25	0	0	0	0	20	0
a-c		33	33	33	44	45	45	37	33	50	49	25	33	33	45	33
a-d		67	67	67	76	80	75	86	90	80	78	75	67	67	75	67
SDx		1524	1524	1524	1524	1524	1524	1524	1524	1524	1524	1524	1524	1524	1524	1524
RDx_Lo		400	610	1219	610	1219	610	305	1219	1219	1524	1219	1524	1524	610	762
RDx_Up		400	610	1829	1219	1524	1219	610	1524	1524	1829	1524	1524	1524	610	610
AW_Lo		0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
AW_Up		0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
AD %		50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Table 10. The first 28 rows of the file containing the critical year information including: the crop type number, the begin (BD) and end (ED) calendar dates and day of the year, the Kc values from dates a-b (Kc1), dates c-d (Kc2), and date E (Kc3), the percentages of the season from dates a-b, a-c, and a-d, the maximum soil depth (SDx), the maximum root depth for the lowlands (RDx_Lo) and uplands (RDx_Up) Delta regions, the available water for the lowlands (AW_Lo) and uplands (AW_Up), and the allowable depletion (50%). Row 5 contains the sub-area number, uplands or lowlands indicator, surface area in hectares and the type number that identifies uplands or lowlands. Table 5 contains symbol definitions.

Acreage Planted by crop and year BD = begin date ED = end date; IF = irrig. freq. init. growth; Kc1 = init. growth Kc; Kc2 = midseason Kc; Kc3 = end season Kc

A x

0.404687

These are values for Critical Years

DICU			Irrig				Irrig		Truck				Riparian	Water	Non-irrig	Native
Crop		Urban	Pasture	Alfalfa	Field	Sugarbeet	Grains	Rice	Crops	Tomato	Orchard	Vineyard	Vegetation	Surfaces	Grain	Vegetation
Code	Type	UR	PA	AL	FI	SB	GR	RI	TR	TO	OR	VI	RV	WS	DG	NV
Number	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Type		3	2	2	1	1	1	1	1	1	3	3	3	2	1	3
BD		1-Jan	1-Jan	14-Apr	28-Apr	14-Mar	31-Oct	14-May	28-Jan	31-Mar	30-Mar	31-Mar	1-Jan	1-Jan	31-Oct	1-Jan
ED		31-Dec	31-Dec	30-Oct	29-Sep	29-Sep	30-May	29-Sep	3-Dec	30-Aug	13-Nov	31-Oct	31-Dec	31-Dec	31-May	31-Dec
BD		1	1	105	119	74	305	135	29	91	90	91	1	1	305	1
ED		366	366	304	273	273	516	273	339	243	318	305	366	366	517	366
F		30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Kc1		0.59	0.95	1	0.21	0.2	0.33	1.2	0.37	0.3	0.55	0.45	0.8	1.1	0.33	1
Kc2		0.29	0.95	1	1.04	1.15	1.1	1.05	1.01	1.1	1.05	0.8	1	1.1	0.9	0.05
Kc3		0.59	0.95	1	0.57	0.95	0.15	0.8	0.38	0.65	0.8	0.35	0.8	1.1	0.15	1
a-b		0	0	0	19	15	20	22	14	25	0	0	0	0	20	0
a-c		33	33	33	44	45	45	37	31	50	49	25	33	33	45	33
a-d		67	67	67	76	80	75	86	92	80	75	75	67	67	75	67
SDx		1524	1524	1524	1524	1524	1524	1524	1524	1524	1524	1524	1524	1524	1524	1524
RDx_Lo		400	610	1219	610	1219	610	305	1219	1219	1524	1219	1524	1524	610	762
RDx_Up		400	610	1829	1219	1524	1219	610	1524	1524	1829	1524	1524	1524	610	610
AW_Lo		0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
AW_Up		0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
AD %		50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Calculating the yield threshold depletion

Soil water-holding characteristics, effective rooting depths, and irrigation frequency are used with rainfall and ET_c data to calculate a daily water balance and determine effective rainfall and ET_{aw}, which is equal to the seasonal cumulative ET_c minus the effective rainfall. Irrigations are timed so that the estimated soil water content does not fall below the yield threshold depletion, which is calculated from input soil depth, rooting depth, and percentage allowable depletion. In the off-season, the soil water depletion (*SWD*) is allowed to drop to a maximum 50% depletion of the available water in the top 0.3 m.

Crop rooting depth, maximum soil depth, and water holding characteristics are used to calculate the yield threshold depletion (*YTD*), which is used to make a crop and soil specific irrigation schedule. The user selects one of three general categories for the soil water holding characteristics. If a light soil is selected, the program uses 0.075 mm per mm for the available water holding capacity of the soil. A value of 0.125 mm per mm is used for the available water holding capacity of a medium textured soil. For a heavy soil, a value of 0.175 mm per mm is used. The selected value is multiplied by the smaller of the rooting depth or the soil depth to determine the plant available water (*PAW*) within the soil reservoir at the maximum rooting depth for the crop. To simplify graphing, the water holding content at field capacity is estimated as twice the available water holding content. The *YTD* is calculated as the product of the crop-specific allowable depletion and the *PAW*. In reality, the rooting depth and *PAW* increase as the roots grow, but, because of the additional complexity, this is ignored in the DETAW model. The maximum rooting depths vary depending whether the sub-area is in the lowlands or uplands of the Delta and on the land-use category. The maximum rooting depths (Table 11) were provide by DWR.

Table 11. Maximum root and soil depths* by surface type and location (i.e., Delta upland and lowland) provided by DWR.

	Root depths			
	Lowland	Upland	Lowland	Upland
	ft	ft	mm	mm
PA	2	2	610	610
AL	4	6	1219	1829
FI	2	4	610	1219
SB	4	5	1219	1524
GR	2	4	610	1219
RI	1	2	305	610
TR	4	5	1219	1524
TO	4	5	1219	1524
OR	5	6	1524	1829
VI	4	5	1219	1524
DG	2	2	610	610
NV	2.5	2	762	610

*Maximum soil depths were set at 1524 mm

ET of applied water calculations

The K_c values were based on the ET_o data and crop, soil, and management specific parameters from a row in the 'DAUnnn.csv' file. During the off-season, crop coefficient values were estimated from bare soil evaporation as previously described. For effective rainfall calculations, it is assumed that all water additions to the soil come from rainfall and losses are only due to deep percolation. Because the water balance was calculated each day, rainfall runoff and surface water running onto a cropped field are ignored.

In the DETAW program, seepage of from the rivers and canals to the ground water and into the effect root zone is estimated as 0.3 inches per foot of root depth for all surfaces except rice and open water, which are assumed to be in equilibrium with the influx of seepage water.

During the off-season, the maximum depletion allowed is 50% of the *PAW* in the upper 30 cm of soil. It is assumed that soil evaporation is minimal once 50% of the available water is removed. If the soil water depletion (*SWD*) is less than this value, the ET_c is added to the previous day's *SWD* to estimate the current *SWD*. Once the *SWD* reaches the maximum depletion, it remains at the maximum depletion unless rainfall decreases the depletion. If rainfall occurs, the *SWD* depletion is decreased by the rainfall amount but never less than zero. If the *SWD* at the end of a cropping season starts at some value greater than the maximum soil water depletion, the *SWD* is allowed to decrease with rainfall additions but it is not allowed to increase with ET_c (Fig. 4).

If a crop is pre-irrigated, then the *SWD* is set equal to zero on the day preceding the season. If it is not pre-irrigated, then the *SWD* on the day preceding the season is determined by water balance during the off-season before planting or leaf-out. It is assumed that the *SWD* equals zero on September 30, 1921. After that the *SWD* is calculated using water balance for the entire period of record.

During the growing season, the *SWD* is updated by adding the ET_c on the current day to the *SWD* on the previous day (Fig. 4). If rainfall occurs, *SWD* is reduced by an amount equal to the rainfall. However, the *SWD* is not allowed to be less than zero. This automatically determines the effective rainfall as equal to the recorded rainfall if the amount is less than the *SWD*. If the recorded rainfall is more than the *SWD*, then the effective rainfall equals the *SWD*. This method ignores runoff and water running on to the field, but this is a minor problem in most irrigated fields in California. Irrigation events are timed on dates when the *SWD* would exceed the *YTD*. It is assumed that the *SWD* returns to zero on each irrigation date. The ET_{aw} is calculated both on a seasonal and an annual basis as the cumulative ET_c minus the effective rainfall. The calculations are made for each year over the period of record as well as an overall average over years. The results are output to a summary table.

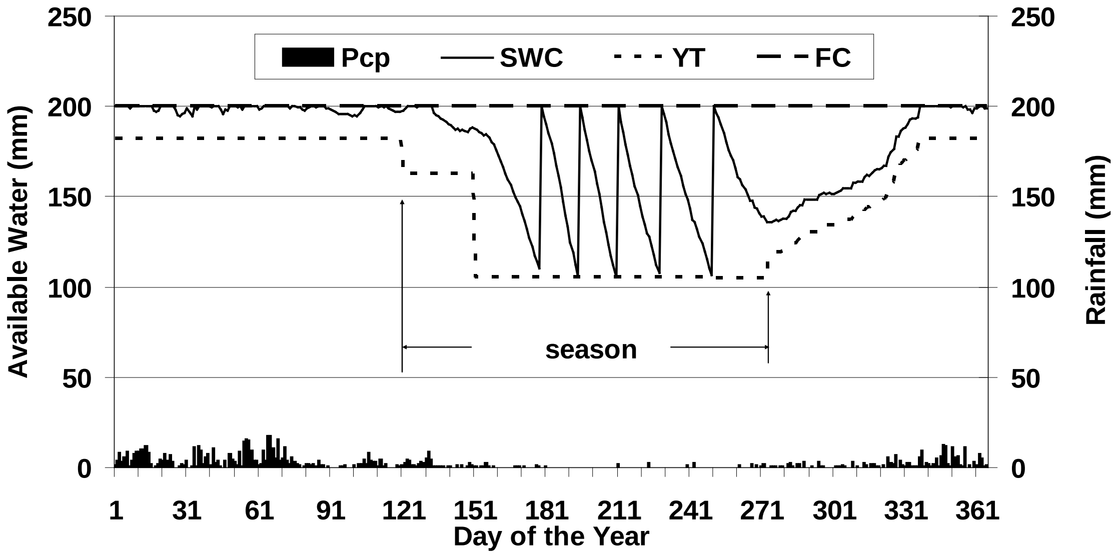


Fig. 4. An annual water balance for maize showing fluctuations in soil water content (*SWC*) between field capacity (*FC*) and the yield threshold (*YT*) and precipitation (Pcp).

Final Output

All input data and calculations in the DETAW application are in metric units. Except for the ETaw output file, the output is also all in metric units. The ETaw output file '.eaw' has all of the volumes converted to acre-feet (A-ft). These values include the in-season CETc, CEr, Cspg, and ETaw, where the values correspond to the cumulative total in-season crop evapotranspiration, effective rainfall, seepage contribution, and ETaw, respectively. Similar values are supplied for the off-season using the symbols OCETc, OCEr, OCspg, and OETaw. In addition, the total annual values are output using the symbols ACETc, ACEr, ACspg, and AETaw. Again, all of these data are output in the units A-ft for the respective land-use categories. To covert to A-ft, the depth of water (mm) is multiplied by the area of the land-use category (hectares) and the product is multiplied by 0.008107.

Conversion process: $\mathrm{mm} \times \frac{1\mathrm{m}}{10^3\,\mathrm{mm}} \times \mathrm{ha} \times \frac{10^4\,\mathrm{m}^2}{\mathrm{ha}} \times \frac{1\mathrm{A-ft}}{1233.482\,\mathrm{m}^3} = 0.008107\,\mathrm{A-ft}$

Summary of Delta ETaw

A daily water balance was used to estimate the volume of irrigation water needed for each of the 15 land use categories by sub-area. While there are 15 land-use categories, one can also separate the land use into Agriculture and non-Agricultural uses, which include urban, riparian vegetation, water surfaces, and native vegetation. The areas represented by these surfaces vary from year to year depending on whether it is a critical or non-critical year. Data files containing the area covered (hectares) by each of the 15 surfaces within each sub-area are used by DETAW to determine year-to-year changes in volumes of ETc and ETaw based on the daily water balances. The filenames are SA0001.csv through SA0168.csv and the same filenames are used for both the historical and the projected sets of data files. The land use areas vary as observed from 1921-2003 in the set of historical data files. In the set of projected data files, the land usage is fixed for all critical years and a different fixed value is used for non-critical years. Therefore, the historical land use data files represent an estimate of actual land use from 1921-2003 and the projected land use data files represent a simulation with land use varying depending on whether a year is a critical or non-critical water year.

Table 12. Volumetric water-year ETc over all land uses, water-year ETaw for agriculture and non-agricultural land-uses, and total water-year ETaw for both historical and projected land usage for the years 1922-2003. All volumes are in acre-feet.

	Historical				Projected			
Year	Water-Yr ETc	Water-Yr ETaw Agriculture	Water-Yr ETaw non-Agriculture	Water-Yr ETaw Total	Water-Yr ETc	Water-Yr ETaw Agriculture	Water-Yr ETaw non-Agriculture	Water-Yr ETaw Total
1922	1,889,175	1,166,554	174,467	1,341,021	1,902,008	1,120,678	276,575	1,397,254
1923	1,798,293	1,075,084	164,043	1,239,127	1,832,721	1,052,643	255,015	1,307,658
1924	1,870,963	1,190,419	185,902	1,376,321	1,871,699	1,144,412	242,357	1,386,769
1925	1,796,695	936,252	148,192	1,084,444	1,847,608	936,653	175,351	1,112,003
1926	2,038,971	1,311,723	207,844	1,519,566	2,045,175	1,273,566	256,481	1,530,047
1927	1,981,299	1,141,455	179,873	1,321,328	2,041,681	1,157,406	286,351	1,443,757
1928	2,043,222	1,243,429	191,056	1,434,485	2,067,323	1,205,268	290,845	1,496,113
1929	1,932,548	1,221,876	184,303	1,406,179	1,898,875	1,147,310	239,757	1,387,067
1930	1,831,970	1,135,682	167,139	1,302,821	1,762,225	1,029,106	215,585	1,244,690
1931	2,156,568	1,373,779	212,610	1,586,388	2,090,722	1,259,741	265,097	1,524,838
1932	2,048,558	1,361,175	211,650	1,572,825	1,980,955	1,250,266	265,987	1,516,253
1933	2,002,814	1,325,288	207,432	1,532,720	1,954,704	1,237,369	264,439	1,501,807
1934	2,081,182	1,389,266	223,301	1,612,567	2,025,748	1,292,053	288,535	1,580,588

	Historical				Projected			
Year	Water-Yr ETc	Water-Yr ETaw Agriculture	Water-Yr ETaw non-Agriculture	Water-Yr ETaw Total	Water-Yr ETc	Water-Yr ETaw Agriculture	Water-Yr ETaw non-Agriculture	Water-Yr ETaw Total
1935	2,074,770	1,264,710	194,182	1,458,892	2,088,907	1,225,164	290,755	1,515,919
1936	2,160,165	1,229,428	265,160	1,494,588	2,146,083	1,247,486	304,907	1,552,393
1937	2,072,197	1,266,067	284,587	1,550,654	2,050,451	1,273,506	325,605	1,599,110
1938	2,094,025	1,183,606	253,203	1,436,809	2,097,928	1,211,758	295,228	1,506,985
1939	2,090,962	1,267,735	274,175	1,541,911	2,028,809	1,247,679	255,611	1,503,290
1940	2,104,235	1,240,492	276,906	1,517,398	2,073,049	1,241,258	315,774	1,557,032
1941	2,070,232	1,122,925	236,777	1,359,702	2,035,692	1,116,455	271,945	1,388,400
1942	2,094,004	1,134,840	230,586	1,365,426	2,062,393	1,145,615	269,055	1,414,670
1943	2,086,584	1,161,394	244,196	1,405,591	2,040,893	1,140,569	284,549	1,425,117
1944	2,131,655	1,236,978	272,730	1,509,708	2,008,255	1,162,318	252,863	1,415,181
1945	2,144,069	1,310,314	263,282	1,573,596	2,063,919	1,257,226	308,911	1,566,137
1946	2,170,482	1,272,483	256,993	1,529,477	2,078,681	1,210,479	301,226	1,511,706
1947	2,180,501	1,388,204	282,896	1,671,100	2,003,628	1,253,026	266,399	1,519,425
1948	2,142,985	1,109,574	214,998	1,324,572	2,044,969	1,050,761	250,231	1,300,991
1949	2,214,664	1,384,938	277,178	1,662,116	2,025,573	1,235,919	261,403	1,497,322
1950	2,193,259	1,391,674	270,162	1,661,836	2,037,898	1,268,570	316,119	1,584,689
1951	2,186,282	1,289,887	250,483	1,540,370	2,040,551	1,180,367	294,035	1,474,403
1952	2,199,767	1,302,444	246,237	1,548,681	2,046,889	1,179,535	287,330	1,466,866
1953	2,164,226	1,330,191	272,092	1,602,283	2,000,572	1,201,112	315,031	1,516,143
1954	2,207,987	1,333,926	260,415	1,594,341	2,042,843	1,199,423	302,131	1,501,554
1955	2,183,715	1,340,404	270,721	1,611,125	1,961,096	1,162,743	247,555	1,410,299
1956	2,199,855	1,319,295	266,357	1,585,652	2,028,983	1,182,910	300,113	1,483,024
1957	2,211,282	1,263,348	252,709	1,516,057	2,051,650	1,140,296	285,034	1,425,329
1958	2,222,476	1,250,886	237,171	1,488,056	2,063,089	1,118,761	269,463	1,388,225
1959	2,195,325	1,408,539	295,577	1,704,116	2,015,403	1,268,140	333,174	1,601,313
1960	2,235,924	1,460,257	302,956	1,763,213	2,002,005	1,264,803	276,962	1,541,765
1961	2,201,233	1,379,385	275,953	1,655,338	1,976,254	1,192,850	249,402	1,442,252
1962	2,142,285	1,413,736	290,098	1,703,835	1,971,754	1,270,137	326,571	1,596,707
1963	2,114,995	1,165,700	219,096	1,384,796	1,980,260	1,058,233	247,740	1,305,974
1964	2,106,541	1,286,072	267,118	1,553,189	1,933,619	1,148,266	243,072	1,391,338
1965	2,127,449	1,219,320	241,722	1,461,042	2,005,164	1,116,974	272,281	1,389,255
1966	2,119,100	1,363,229	294,290	1,657,519	1,995,025	1,254,318	330,798	1,585,116
1967	2,094,699	1,211,831	245,343	1,457,174	1,996,015	1,128,166	275,931	1,404,096
1968	2,155,691	1,325,556	281,380	1,606,936	2,053,968	1,238,781	314,714	1,553,494
1969	2,193,278	1,337,444	283,454	1,620,898	2,114,489	1,266,574	316,336	1,582,910
1970	2,150,116	1,345,514	294,781	1,640,295	2,082,410	1,287,067	327,869	1,614,936
1971	2,049,100	1,208,706	262,850	1,471,556	2,003,259	1,169,479	291,524	1,461,003
1972	2,071,534	1,321,623	301,497	1,623,120	2,025,316	1,280,442	333,216	1,613,658
1973	2,193,247	1,285,424	274,935	1,560,360	2,164,396	1,260,676	303,758	1,564,434
1974	2,283,033	1,270,212	282,556	1,552,768	2,248,587	1,239,655	304,124	1,543,779
1975	2,125,861	1,229,093	281,741	1,510,834	2,116,665	1,222,080	302,763	1,524,843
1976	2,073,949	1,207,041	289,716	1,496,757	2,038,513	1,180,680	249,857	1,430,537
1977	2,026,777	1,200,878	288,204	1,489,082	1,984,580	1,167,110	248,735	1,415,844
1978	2,064,396	1,179,432	277,923	1,457,355	2,081,834	1,194,866	294,608	1,489,474

	Historical				Projected			
Year	Water-Yr ETc	Water-Yr ETaw Agriculture	Water-Yr ETaw non-Agriculture	Water-Yr ETaw Total	Water-Yr ETc	Water-Yr ETaw Agriculture	Water-Yr ETaw non-Agriculture	Water-Yr ETaw Total
1979	1,963,445	1,176,124	288,756	1,464,880	1,994,858	1,199,218	306,009	1,505,227
1980	1,940,002	1,048,738	250,506	1,299,244	1,966,635	1,073,135	263,732	1,336,867
1981	2,026,418	1,240,682	305,107	1,545,789	1,997,448	1,218,530	258,498	1,477,028
1982	2,028,182	1,030,588	234,959	1,265,547	2,052,614	1,049,555	245,462	1,295,017
1983	1,887,893	898,011	236,606	1,134,617	2,051,483	1,040,008	243,435	1,283,442
1984	2,028,201	1,235,045	309,823	1,544,868	2,052,383	1,256,961	320,705	1,577,666
1985	1,985,791	1,128,505	278,408	1,406,913	1,990,368	1,142,675	230,080	1,372,755
1986	1,930,222	1,066,919	276,089	1,343,007	2,030,857	1,168,190	283,485	1,451,675
1987	1,962,201	1,193,031	335,858	1,528,888	2,006,263	1,249,563	272,918	1,522,481
1988	1,972,728	1,124,045	309,273	1,433,318	2,009,458	1,181,027	253,325	1,434,352
1989	1,989,243	1,123,869	292,770	1,416,639	2,011,014	1,163,347	241,700	1,405,047
1990	2,071,263	1,189,859	312,933	1,502,792	2,074,531	1,208,191	258,552	1,466,742
1991	2,004,998	1,128,023	301,566	1,429,590	2,005,940	1,146,965	246,949	1,393,914
1992	2,084,127	1,227,941	316,878	1,544,818	2,084,075	1,243,260	258,555	1,501,815
1993	2,061,323	1,074,706	285,132	1,359,837	2,120,154	1,136,978	286,315	1,423,293
1994	1,991,648	1,144,063	302,532	1,446,594	1,993,015	1,159,091	245,548	1,404,639
1995	2,066,834	1,114,229	267,827	1,382,056	2,040,042	1,085,136	268,422	1,353,558
1996	2,082,167	1,237,576	321,462	1,559,038	2,101,888	1,251,787	321,148	1,572,935
1997	2,057,931	1,278,243	333,598	1,611,841	2,051,525	1,268,310	332,918	1,601,229
1998	2,139,199	1,086,200	255,825	1,342,026	2,102,621	1,049,039	253,427	1,302,466
1999	2,084,511	1,205,577	283,758	1,489,336	2,026,393	1,149,503	280,280	1,429,782
2000	2,127,008	1,259,823	323,345	1,583,168	2,093,943	1,231,351	319,448	1,550,799
2001	2,144,046	1,255,933	313,708	1,569,641	2,084,804	1,212,298	247,065	1,459,364
2002	2,092,299	1,275,817	330,223	1,606,040	2,032,308	1,228,408	260,602	1,489,010
2003	2,093,430	1,193,533	290,586	1,484,119	2,060,386	1,160,071	282,981	1,443,052
Mean	2,080,638	1,231,997	262,448	1,494,445	2,027,668	1,185,870	278,276	1,464,146

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APPENDIX A. Tables of data used in the DETAW model

Table A.1. Delta sub-area number, upland and lowland, acreage, precipitation station and ETo correction factor information.

Sub-area Name	Sub-area Number (New)	Sub-area Number (Original)	Uplands / Lowlands	Acreage	Precipitation Station (Thiessen Polygons)	Correction Factor (Isolines)
UNION ISLAND (EAST)	1	1	Lowlands	11851.38	Stockton Tracy Carbona	1.013630
UNION ISLAND (WEST)	2	2	Lowlands	13698.20	Brentwood Stockton Tracy Carbona	1.039110
GRAND ISLAND	3	3	Lowlands	16781.43	Rio Vista	0.994821
MOSSDALE	4	4	Uplands	402.86	Tracy Carbona	0.990420
MERRITT ISLAND	5	5	Lowlands	4909.53	Galt Rio Vista Davis	0.901491
LISBON DISTRICT	6	6	Lowlands	5948.98	Galt Davis	0.898839
ANDRUS ISLAND (LOWER)	7	7	Lowlands	3545.33	Rio Vista	1.054680
SHERMAN ISLAND	8	8	Lowlands	10445.00	Rio Vista	1.077990
NEW HOPE TRACT	9	9	Lowlands	9710.28	Galt	0.830500
SUTTER ISLAND	10	10	Lowlands	2619.83	Rio Vista	0.982798
ROUGH AND READY	11	11	Lowlands	1432.97	Stockton	0.882488
MOSS TRACT (BOGGS)	12	12	Lowlands	746.51	Stockton	0.820928
ANDRUS ISLAND (MIDDLE)	13	13	Lowlands	1799.17	Rio Vista	1.039080
RYER ISLAND	14	14	Lowlands	11966.83	Rio Vista	1.034450
ROBERTS ISLAND (MIDDLE)	15	15	Lowlands	11976.36	Stockton	0.948185
EGBERT TRACT	16	16	Lowlands	5599.56	Rio Vista	1.074900
EGBERT TRACT	17	17	Uplands	89.37	Rio Vista	1.078580
ROBERTS ISLAND (UPPER)	18	18	Lowlands	7605.68	Stockton Tracy Carbona	0.977793
TERMINOUS TRACT	19	19	Lowlands	11181.31	Lodi Rio Vista Stockton	0.899747
PIERSON DISTRICT	20	20	Lowlands	9154.54	Galt Rio Vista	0.915694
WALNUT GROVE	21	21	Lowlands	424.14	Galt Rio Vista	0.907011
ANDRUS	22	22	Lowlands	2573.70	Rio Vista	0.962062

Sub-area Name	Sub-area Number (New)	Sub-area Number (Original)	Uplands / Lowlands	Acreage	Precipitation Station (Thiessen Polygons)	Correction Factor (Isolines)
ISLAND (UPPER)						
TYLER ISLAND	23	23	Lowlands	8940.13	Rio Vista	0.989563
POCKET DISTRICT	24	24	Lowlands	696.13	Davis	0.898070
ROBERTS ISLAND (LOWER)	25	25	Lowlands	11306.99	Stockton	0.958752
SCRIBNER	26	26	Lowlands	1612.05	Galt Davis	0.900000
HOOD JUNCTION	27	27	Lowlands	113.45	Galt	0.879482
RANDALL ISLAND	28	28	Lowlands	392.56	Galt Rio Vista	0.912450
BOULDIN ISLAND	29	29	Lowlands	6682.87	Rio Vista Stockton	1.010950
GLIDE DISTRICT	30	30	Lowlands	1340.16	Davis	0.893306
EL PESCADERO	31	31	Lowlands	7193.41	Brentwood Tracy Carbona	1.042270
HOTCHKISS TRACT	32	32	Lowlands	3128.87	Brentwood Rio Vista	1.049400
BRYON TRACT	33	33	Lowlands	5905.86	Brentwood	1.036730
CLIFTON COURT	34	34	Lowlands	3838.31	Brentwood	1.028990
INACTIVE	35	35	Lowlands	2247.26	Galt	0.884435
WEBER TRACT	36	36	Uplands	241.50	Stockton	0.818116
JERSEY ISLAND	37	37	Lowlands	3571.53	Rio Vista	1.057570
WEST SACRAMENTO	38	38	Lowlands	9422.67	Davis	0.890709
NETHERLANDS (COUNTIES 48 & 57)	39	39	Lowlands	26036.42	Galt Rio Vista Davis	0.949220
UNNAMED	40	40	Lowlands	6746.09	Galt	0.863781
PICO AND NAGLEE	41	41	Uplands	10457.02	Brentwood Tracy Carbona	1.041430
TWITCHELL ISLAND	42	42	Lowlands	3694.80	Rio Vista	1.072970
SMITH RANCH	43	43	Lowlands	223.39	Stockton	0.826821
PRIVATELY OWNED	44	44	Uplands	1782.00	Galt	0.796897
SMITH TRACT	45	45	Uplands	128.16	Stockton	0.811835
PROSPECT ISLAND	46	46	Lowlands	2503.33	Rio Vista	1.037930
MILDRED ISLAND	47	47	Lowlands	1607.69	Stockton	1.016980
VENICE ISLAND	48	48	Lowlands	4396.58	Rio Vista Stockton	1.015030
ORWOOD TRACT	49	49	Lowlands	2291.61	Brentwood	1.046390
HOLLAND	50	50	Lowlands	4302.18	Brentwood	1.042240

Sub-area Name	Sub-area Number (New)	Sub-area Number (Original)	Uplands / Lowlands	Acreage	Precipitation Station (Thiessen Polygons)	Correction Factor (Isolines)
TRACT					Rio Vista	
WEBB TRACT	51	51	Lowlands	5510.29	Rio Vista	1.052420
MANDEVILLE ISLAND	52	52	Lowlands	7316.27	Rio Vista Stockton	1.023200
BACON ISLAND	53	53	Lowlands	6535.95	Brentwood Rio Vista Stockton	1.029770
EMPIRE TRACT	54	54	Lowlands	4908.84	Stockton	0.972400
MCDONALD TRACT	55	55	Lowlands	3639.30	Stockton	1.004100
BRACK TRACT	56	56	Lowlands	5071.86	Lodi Rio Vista	0.870689
PALM TRACT	57	57	Lowlands	2604.15	Brentwood	1.043730
RINDGE TRACT	58	58	Lowlands	7252.99	Stockton	0.924241
JONES TRACT (LOWER)	59	59	Lowlands	5988.94	Stockton	1.014200
JONES TRACT (UPPER)	60	60	Lowlands	6746.09	Stockton	1.019630
VICTORIA ISLAND	61	61	Lowlands	7943.17	Brentwood Stockton	1.042270
MEDFORD ISLAND	62	62	Lowlands	1527.07	Rio Vista Stockton	1.008160
BISHOP TRACT	63	63	Lowlands	2331.56	Stockton	0.837608
KING ISLAND	64	64	Lowlands	3638.51	Stockton	0.898976
PESCADERO DISTRICT	65	65	Lowlands	5088.73	Tracy Carbona	1.023220
PESCADERO DISTRICT	66	66	Uplands	3661.89	Tracy Carbona	1.037590
BRADFORD ISLAND	67	67	Lowlands	2146.55	Rio Vista	1.066550
HASTINGS TRACT	68	68	Lowlands	7530.74	Rio Vista	1.058870
STEWART TRACT	69	69	Lowlands	4330.83	Tracy Carbona	1.000110
RIVER JUNCTION	70	70	Uplands	1266.24	Tracy Carbona	1.027690
VEALE TRACT	71	71	Lowlands	1476.61	Brentwood	1.046800
BRANNON ISLAND	72	72	Lowlands	7593.64	Rio Vista	1.073320
YOLANO (COUNTIES 48 & 57)	73	73	Uplands	13925.83	Rio Vista Davis	1.021160
WOODWARD ISLAND	74	74	Lowlands	1850.99	Brentwood Stockton	1.036230
SARGENT-BARNHART TRACT	75	75	Lowlands	817.60	Stockton	0.852929
MCMULLIN RANCH	76	76	Uplands	1958.39	Tracy Carbona	1.011050
INACTIVE	77	77	Uplands	19646.68	Rio Vista Davis	0.988669

Sub-area Name	Sub-area Number (New)	Sub-area Number (Original)	Uplands / Lowlands	Acreage	Precipitation Station (Thiessen Polygons)	Correction Factor (Isolines)
UNNAMED	78	78	Lowlands	2766.09	Rio Vista	1.065930
KASSON	79	79	Uplands	2191.25	Tracy Carbona	1.038700
CANAL RANCH	80	80	Lowlands	3083.66	Galt Lodi Rio Vista	0.870264
CANAL RANCH	81	81	Uplands	274.44	Galt	0.802446
STARK TRACT	82	82	Lowlands	752.64	Tray Carbona	1.020570
LIBERTY ISLAND (COUNTIES 48 & 57)	83	83	Lowlands	4609.96	Rio Vista	1.038110
WALTHALL TRACT	84	84	Uplands	1316.88	Tracy Carbona	0.997777
PARADISE JUNCTION	85	85	Uplands	5959.09	Tracy Carbona	1.026790
WETHERBEE LAKE	86	86	Uplands	371.27	Tracy Carbona	0.992169
CACHE-HAAS AREA	87	87	Lowlands	3518.47	Rio Vista	1.044770
CACHE-HAAS AREA	88	88	Uplands	1929.78	Rio Vista Davis	1.042170
PETER POCKET	89	89	Uplands	1477.82	Rio Vista	1.051110
MOSSDALE 2	90	90	Lowlands	524.82	Tracy Carbona	0.999217
MOSSDALE 2	91	91	Uplands	1009.01	Tracy Carbona	1.000070
UNDESIGNATED AREA	92	92	Lowlands	13729.84	Brentwood Galt Rio Vista	1.062050
UNDESIGNATED AREA	93	93	Uplands	187.40	Galt	0.900000
EHRHARDT CLUB (ARD)	94	94	Lowlands	601.04	Galt	0.883519
COSUMNES-MOKELUMNE	95	95	Uplands	4420.66	Galt	0.816879
DEAD HORSE ISLAND	96	96	Lowlands	223.27	Galt Rio Vista	0.902635
HOOD AREA	97	97	Lowlands	224.39	Galt	0.888890
IDA ISLAND	98	98	Lowlands	57.76	Rio Vista	1.061470
LOCKE AREA	99	99	Lowlands	884.98	Galt Rio Vista	0.894628
MCCORMACK-WILLIAMSON TRACT	100	100	Lowlands	1809.56	Galt	0.872345
STONE LAKE AREA	101	101	Uplands	5190.84	Galt	0.878117
UNDESIGNATED AREA	102	102	Lowlands	1025.39	Tracy Carbona	1.018470
UNDESIGNATED AREA	103	103	Uplands	30041.83	Brentwood Tracy Carbona	1.030630
ACKER ISLAND	104	104	Lowlands	110.34	Stockton	0.980343
ATLAS TRACT	105	105	Lowlands	340.27	Stockton	0.812787
ATLAS TRACT	106	106	Uplands	87.07	Stockton	0.806919

Sub-area Name	Sub-area Number (New)	Sub-area Number (Original)	Uplands / Lowlands	Acreage	Precipitation Station (Thiessen Polygons)	Correction Factor (Isolines)
DREXLER TRACT	107	107	Lowlands	3390.05	Stockton	1.015230
ELMWOOD TRACT	108	108	Lowlands	939.23	Stockton	0.873029
FERN ISLAND	109	109	Lowlands	106.95	Stockton	1.003000
HEADREACH ISLAND	110	110	Lowlands	211.82	Stockton	0.998476
HENNING TRACT	111	111	Lowlands	2793.47	Stockton	1.009150
HOG ISLAND	112	112	Lowlands	248.39	Stockton	0.969480
HONKER LAKE TRACT	113	113	Lowlands	2266.79	Stockton	0.996155
MORRISON ISLAND	114	114	Lowlands	110.71	Stockton	0.921526
RIO BLANCO TRACT	115	115	Lowlands	793.20	Lodi Stockton	0.819986
SHIMA TRACT	116	116	Lowlands	1946.29	Stockton	0.836031
SHIN KEE TRACT	117	117	Lowlands	1568.57	Lodi Stockton	0.827988
SPUD ISLAND	118	118	Lowlands	205.19	Stockton	0.983777
STATEN ISLAND	119	119	Lowlands	9660.41	Galt Rio Vista	0.958211
WRIGHT TRACT	120	120	Lowlands	1521.35	Stockton	0.873795
UNDESIGNATED AREA	121	121	Lowlands	560.40	Rio Vista	1.077980
UNDESIGNATED AREA	122	122	Uplands	2075.86	Rio Vista	1.081670
DECKER ISLAND	123	123	Lowlands	611.71	Rio Vista	1.087310
LITTLE HOLLAND TRACT	124	124	Lowlands	672.92	Rio Vista	1.018720
UNDESIGNATED AREA	125	125	Lowlands	1190.27	Galt Rio Vista Davis	0.909229
UNDESIGNATED AREA	126	126	Uplands	499.54	Davis	1.001870
LITTLE HOLLAND TRACT	127	127	Lowlands	2429.50	Rio Vista	1.019710
UNDESIGNATED AREA	128	128	Uplands	4150.96	Brentwood Tracy Carbona	1.009500
UNDESIGNATED AREA	129	129	Lowlands	342.15	Brentwood	1.027190
UNDESIGNATED AREA	130	130	Uplands	28474.22	Brentwood	1.007270
BETHEL ISLAND	131	131	Lowlands	3056.04	Rio Vista	1.050180
CONEY ISLAND	132	132	Lowlands	1067.96	Brentwood	1.042710
DUTCH	133	133	Lowlands	222.15	Brentwood	1.049780

Sub-area Name	Sub-area Number (New)	Sub-area Number (Original)	Uplands / Lowlands	Acreage	Precipitation Station (Thiessen Polygons)	Correction Factor (Isolines)
SLOUGH AND PORTION OF SAND MOUND SLOUGH					Rio Vista	
FALSE RIVER,PIPER SL.,SAND MOUND SL.,& ROCK SLOUGH	134	134	Lowlands	1536.79	Brentwood Rio Vista	1.048550
FISHERMAN CUT WATERWAY	135	135	Lowlands	112.24	Rio Vista	1.061270
FRANKS TRACT	136	136	Lowlands	3660.98	Rio Vista	1.045490
OLD RIVER, HOLLAND CUT, AND INDIAN SLOUGH	137	137	Lowlands	1209.52	Brentwood Rio Vista	1.039620
QUIMBY ISLAND	138	138	Lowlands	965.88	Rio Vista	1.033030
RHODE ISLAND	139	139	Lowlands	115.60	Rio Vista	1.034590
SAN JOAQUIN RIVER WATERWAY	140	140	Lowlands	2105.66	Rio Vista	1.059490
SAN JOAQUIN WATERWAY NORTH OF INDUSTRIAL STRIP	141	141	Lowlands	1530.83	Brentwood Rio Vista	1.063370
TAYLOR SLOUGH WATERWAY	142	142	Lowlands	138.22	Rio Vista	1.055180
MOSSDALE	143	4	Uplands	6969.10	Stockton Tracy Carbona	0.916330
EGBERT TRACT	144	17	Uplands	215.00	Rio Vista	1.084170
EGBERT TRACT	145	17	Uplands	202.80	Rio Vista	1.087790
UNDESIGNATED AREA	146	92	Lowlands	627.36	Galt	0.895205
UNDESIGNATED AREA	147	93	Uplands	5069.56	Galt Davis	0.897927
UNDESIGNATED AREA	148	93	Uplands	94.02	Davis	0.893742
UNDESIGNATED AREA	149	102	Lowlands	247.60	Stockton	0.867227
UNDESIGNATED AREA	150	102	Lowlands	122.83	Stockton	0.811327
UNDESIGNATED AREA	151	102	Lowlands	35.30	Stockton	0.802895
UNDESIGNATED AREA	152	102	Uplands	144.81	Galt	0.794857
UNDESIGNATED AREA	153	103	Uplands	10974.35	Galt Lodi	0.794726

Sub-area Name	Sub-area Number (New)	Sub-area Number (Original)	Uplands / Lowlands	Acreage	Precipitation Station (Thiessen Polygons)	Correction Factor (Isolines)
					Stockton	
UNDESIGNATED AREA	154	103	Uplands	1170.04	Galt	0.797510
UNDESIGNATED AREA	155	103	Uplands	68.04	Stockton	0.785958
UNDESIGNATED AREA	156	103	Uplands	1732.39	Tracy Carbona	1.024580
UNDESIGNATED AREA	157	103	Uplands	1204.53	Stockton	0.808404
UNDESIGNATED AREA	158	121	Lowlands	5246.79	Rio Vista	1.074170
UNDESIGNATED AREA	159	122	Uplands	4728.64	Rio Vista	1.081460
UNDESIGNATED AREA	160	122	Uplands	881.17	Rio Vista	1.054750
UNDESIGNATED AREA	161	122	Uplands	168.44	Rio Vista	1.049380
UNDESIGNATED AREA	162	122	Uplands	486.48	Rio Vista Davis	1.032660
UNDESIGNATED AREA	163	122	Uplands	396.49	Davis	1.021420
UNDESIGNATED AREA	164	126	Uplands	13525.75	Davis	0.931437
UNDESIGNATED AREA	165	129	Lowlands	1766.35	Brentwood	1.035800
UNDESIGNATED AREA	166	129	Lowlands	463.21	Brentwood	1.048910
UNDESIGNATED AREA	167	129	Lowlands	3310.77	Brentwood Rio Vista	1.054140
UNDESIGNATED AREA	168	130	Uplands	255.46	Brentwood	1.051620

Table A.2. Sample HISTORICAL file for annual areas planted by land-use category and year for sub-area 1. The symbols 'D' and 'C' in the second column indicate critical years (i.e., with a water shortage). Other Sub-area csv files have a similar format. All of the input land-use areas are in hectares. The filename for this file is SA0001.csv.

DATE	Type	UR	PA	AL	FI	SB	GR	RI	TR	TO	OR	VI	RV	WS	DGR	NV
Number	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1922	AN	13	75	387	1070	147	879	0	1642	0	227	0	36	141	0	178
1923	BN	13	90	385	1082	160	825	0	1459	0	236	0	49	195	0	302
1924	C	13	18	442	934	180	1042	0	1334	0	235	0	52	208	0	338
1925	D	13	90	370	902	141	950	0	1314	0	186	0	65	258	0	507
1926	D	13	72	372	1108	67	871	0	1401	0	257	0	55	217	0	364
1927	W	13	47	375	1093	122	854	0	1345	0	250	0	58	231	0	409
1928	AN	13	108	382	1153	124	812	0	1444	0	229	0	48	192	0	292
1929	C	13	47	387	1071	181	858	0	1549	0	216	0	44	176	0	254
1930	D	13	131	384	1226	203	822	0	1688	0	210	0	14	55	0	50
1931	C	13	217	384	1173	261	733	0	1601	0	157	0	27	109	0	121
1932	D	13	217	391	1112	266	774	0	1593	0	148	0	30	117	0	135
1933	C	13	216	400	1050	272	813	0	1587	0	137	0	32	126	0	150
1934	C	13	216	409	988	278	852	0	1580	0	128	0	34	134	0	164
1935	BN	13	214	417	927	285	891	0	1573	0	117	0	36	143	0	182
1936	BN	13	214	427	865	292	933	0	1565	0	107	0	38	149	0	194
1937	BN	13	212	436	805	298	972	0	1559	0	97	0	39	156	0	208
1938	W	13	212	445	743	304	1012	0	1552	0	90	0	41	162	0	222
1939	D	13	230	442	723	298	1045	0	1552	0	88	0	39	156	0	209
1940	AN	13	250	439	703	293	1077	0	1550	0	87	0	38	150	0	196
1941	W	13	268	435	685	286	1111	0	1549	0	87	0	36	144	0	183
1942	W	13	287	430	663	279	1143	0	1548	0	85	0	35	139	0	174
1943	W	13	307	427	643	274	1176	0	1546	0	85	0	33	132	0	160
1944	D	13	325	423	623	267	1208	0	1545	0	84	0	32	127	0	151
1945	BN	13	347	420	601	262	1241	1	1545	82	82	0	22	89	0	92
1946	BN	13	366	415	583	255	1274	1	1543	124	81	0	16	64	0	60
1947	D	13	386	414	564	249	1306	1	1543	165	79	0	9	36	0	30
1948	BN	13	404	409	544	244	1341	1	1542	207	79	0	2	6	0	5

DATE	Type	UR	PA	AL	FI	SB	GR	RI	TR	TO	OR	VI	RV	WS	DGR	NV
Number	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1949	D	13	402	420	617	245	1277	2	1509	225	79	0	1	4	0	3
1950	BN	13	400	432	689	247	1213	2	1479	243	78	0	0	0	0	0
1951	AN	13	398	442	759	248	1149	2	1448	262	76	0	0	0	0	0
1952	W	13	395	454	829	249	1083	3	1414	280	76	0	0	0	0	0
1953	W	13	393	465	898	250	1019	3	1383	298	74	0	0	0	0	0
1954	AN	13	390	475	968	251	953	3	1352	317	74	0	0	0	0	0
1955	D	13	389	487	1036	252	889	4	1319	335	72	2	0	0	0	0
1956	W	13	375	487	1081	257	872	3	1294	338	75	2	0	0	0	0
1957	AN	13	360	485	1124	262	856	3	1272	341	78	2	0	0	0	0
1958	W	13	347	482	1168	267	839	2	1249	344	83	2	0	0	0	0
1959	BN	13	333	481	1213	272	822	2	1228	347	86	0	0	0	0	0
1960	D	13	320	479	1256	276	806	2	1205	352	89	0	0	0	0	0
1961	D	13	301	474	1287	279	824	1	1172	352	92	0	0	0	0	0
1962	BN	13	302	474	1319	271	852	1	1119	348	95	0	0	0	0	0
1963	W	13	303	474	1348	261	880	1	1071	345	99	0	0	0	0	0
1964	D	14	304	474	1377	252	908	1	1021	342	100	2	0	0	0	0
1965	W	14	305	475	1405	243	935	1	972	339	104	4	0	0	0	0
1966	BN	14	306	475	1435	234	963	1	920	335	107	6	0	0	0	0
1967	W	15	307	476	1463	224	992	1	869	331	110	8	0	0	0	0
1968	BN	15	306	477	1493	214	1021	1	820	327	114	8	0	0	0	0
1969	W	16	307	478	1522	204	1049	1	769	325	116	10	0	0	0	0
1970	W	16	307	477	1548	194	1076	1	716	320	119	14	1	4	0	3
1971	W	17	307	475	1573	183	1102	1	661	316	122	20	2	10	0	7
1972	BN	18	307	474	1597	173	1102	1	608	311	125	30	6	25	0	19
1973	AN	19	307	472	1623	162	1127	1	555	306	128	41	7	27	0	20
1974	W	20	307	471	1654	153	1150	1	502	303	131	53	7	28	0	18
1975	W	21	291	442	1758	185	1099	1	432	294	131	53	11	46	0	32
1976	C	23	273	414	1858	219	1049	1	360	286	131	55	15	65	0	48
1977	C	24	295	493	1741	138	1192	0	324	343	131	55	7	32	0	20
1978	AN	24	266	405	1882	137	1159	0	376	343	129	57	2	9	0	5
1979	BN	25	264	379	1902	140	1133	1	355	331	129	61	9	40	0	26

DATE	Type	UR	PA	AL	FI	SB	GR	RI	TR	TO	OR	VI	RV	WS	DGR	NV
Number	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1980	AN	25	286	393	1767	166	1012	1	361	314	134	63	30	128	0	117
1981	D	26	275	391	1771	171	1164	1	370	317	134	65	13	58	0	39
1982	W	27	260	376	1964	108	857	1	371	327	137	67	32	139	0	129
1983	W	28	250	388	1560	130	730	1	115	301	137	71	77	332	0	675
1984	W	29	237	421	1808	186	841	1	408	303	136	75	37	159	0	156
1985	D	29	228	445	1580	205	930	1	413	294	137	81	44	192	0	216
1986	W	29	226	462	1289	176	975	1	414	287	137	85	61	262	0	392
1987	D	29	225	499	1203	208	980	0	420	272	139	89	62	267	0	404
1988	C	30	225	525	1170	227	1014	0	426	280	139	95	58	251	0	356
1989	D	30	217	523	1230	201	1184	0	428	320	143	101	42	182	0	193
1990	C	30	210	523	1364	195	1205	0	429	331	146	107	29	124	0	102
1991	C	31	210	523	1364	195	1205	0	429	331	146	107	29	124	0	101
1992	C	32	210	523	1364	195	1205	0	429	331	146	107	29	124	0	99
1993	AN	33	216	526	1375	213	1032	0	389	312	141	97	46	199	0	217
1994	C	34	210	523	1364	195	1205	0	429	331	146	107	29	125	0	97
1995	W	35	257	516	2077	77	414	0	527	353	140	140	30	129	0	101
1996	W	35	162	528	2043	37	592	0	435	370	133	241	26	113	0	82
1997	W	35	241	519	2184	34	432	0	375	342	129	307	24	103	0	70
1998	W	36	293	574	2038	26	303	0	433	378	121	345	29	125	0	94
1999	W	36	318	578	1973	34	476	0	420	343	131	331	20	84	0	52
2000	AN	37	284	531	1908	44	455	0	392	325	145	411	31	133	0	102
2001	D	37	251	583	1835	0	612	0	390	275	144	434	28	120	0	86
2002	D	38	251	583	1835	0	612	0	390	275	144	434	28	120	0	85
2003	AN	38	284	531	1908	44	455	0	392	325	145	411	31	133	0	100

Table A.3. Sample PROJECTED file for annual areas planted by land-use category and year for sub-area 1. The symbols ‘D’ and ‘C’ in the second column indicate critical years (i.e., with a water shortage). Other Sub-area csv files have a similar format. All of the input land-use areas are in hectares. The filename for this file is SA0001.csv.

DATE	TYPE	UR	PA	AL	FI	SB	GR	RI	TR	TO	OR	VI	RV	WS	DGR	NV
Number	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1922	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
1923	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1924	C	20	0	937	563	641	714		413	1081	172			46		209
1925	D	20	0	937	563	641	714		413	1081	172			46		209
1926	D	20	0	937	563	641	714		413	1081	172			46		209
1927	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1928	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
1929	C	20	0	937	563	641	714		413	1081	172			46		209
1930	D	20	0	937	563	641	714		413	1081	172			46		209
1931	C	20	0	937	563	641	714		413	1081	172			46		209
1932	D	20	0	937	563	641	714		413	1081	172			46		209
1933	C	20	0	937	563	641	714		413	1081	172			46		209
1934	C	20	0	937	563	641	714		413	1081	172			46		209
1935	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1936	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1937	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1938	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1939	D	20	0	937	563	641	714		413	1081	172			46		209
1940	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
1941	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1942	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1943	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1944	D	20	0	937	563	641	714		413	1081	172			46		209
1945	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1946	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1947	D	20	0	937	563	641	714		413	1081	172			46		209

DATE	TYPE	UR	PA	AL	FI	SB	GR	RI	TR	TO	OR	VI	RV	WS	DGR	NV
Number	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1948	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1949	D	20	0	937	563	641	714		413	1081	172			46		209
1950	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1951	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
1952	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1953	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1954	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
1955	D	20	0	937	563	641	714		413	1081	172			46		209
1956	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1957	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
1958	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1959	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1960	D	20	0	937	563	641	714		413	1081	172			46		209
1961	D	20	0	937	563	641	714		413	1081	172			46		209
1962	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1963	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1964	D	20	0	937	563	641	714		413	1081	172			46		209
1965	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1966	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1967	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1968	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1969	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1970	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1971	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1972	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1973	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
1974	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1975	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1976	C	20	0	937	563	641	714		413	1081	172			46		209

DATE	TYPE	UR	PA	AL	FI	SB	GR	RI	TR	TO	OR	VI	RV	WS	DGR	NV
Number	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1977	C	20	0	937	563	641	714		413	1081	172			46		209
1978	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
1979	BN	35	95	1319	1059	309	213		475	753	195	88		82		172
1980	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
1981	D	20	0	937	563	641	714		413	1081	172			46		209
1982	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1983	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1984	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1985	D	20	0	937	563	641	714		413	1081	172			46		209
1986	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1987	D	20	0	937	563	641	714		413	1081	172			46		209
1988	C	20	0	937	563	641	714		413	1081	172			46		209
1989	D	20	0	937	563	641	714		413	1081	172			46		209
1990	C	20	0	937	563	641	714		413	1081	172			46		209
1991	C	20	0	937	563	641	714		413	1081	172			46		209
1992	C	20	0	937	563	641	714		413	1081	172			46		209
1993	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
1994	C	20	0	937	563	641	714		413	1081	172			46		209
1995	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1996	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1997	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1998	W	35	95	1319	1059	309	213		475	753	195	88		82		172
1999	W	35	95	1319	1059	309	213		475	753	195	88		82		172
2000	AN	35	95	1319	1059	309	213		475	753	195	88		82		172
2001	D	20	0	937	563	641	714		413	1081	172			46		209
2002	D	20	0	937	563	641	714		413	1081	172			46		209
2003	AN	35	95	1319	1059	309	213		475	753	195	88		82		172

Table A.4. A sample of the temperature and precipitation data from the Lodi NCDC station is presented. The full dataset includes data from 1 October 1921 through 30 September 2003. The data are stored in the comma delimeted file named TxTnLodi.csv.

Date	year	month	day	Pcp(mm)	Tx(oC)	Tn(oC)
10/1/1921	1921	10	1	0	27.8	9.4
10/2/1921	1921	10	2	0	27.2	10.6
10/3/1921	1921	10	3	0	25	11.7
10/4/1921	1921	10	4	0	28.3	13.3
10/5/1921	1921	10	5	0	26.1	10.6
10/6/1921	1921	10	6	0	24.4	11.1
10/7/1921	1921	10	7	0	27.8	10
10/8/1921	1921	10	8	0	28.3	11.1
10/9/1921	1921	10	9	0	27.2	12.2
10/10/1921	1921	10	10	0	27.2	10
10/11/1921	1921	10	11	0	26.7	11.7
10/12/1921	1921	10	12	0	21.7	8.9
10/13/1921	1921	10	13	0	23.3	12.2
10/14/1921	1921	10	14	3.9	17.2	14.4
10/15/1921	1921	10	15	0	24.4	15
10/16/1921	1921	10	16	0	25.6	9.4
10/17/1921	1921	10	17	0	26.7	8.3
10/18/1921	1921	10	18	0	29.4	10.6
10/19/1921	1921	10	19	0	30	10.6
10/20/1921	1921	10	20	0	30	10.6
10/21/1921	1921	10	21	0	23.9	15.6
10/22/1921	1921	10	22	0	16.1	9.4
10/23/1921	1921	10	23	5.2	16.1	11.7
10/24/1921	1921	10	24	0	16.7	5.6
10/25/1921	1921	10	25	0	16.1	8.3
10/26/1921	1921	10	26	0	14.4	8.3
10/27/1921	1921	10	27	0	15	3.9
10/28/1921	1921	10	28	0	20	3.9
10/29/1921	1921	10	29	0	22.2	5.6
10/30/1921	1921	10	30	0	23.3	4.4
10/31/1921	1921	10	31	0	22.2	3.9
11/1/1921	1921	11	1	0	26.1	6.1
11/2/1921	1921	11	2	0	25.6	6.1
11/3/1921	1921	11	3	0	22.8	6.1
11/4/1921	1921	11	4	0	27.2	6.7
11/5/1921	1921	11	5	0	25.6	11.1
11/6/1921	1921	11	6	0	27.8	6.1
11/7/1921	1921	11	7	0	25.6	7.2
11/8/1921	1921	11	8	0	25	4.4
11/9/1921	1921	11	9	0	25.6	4.4
11/10/1921	1921	11	10	0	25	3.9

Table A.5. Correction factors to convert from Lodi NCDC station ET_o to estimated ETo at each of the 168 sub-areas. The Lodi ETo was calculated using the Hargreaves-Samani equation whereas the ETo of the SAs are estimates of daily (24-hour) ETo using the standardized Penman-Monteith equation for short canopies (ASCE-EWRI, 2005).

SA	C_F	SA	C_F	SA	C_F	SA	C_F	SA	C_F	SA	C_F	SA	C_F
1	1.014	26	0.900	51	1.052	76	1.011	101	0.878	126	1.002	151	0.803
2	1.039	27	0.879	52	1.023	77	0.989	102	1.018	127	1.020	152	0.795
3	0.995	28	0.912	53	1.030	78	1.066	103	1.031	128	1.010	153	0.795
4	0.990	29	1.011	54	0.972	79	1.039	104	0.980	129	1.027	154	0.798
5	0.901	30	0.893	55	1.004	80	0.870	105	0.813	130	1.007	155	0.786
6	0.899	31	1.042	56	0.871	81	0.802	106	0.807	131	1.050	156	1.025
7	1.055	32	1.049	57	1.044	82	1.021	107	1.015	132	1.043	157	0.808
8	1.078	33	1.037	58	0.924	83	1.038	108	0.873	133	1.050	158	1.074
9	0.831	34	1.029	59	1.014	84	0.998	109	1.003	134	1.049	159	1.081
10	0.983	35	0.884	60	1.020	85	1.027	110	0.998	135	1.061	160	1.055
11	0.882	36	0.818	61	1.042	86	0.992	111	1.009	136	1.045	161	1.049
12	0.821	37	1.058	62	1.008	87	1.045	112	0.969	137	1.040	162	1.033
13	1.039	38	0.891	63	0.838	88	1.042	113	0.996	138	1.033	163	1.021
14	1.034	39	0.949	64	0.899	89	1.051	114	0.922	139	1.035	164	0.931
15	0.948	40	0.864	65	1.023	90	0.999	115	0.820	140	1.059	165	1.036
16	1.075	41	1.041	66	1.038	91	1.000	116	0.836	141	1.063	166	1.049
17	1.079	42	1.073	67	1.067	92	1.062	117	0.828	142	1.055	167	1.054
18	0.978	43	0.827	68	1.059	93	0.900	118	0.984	143	0.916	168	1.052
19	0.900	44	0.797	69	1.000	94	0.884	119	0.958	144	1.084		
20	0.916	45	0.812	70	1.028	95	0.817	120	0.874	145	1.088		
21	0.907	46	1.038	71	1.047	96	0.903	121	1.078	146	0.895		
22	0.962	47	1.017	72	1.073	97	0.889	122	1.082	147	0.898		
23	0.990	48	1.015	73	1.021	98	1.061	123	1.087	148	0.894		
24	0.898	49	1.046	74	1.036	99	0.895	124	1.019	149	0.867		
25	0.959	50	1.042	75	0.853	100	0.872	125	0.909	150	0.811		

Table A.6. Weighting factors for calculating rainfall for each of the Delta Sub-Areas. When rainfall occurs at a precipitation location, the fraction is multiplied by the rainfall amount and the sum of the products for the seven stations provides the estimated rainfall amount for the Delta Sub-Area.

	Station Location						
Sub-Area	Brentwood	Davis	Galt	Lodi	Rio Vista	Stockton	Tracy_Carbona
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.5939	0.4061
2	0.1597	0.0000	0.0000	0.0000	0.0000	0.3628	0.4775
3	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
5	0.0000	0.0267	0.5786	0.0000	0.3947	0.0000	0.0000
6	0.0000	0.9428	0.0572	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
8	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
9	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
10	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
12	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
13	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
14	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
15	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
16	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
17	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
18	0.0000	0.0000	0.0000	0.0000	0.0000	0.4963	0.5037
19	0.0000	0.0000	0.0000	0.7471	0.0532	0.1997	0.0000
20	0.0000	0.0000	0.3118	0.0000	0.6882	0.0000	0.0000
21	0.0000	0.0000	0.5209	0.0000	0.4791	0.0000	0.0000
22	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
23	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
24	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
25	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
26	0.0000	0.1619	0.8381	0.0000	0.0000	0.0000	0.0000
27	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
28	0.0000	0.0000	0.0304	0.0000	0.9696	0.0000	0.0000
29	0.0000	0.0000	0.0000	0.0000	0.9509	0.0491	0.0000
30	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
31	0.0330	0.0000	0.0000	0.0000	0.0000	0.0000	0.9670
32	0.8843	0.0000	0.0000	0.0000	0.1157	0.0000	0.0000
33	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
34	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
35	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
36	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
37	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
38	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
39	0.0000	0.5558	0.0000	0.0000	0.4442	0.0000	0.0000
40	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
41	0.0879	0.0000	0.0000	0.0000	0.0000	0.0000	0.9121

Sub-Area	Station Location						
	Brentwood	Davis	Galt	Lodi	Rio Vista	Stockton	Tracy_Carbona
42	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
43	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
44	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
45	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
46	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
47	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
48	0.0000	0.0000	0.0000	0.0000	0.8400	0.1600	0.0000
49	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
50	0.1963	0.0000	0.0000	0.0000	0.8037	0.0000	0.0000
51	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
52	0.0000	0.0000	0.0000	0.0000	0.8238	0.1762	0.0000
53	0.2382	0.0000	0.0000	0.0000	0.4189	0.3429	0.0000
54	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
55	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
56	0.0000	0.0000	0.0000	0.8690	0.1310	0.0000	0.0000
57	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
58	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
59	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
60	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
61	0.6572	0.0000	0.0000	0.0000	0.0000	0.3428	0.0000
62	0.0000	0.0000	0.0000	0.0000	0.0270	0.9730	0.0000
63	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
64	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
65	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
66	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
67	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
68	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
69	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
70	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
71	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
72	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
73	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
74	0.6085	0.0000	0.0000	0.0000	0.0000	0.3915	0.0000
75	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
76	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
77	0.0000	0.8650	0.0000	0.0000	0.1350	0.0000	0.0000
78	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
79	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
80	0.0000	0.0000	0.8070	0.1280	0.0650	0.0000	0.0000
81	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
82	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
83	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
84	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
85	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
86	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
87	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000

Sub-Area	Station Location						
	Brentwood	Davis	Galt	Lodi	Rio Vista	Stockton	Tracy_Carbona
88	0.0000	0.2260	0.0000	0.0000	0.7740	0.0000	0.0000
89	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
90	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
91	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
92	0.1403	0.0000	0.0085	0.0000	0.8512	0.0000	0.0000
93	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
94	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
95	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
96	0.0000	0.0000	0.7746	0.0000	0.2254	0.0000	0.0000
97	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
98	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
99	0.0000	0.0000	0.9682	0.0000	0.0318	0.0000	0.0000
100	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
101	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
102	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
103	0.0033	0.0000	0.0000	0.0000	0.0000	0.0000	0.9967
104	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
105	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
106	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
107	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
108	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
109	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
110	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
111	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
112	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
113	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
114	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
115	0.0000	0.0000	0.0000	0.3768	0.0000	0.6232	0.0000
116	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
117	0.0000	0.0000	0.0000	0.9451	0.0000	0.0549	0.0000
118	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
119	0.0000	0.0000	0.1408	0.0000	0.8592	0.0000	0.0000
120	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
121	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
122	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
123	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
124	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
125	0.0000	0.1615	0.5374	0.0000	0.3010	0.0000	0.0000
126	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
127	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
128	0.9196	0.0000	0.0000	0.0000	0.0000	0.0000	0.0804
129	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
130	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
131	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
132	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
133	0.0163	0.0000	0.0000	0.0000	0.9837	0.0000	0.0000

Sub-Area	Station Location						
	Brentwood	Davis	Galt	Lodi	Rio Vista	Stockton	Tracy_Carbona
134	0.0217	0.0000	0.0000	0.0000	0.9783	0.0000	0.0000
135	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
136	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
137	0.6730	0.0000	0.0000	0.0000	0.3270	0.0000	0.0000
138	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
139	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
140	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
141	0.7277	0.0000	0.0000	0.0000	0.2723	0.0000	0.0000
142	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
143	0.0000	0.0000	0.0000	0.0000	0.0000	0.6624	0.3376
144	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
145	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
146	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
147	0.0000	0.3082	0.6918	0.0000	0.0000	0.0000	0.0000
148	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
149	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
150	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
151	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
152	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
153	0.0000	0.0000	0.2133	0.3974	0.0000	0.3893	0.0000
154	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
155	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
156	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
157	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
158	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
159	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
160	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
161	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
162	0.0000	0.8486	0.0000	0.0000	0.1514	0.0000	0.0000
163	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
164	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
165	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
166	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
167	0.4447	0.0000	0.0000	0.0000	0.5553	0.0000	0.0000
168	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Appendix B. Calculation of Reference Evapotranspiration.

STEP 1: Extraterrestrial radiation (R_a) is calculated for each day using the following equations from Duffie and Beckman (1980).

G_{SC} = solar constant in MJ m^{-2} min^{-1}

$$G_{SC} = 0.082$$

σ = Steffan-Boltzman constant in MJ m^{-2} d^{-1} K^{-4}

$$\sigma = 4.90 \times 10^{-9}$$

ϕ = latitude in radians converted from latitude (L) in degrees

$$\phi = \frac{\pi L}{180}$$

d_r = correction for eccentricity of Earth's orbit around the sun on day i of the year

$$d_r = 1 + 0.033 cos\left(\frac{2\pi}{365} i\right) \tag{1}$$

δ = declination of the sun above the celestial equator in radians on day i of the year

$$\delta = 0.409\, sin\left(\frac{2\pi}{365} i - 1.39\right) \tag{2}$$

ω_s = sunrise hour angle in radians

$$\omega_s = cos^{-1}\left[-tan\,\phi\, tan\,\delta\right] \tag{3}$$

R_a = extraterrestrial radiation (MJ m^{-2} d^{-1})

$$R_a = \left(\frac{24 \cdot 60}{\pi}\right) G_{SC}\, d_r \left[\omega_s \sin\delta \sin\phi + \cos\phi \cos\delta \sin\omega_s\right] \tag{4}$$

STEP 2: Calculate the daily net radiation (R_n) expected over grass in MJ m^{-2} d^{-1} using equations from Allen et al. (1994).

R_{so} = clear sky total global solar radiation at the Earth's surface in MJ m^{-2} d^{-1}

$$R_{so} = R_a\left(0.75 + 2.0 \times 10^{-5} E_l\right) \tag{5}$$

R_{ns} = net solar radiation over grass as a function of measured solar radiation (R_S) in MJ m^{-2} d^{-1}

$$R_{ns} = (1 - 0.23) R_s \tag{6}$$

f = a cloudiness function of R_s and R_{so}

$$f = 1.35 \frac{R_s}{R_{so}} - 0.35 \tag{7}$$

$e_s(T_x)$ = saturation vapor pressure (kPa) at the maximum daily air temperature (T_X) in ^{o}C

$$e_s(T_x) = 0.6108 \exp\left(\frac{17.27 T_x}{T_x + 237.3}\right) \tag{8}$$

$e_s(T_n)$ = saturation vapor pressure (kPa) at the minimum daily air temperature (T_n) in ^{o}C

$$e_s(T_n) = 0.6108 \exp\left(\frac{17.27 T_n}{T_n + 237.3}\right) \tag{9}$$

e_a = actual vapor pressure or saturation vapor pressure (kPa) at the mean dew point temperature from the daily maximum (T_x) and minimum (T_n) temperature (°C) and maximum (RH_x) and minimum (RH_n) relative humidity (%).

$$e_a = \frac{\left(\frac{RH_x + RH_n}{2}\right)}{\left(\frac{50}{e_s(T_x)} + \frac{50}{e_s(T_n)}\right)} \tag{10}$$

e_a = actual vapor pressure or saturation vapor pressure (kPa) at the daily mean dew point (T_d) temperature.

$$e_a = 0.6108 \exp\left[\frac{17.27 T_d}{T_d + 237.3}\right] \tag{11}$$

ε' = apparent 'net' clear sky emissivity

$$\varepsilon' = 0.34 - 0.14\sqrt{e_a} \tag{12}$$

Note that $\varepsilon' = \varepsilon_{vs} - \varepsilon_a$, where ε_{vs} is the emissivity of the grass and ε_a is the emissivity from the atmosphere. It is called 'apparent' because the temperature from a standard shelter rather than the surface temperature and atmosphere temperature are used to calculate the 'net' long–wave radiation balance. Equation 11 is called the 'Brunt form' equation for net emittance because the form of the equation is similar to Brunt's equation for apparent long-wave emissivity from a clear sky.

R_{nl} = net long wave radiation in MJ m^{-2} d^{-1}

$$R_{nl} = -f\, \varepsilon' \sigma \left[\frac{(T_x + 273.15)^4 + (T_n + 273.15)^4}{2}\right] \tag{13}$$

R_n = net radiation over grass in MJ m^{-2} d^{-1}

$$R_n = R_{ns} + R_{nl} \tag{14}$$

STEP 3: Calculate variables needed to compute *ET_h*, *ET_o* and *ET_r*.

β = barometric pressure in kPa as a function of elevation (E_l) in meters

$$\beta = 101.3\left(\frac{293 - 0.0065 E_l}{293}\right)^{5.26} \tag{15}$$

λ = latent heat of vaporization in (MJ kg^{-1})

$$\lambda = 2.45 \tag{16}$$

γ = psychrometric constant in kPa $^oC^{-1}$

$$\gamma = 0.00163\frac{\beta}{\lambda} \tag{17}$$

T_m = mean daily temperature in °C

$$T_m = \frac{T_x + T_n}{2} \tag{18}$$

e^o = saturation vapor pressure at T_m

$$e^o = 0.6108 \exp\left(\frac{17.27 T_m}{T_m + 237.3}\right) \tag{19}$$

Δ = slope of the saturation vapor pressure curve (kPa $^oC^{-1}$) at mean air temperature (T_m)

$$\Delta = \frac{4099 e^o}{(T_m + 237.3)^2} \tag{20}$$

G = soil heat flux density in MJ m^{-2} d^{-1}

$$G \approx 0 \tag{21}$$

e_s = mean daily saturation vapor pressure (kPa)

$$e_s = \frac{e_s(T_x) + e_s(T_n)}{2} \tag{22}$$

STEP 4: Calculate ET_h using the Hargreaves-Samani (1982); Hargreaves-Samani (1985) equation.

Hargreaves-Samani equation for ET of a short, 0.12 m tall reference surface

$$ET_h = 0.408\left(0.0023 R_a [T_m + 17.8]\sqrt{T_x - T_n}\right) \tag{23}$$

where the 0.408 =1/λ factor converts from MJ m^{-2}d^{-1} to mm d^{-1}.

STEP 5: Calculate ET_o using the ASCE-EWRI (2004) standardized equation for short canopy reference *ET*.

R_o = radiation term of the Penman-Monteith equation for short canopy reference *ET* with U_2 the wind speed at 2 m height

$$R_o = \frac{0.408\Delta(R_n - G)}{\Delta + \gamma(1 + 0.34U_2)} \tag{24}$$

where 0.408=1/2.45 converts the units from MJ m^{-2} d^{-1} to mm d^{-1}.

A_o = aerodynamic term of the Penman-Monteith equation for short canopy reference *ET* with u_2 the wind speed at 2 m height

$$A_o = \frac{\left(\frac{900\gamma}{T_M + 273}\right) U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{25}$$

Standardized Reference Evapotranspiration for a short, 0.12 m reference surface in mm d^{-1}.

$$ET_o = R_o + A_o \tag{26}$$

Appendix C. Determining Crop Coefficients.

Soil evaporation

It is well known that soil evaporation rates follow a two-stage process (Ritchie, 1972). During stage-1 evaporation, the evaporation rate is determined by the amount of energy available to vaporize water in the upper layer of the soil. During stage-2, evaporation rates are limited by the lack of water in the upper soil layer and soil hydraulic factors that determine the transfer of liquid and vaporized water to the surface. Ritchie (1972) reported that the stage-2 evaporation rate decreases as a function of the square root of time after wetting. However, both Stroonsnjider (1987) and Gallardo et al. (1996) found a good relationship between cumulative bare soil evaporation and cumulative reference evapotranspiration (CETo). Like the model of Ritchie (1972), soil evaporation is described as a two-stage process. A soil hydraulic factor (β) defines the point where the evaporation changes from stage-1 to stage-2 and the evaporation rate during stage-2.

Ventura et al. (2000) reported on a model to estimate soil evaporation based on these concepts. When the soil evaporation (E_s) is in stage-1 and is not limited by soil hydraulic factors, then the crop coefficient for the maximum soil evaporation rate (E_x) is given by $E_x = 1.22 - 0.04 \cdot ET_o$ for ET_o in mm d^{-1}. During stage-1 evaporation, the soil evaporation (E_s) is equal to E_x and therefore the cumulative soil evaporation (CE_s) is equal to CE_x (Figure 1). The end of stage 1 and beginning of stage-2 evaporation is identified by the factor β, which corresponds to the value of $\sqrt{CE_x}$ where a plot of CE_s versus $\sqrt{CE_x}$ departs from a plot of CE_x versus $\sqrt{CE_x}$. The plot of CE_x versus $\sqrt{CE_x}$ is a curve and CE_s falls on the CE_x curve during stage-1 evaporation (Fig. nn). After $\sqrt{CE_x} > \beta$, then the plot of CE_s versus $\sqrt{CE_x}$ becomes linear with a slope through the origin equal to β. Good results were reported on using this method to estimate soil evaporation (Ventura et al., 2006). Using $\beta = 2.6$, the soil evaporation model approximately gives the same widely used plot of K_c factors for bare soil reported by Doorenbos and Pruitt (1977).

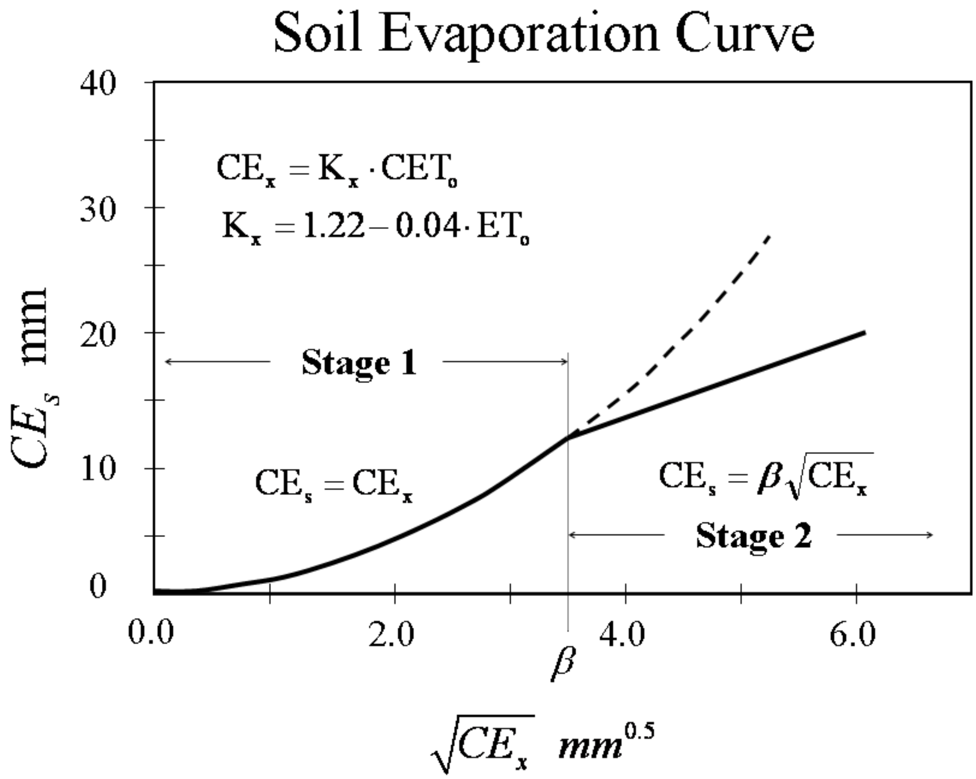

Figure 1. Methodology used to estimate bare soil evaporation (based on Snyder et al., 2000, and Ventura et al., 2005),

In DETAW, the soil evaporation model is used to estimate soil evaporation during the off season and to identify the crop coefficient during initial growth of type 1 field and row crops. The soil wetting frequency is estimated from the daily rainfall records. Only days with significant rainfall were considered as wet days, where significant rainfall occurs when the rainfall on a given date is greater than the mean daily ET_o rate since the previous significant rainfall. On a date with significant rainfall, the accumulation of CE_x is started again by resetting the CET_o to ET_o on the rainfall date. Then the ET_o values on following days are accumulated until the next significant rainfall event. On each of these intermediate days, the CE_x is calculated as $CET_o \times K_x$. Then the $\sqrt{CE_x}$ is computed on each of the intermediate dates. If $\sqrt{CE_x} < \beta$ on a given date, then CEs =CEx, otherwise, $CE_s = \beta \cdot \sqrt{CE_x}$. Then E_s on any given is calculated as the difference in CE_s on the current and previous date ($E_s = CE_s - PE_s$), where PEs equals the CE_s up through the previous date.

The ET_o rates are used to identify the daily off-season K_c factors for bare soil as $OK_c = E_s/ET_o$. It is clear (Figure 2) that the OK_c for bare soil is higher when the ET_o rate is low and it is higher when there is more frequent soil wetting. Thus, the bare soil K_c values tend to be high during the rainy low ET_o winter and they tend to be low during the dry, high ET_o summer. The annual curve of derived daily OK_c values is used as a base line K_c curve for computing the annual surface/crop K_c values. A sample annual K_c curve for Davis, California is shown in Figure 3. Whenever the daily OK_c value is higher than the in-season K_c (IKc) curves, then the higher value is used, assuming that the crop K_c value will not be lower than expected for a bare soil.

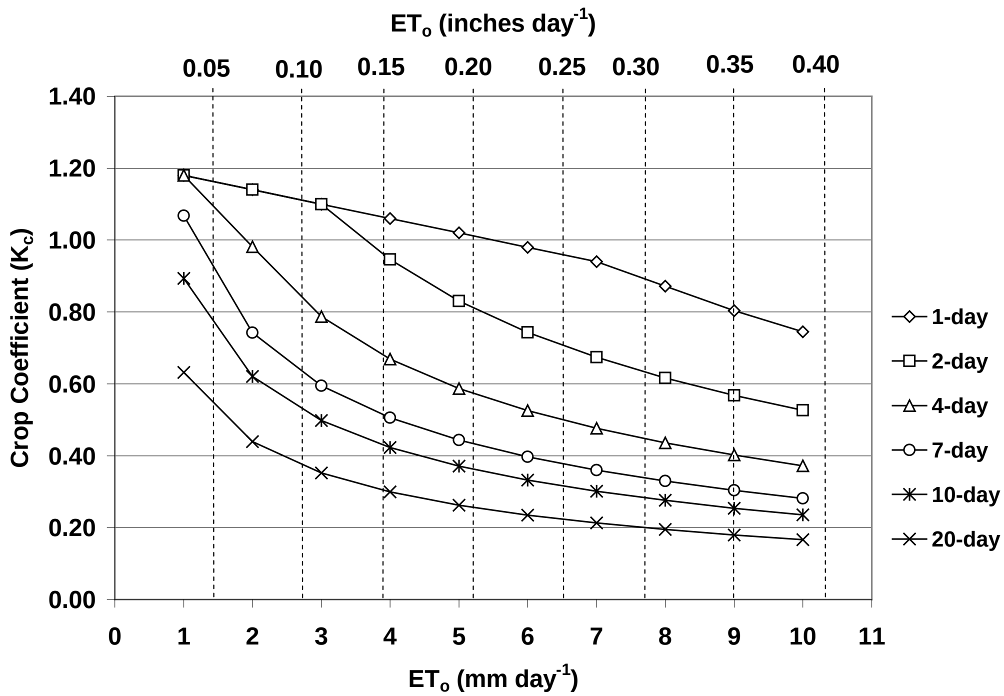

Figure 2. A plot of the crop coefficient (K_c) for bare soil as a function of ET_o rate and the wetting frequencies 1, 2, 4, 7, 10, and 20 days.

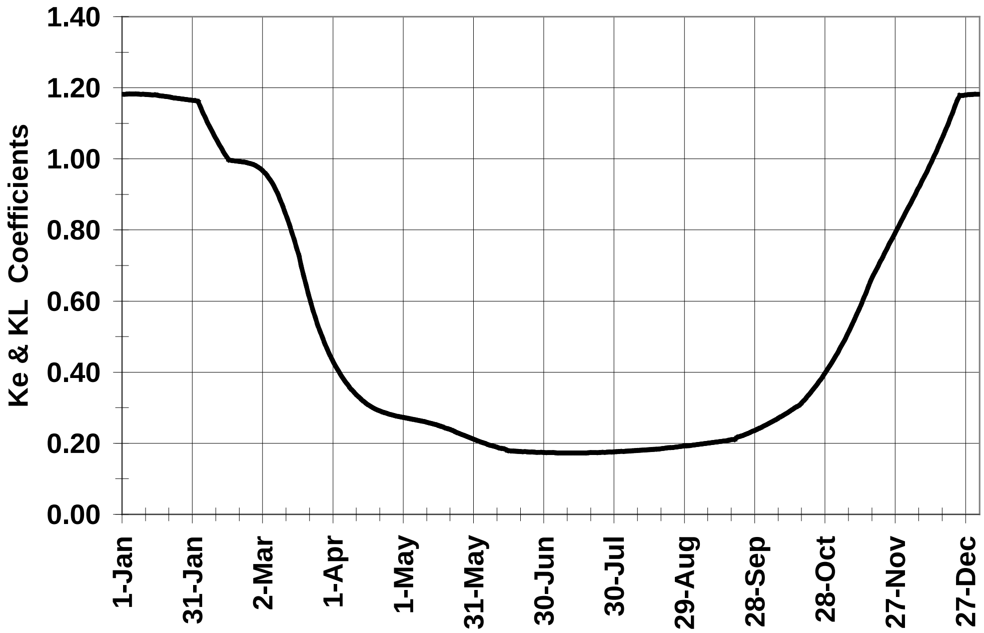

Figure 3. A plot of the base-line, bare-soil K_c curve for Davis, California based on mean ET_o rates and rainfall frequency.

Crop coefficient methods

While ET_o is a measure of the 'evaporative demand' of the atmosphere, crop coefficients account for the difference between the crop evapotranspiration (ET_c) and ET_o. The main factors affecting the difference are (1) light absorption by the canopy, (2) canopy roughness, which affects turbulence, (3) crop physiology, (4) leaf age, and (5) surface wetness. Because evapotranspiration is the sum of evaporation (*E*) from soil and plant surfaces and transpiration (*T*), which is vaporization that occurs inside of the plant leaves, it is often best to consider the two components separately.

When not limited by water availability, both transpiration and evaporation are limited by the availability of energy to vaporize water. During early growth of crops, ET_c is dominated by soil evaporation and the rate depends on whether or not the soil surface is wet. If a nearly bare-soil surface is wet, the ET_c rate varies from slightly higher than ET_o for low evaporative demand to about 80% of ET_o under high evaporation conditions. As a canopy develops, interception of radiation by the foliage increases and transpiration rather than soil evaporation dominates ET_c.

Field and row crop K_c values generally increase until the canopy ground cover reaches about 75% and the peak K_c is reached when the canopy of tree and vine crops has reached about 70% ground cover. The ground cover percentage associated with the peak K_c is slightly lower for tree and vine crops because the taller plants intercept more solar radiation at the same ground cover.

During the off-season and during initial crop growth, E is the main component of ET_c. Therefore, a good estimate of the K_c for bare soil is useful to estimate off-season soil evaporation and ET_c early in the season. A two-stage method for estimating soil evaporation presented by Stroosnijder (1987) and refined by Snyder et al. (2000) and Ventura et al. (2006) is used to estimate bare-soil crop coefficients. Using a soil hydraulic factor of $\beta = 2.65$, this method gives K_c values as a function of wetting frequency and ET_o that are similar to the widely-used bare soil coefficients that were published in Doorenbos and Pruitt (1977). The soil evaporation model is used to estimate crop coefficients for bare soil using the daily mean ET_o rate and the expected number of days between significant precipitation (P_s) on each day of the year. Daily precipitation is considered significant when $P_s > 2 \times ET_o$, where ET_o is estimated using the Hargreaves-Samani equation (Walter et al., 2000).

Field and row crops

Crop coefficients are determined using a modified Doorenbos and Pruitt (1977) method. The season is separated into initial (date A-B), rapid (date B-C), midseason (date C-D), and late season (date D-E) growth periods (Fig. 4). Tabular default K_c values corresponding to important inflection points in Fig. 4 are stored in the SIMETAW program. The K_c value on date A (K_cA) is set equal to that on date B (K_cB). Initially, a fixed K_c value is assigned to the midseason period, but the K_c values for dates C (K_cC) and D (K_cD) are adjustable for the percentage shading by the canopy to account for sparse or immature canopies. During the rapid growth period, between dates B and C, the K_c value changes linearly from K_cB to K_cC. During late season, the K_c changes linearly from K_cD on date D to K_cE at the end of the season. If the K_c from the linear interpolation method is less than the K_c for bare soil evaporation based on ET_o and rainfall frequency, the higher K_c value is used.

For estimating crop water demand, some field and row crops have relatively fixed Kc values during the entire season (e.g., alfalfa and pasture). To simplify, calculations, this type of crop is assigned to crop category 2. Type 2 crops will have the same in-season Kc value from the begin to the end date of the season. If the bare-soil Kc value is higher than the in-season value, then the higher Kc value is used.

Deciduous tree and vine crops

Deciduous tree and vine crops, without a cover crop, have similar K_c curves to field and row crops but without the initial growth period (Fig. 5). The K_c values depend on (1) energy balance characteristics, (2) canopy morphology effects on turbulence, and (3) plant physiology differences between the crop and reference crop. The season begins with rapid growth at leaf-out when the K_c increases from K_cB to K_cC. The midseason period begins at approximately 70% ground cover and generally the K_c value is fixed at K_cC until the onset of senescence on date D. Therefore, K_cD is usually equal to K_cC, but K_cD can be changed if the crop is known to change the K_c during the midseason period. During late season, when the crop plants are senescing, the K_c decreases from K_cD to K_cE. The end of the season occurs at about leaf drop or when the tree or vine transpiration is near zero. At any time during the season, if K_c values are less than the K_c for bare soil evaporation based on ET_o and rainfall frequency on the same date, the higher K_c value is used. Adjustments can also be made for the presence of a cover crop. With a cover crop, the K_c values for deciduous trees and vines are increased by 0.35 depending on the amount of cover. However, the K_c is not permitted to exceed 1.15.

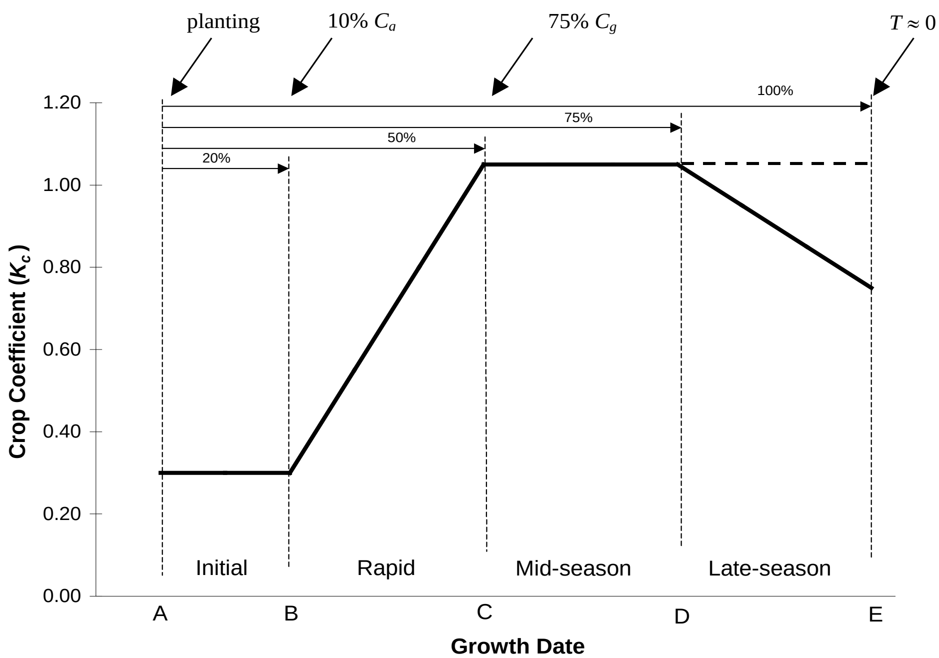

Fig. 4. Hypothetical crop coefficient (K_c) curve for typical field and row crops showing the growth stages and percentages of the season from planting to critical growth dates. Inflection points in the K_c curve occur at 10% and 75% ground cover (C_g) and at the onset of late season (date D). The season ends when transpiration (T) from the crop ceases ($T \approx 0$).

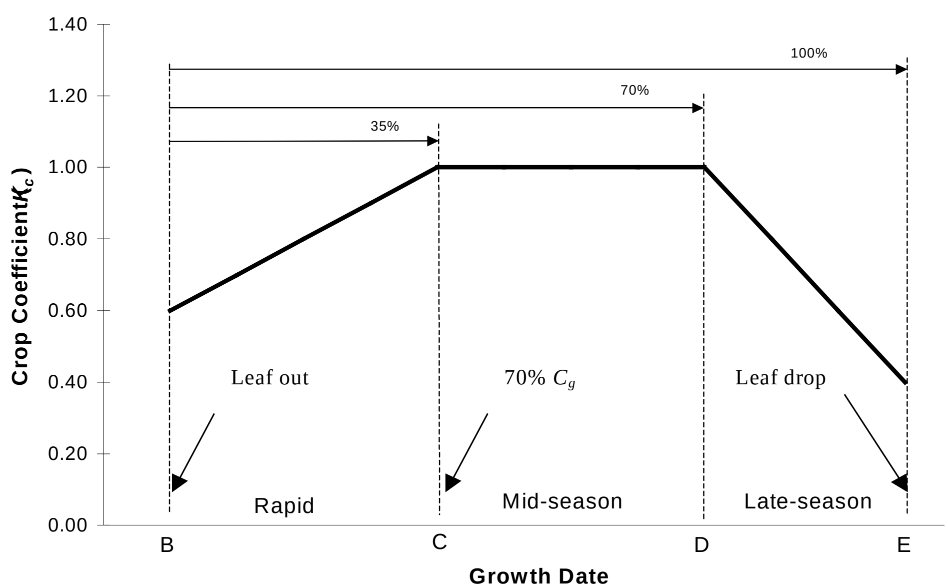

Fig. 5. Hypothetical crop coefficient (K_c) curve for typical deciduous orchard and vine crops showing the growth stages and percentages of the season from leaf out to critical growth dates. Inflection points occur at 70% ground cover (C_g) and at the onset of late season (date D).

Crop Coefficients in DETAW

Planting records for the Delta are available for general land-use categories and there are some estimates of the percentage of the land-use category contributed by various surfaces. For example, the area planted to truck crops is known and rough percentages of each crop within the "truck crop" land-use category are known. Using the percentages, weighted means for crop coefficients and growth dates were determined for each land-use category. In some instances, the crop type 3 category was used for non-crop surfaces (Tables 3 and 4). For example, riparian vegetation and urban surfaces were considered type 3 crops because the resulting K_c curves seemed to best fit reality. Figures 6 and 7 show the in-season crop coefficient curves for the 15 land-use categories for non-critical and critical years, respectively. Critical years are years that are considered "water short" and the areas planted to various crops vary from non-critical years.

Crop coefficients for land-use categories were determined as weighted averages of the Kc curves for surfaces within a category. The Kc curve information for surfaces within each of the 15 categories is provided in Table C.1 for non-critical years and in Table C.2 for critical years. The category area percentages were used to weight the contribution of each surface within a category to the land-use category. For example, pears, walnuts and apples comprise 34%, 25% and 12% of the orchards category in Table C.1, so they had a strong influence on the Kc curve for that category. The Kc factor curves for each category are provided in

Table C.1. Non-critical year growth dates, crop coefficients, begin and end dates, and the percentage of the land-use category area occupied by the crop. The weighted mean values for date B, C, D, Kc1, Kc2, Kc3, begin date and end date were determined by multiplying the individual crop values by the area percentage and summing the products. Table entries in italic were small with greatly different Kc curves, so they were not used in the weighted mean calculations.

Crop or Surface (type)	**Category Area %**	**Growth Dates**			**Crop Coefficients**			**DOY season**	
OR – Orchards (3)	**%**	**B**	**C**	**D**	**Kc1**	**Kc2**	**Kc3**	**Beg**	**End**
1. Grapefruit	*0*	*0*	*33*	*67*	*1.30*	*1.00*	*1.30*	*1*	*366*
8. Kiwis	*0*	*0*	*22*	*67*	*0.30*	*1.05*	*1.00*	*121*	*304*
10. Eucalyptus	*0*	*0*	*33*	*67*	*1.30*	*1.00*	*1.30*	*1*	*366*
1. Apples	12	0	50	75	0.55	1.05	0.80	91	319
10. Misc Deciduous	2	0	50	90	0.55	1.05	0.65	60	288
12. Almonds	9	0	50	90	0.55	1.05	0.65	60	288
13. Walnuts	25	0	50	75	0.55	1.05	0.80	91	319
14. Pistachios	1	0	50	75	0.55	1.05	0.80	91	319

Crop or Surface (type)	Category Area %	Growth Dates			Crop Coefficients			DOY season	
OR – Orchards (3)	**%**	**B**	**C**	**D**	**Kc1**	**Kc2**	**Kc3**	**Beg**	**End**
2. Apricots	10	0	50	90	0.55	1.05	0.65	60	288
3. Cherries	4	0	50	90	0.55	1.05	0.65	60	288
5. Peaches & Nectarines	2	0	50	90	0.55	1.05	0.65	60	288
6. Pears	34	0	50	75	0.55	1.05	0.80	91	319
7. Plums	0	0	50	90	0.55	1.05	0.65	60	288
9. Figs	0	0	50	90	0.55	1.05	0.65	60	288
SB - Sugar Beets (1)	**%**								
5. Sugar Beets	100	15	45	80	0.20	1.15	0.95	74	273
F - Field Crops (1)	**%**								
10. Beans (dry)	6	24	40	91	0.20	1.00	0.10	166.00	273
12. Sunflowers	2	20	45	80	0.20	1.10	0.40	121.00	253
2. Safflower	27	17	45	80	0.20	1.05	0.25	91.00	212
6. Corn (field & Sweet)	60	20	45	75	0.20	1.05	0.60	121.00	273
7. Grain Sorghum	*2*	*20*	*45*	*75*	*0.33*	*1.10*	*0.15*	*305*	*516*
8. Sudan grass	3	10	40	90	0.50	0.90	0.85	121	273
GR – Grain (1)	**%**								
1. Barley	32	20	45	75	0.70	1.10	0.15	305	516
2. Wheat	34	20	45	75	0.33	1.10	0.15	305	516
6. Misc & Mixed Grain & Hay	34	20	45	75	0.33	1.10	0.15	305	516
DG - Non-Irrigated Grain (1)	**%**								
Dry Grain	100	20	45	75	0.33	0.90	0.15	305	516
RV - Native Riparian Vegetation (3)	**%**								
1. Marsh Lands, Tules, & Sedges	65	0	33	67	0.80	1.00	0.80	1	366
3. Trees, Scrubs, & Other Larger Stream Side or Watercourse Vegetation	13	0	33	67	0.80	1.00	0.80	1	366
4. Seasonal Duck Marsh, dry or only partially wet during summer	16	0	33	67	0.80	0.80	0.80	1	366
5. Permanent Duck Marsh, flooded during summer	5	0	33	67	0.80	1.00	0.80	1	366
NV - Native Vegetation (3)	**%**								
Idle - 1. Land not cropped the current or previous crop season, but cropped within past 3 years	11	0	33	67	1.00	0.20	1.00	1	366
NB - Barren & Wasteland	0	0	33	67	1.00	0.20	1.00	1	366
NC - Native Classes Unsegregated	1	0	33	67	1.00	0.20	1.00	1	366
Native	89	0	33	67	1.00	0.20	1.00	1	366
WS - Water Surface (2)	**%**								
Water	100	0	33	67	1.10	1.10	1.10	1	366
AL – Alfalfa (2)	**%**								
1. Alfalfa & Alfalfa Mixtures	100	0	33	67	1.00	1.00	1.00	105	304
PA – Pasture (2)	**%**								
2. Clover	1	0	33	67	0.95	0.95	0.95	1	366
3. Mixed Pasture	78	0	33	67	0.95	0.95	0.95	1	366
4. Native Pasture	14	0.00	33	67	0.95	0.95	0.95	1	366

Crop or Surface (type)	Category Area %	Growth Dates			Crop Coefficients			DOY season	
OR – Orchards (3)	**%**	**B**	**C**	**D**	**Kc1**	**Kc2**	**Kc3**	**Beg**	**End**
6. Misc Grasses (mostly for seed)	4	0	33	67	0.95	0.95	0.95	1	366
7. Turf Farms	3	0	33	67	0.95	0.95	0.95	1	366
RI – Rice (1)	**%**								
Rice	100	22	37	86	1.20	1.05	0.80	135	273
TO – Tomatoes (1)	**%**								
15. Tomatoes	100	25	50	80	0.30	1.10	0.65	91	243
TR – Truck (1)	**%**								
1. Artichokes	0	6	19	90	0.65	0.65	0.65	182	486
10. Onions & Garlic	2	10	26	75	0.80	1.00	0.75	60	274
12. Potatoes	12	20	45	78	0.80	1.10	0.70	105	227
16. Flowers, Nursery, & Christmas Tree Farms	0	20	45	78	0.80	1.10	0.70	105	227
17. Mixed (four or more)	0	25	63	88	0.30	1.00	0.85	213	319
18. Misc truck	0	25	63	88	0.30	1.00	0.85	213	319
2. Asparagus	66	12	25	95	0.25	1.00	0.25	1	366
20. Strawberries	0	15	45	80	0.20	0.70	0.70	121	273
21. Peppers (chilli, bell, etc.)	2	20	45	85	0.80	1.00	0.85	60	243
23. Cabbage	0	25	63	88	0.30	1.00	0.85	213	319
3. Beans (green)	1	22	56	89	0.80	1.00	0.85	60	151
4. Cole Crops	0	25	63	88	0.30	1.00	0.85	213	319
6. Carrots	1	20	50	83	0.85	0.95	0.80	15	135
7. Celery	0	15	40	90	0.80	0.95	0.95	258	380
9. Melons, Squash, & Cucumbers (all types)	15	21	50	83	0.80	0.95	0.75	91	319
VI – Vineyards (3)	**%**								
Vineyards	100	0	25	75	0.45	0.80	0.35	91	305
U – Urban (3)	**%**								
Urban Hard Tops	38	0	33	67	0.00	0.00	0.00	1	366
Urban Vacant Lots	40	0	33	67	1.00	0.40	1.00	1	366
Urban Lawns	23	0	33	67	1.00	0.70	1.00	1	366

Table C.2. Critical year growth dates, crop coefficients, begin and end dates, and the percentage of the land-use category area occupied by the crop. The weighted mean values for date B, C, D, Kc1, Kc2, Kc3, begin date and end date were determined by multiplying the individual crop values by the area percentage and summing the products.

Crop or Surface (type)	Category Area %	Growth Dates			Crop Coefficients			Dates	
OR – Orchards (3)	**%**	**B**	**C**	**D**	**Kc1**	**Kc2**	**Kc3**	**Beg**	**End**
3. Oranges	0.04	0	33	67	1.30	1.00	1.30	1	366
1. Apples	0.13	0	50	75	0.55	1.05	0.80	91	319
13. Walnuts	0.37	0	50	75	0.55	1.05	0.80	91	319
4. Nectarines	1.28	0	50	90	0.55	1.05	0.65	60	288
7. Pears	98.17	0	50	75	0.55	1.05	0.80	91	319
7. Plums	0.01	0	50	90	0.55	1.05	0.65	60	288
SB - Sugar Beets (1)	**%**								
5. Sugar Beets	100	15	45	80	0.20	1.15	0.95	74	273
Fl - Field Crops (1)	**%**								
10. Beans, dry (all types)	3.00	24	40	91	0.20	1.00	0.10	166	273
11. Misc Field	1.08	20	45	75	0.20	1.05	0.60	121	273
2. Safflower	4.04	17	45	80	0.20	1.05	0.25	91	212
7. Corn (field & sweet)	81.36	20	45	75	0.20	1.05	0.60	121	273
7. Grain Sorghum	6.79	16	42	75	0.20	1.05	0.50	91	319
8. Sudan grass	3.70	10	40	90	0.50	0.90	0.85	121	273
9. Castor Beans	0.03	24	40	91	0.20	1.00	0.10	166	273
GR – Grain (1)	**%**								
Grain	100	20	45	75	0.33	1.10	0.15	305	516
DG - Non-Irrig. Grain (1)	**%**								
Dry Grain	100	20	45	75	0.33	0.90	0.15	305	517
RV – Riparian Veg. (3)	**%**								
1. Swamps & Marshes	97.72	0	33	67	0.80	1.00	0.80	1	366
3. Brush	2.24	0	33	77	0.80	0.80	0.80	1	366
4. Trees	0.04	0	33	77	0.80	1.00	0.80	1	366
NV – Native Vegetation (3)	**%**								
Idle 1. Land cropped within past 3 years, but not tilled at time of survey	2.00	0	33	67	1.00	0.20	1.00	1	366
Idle 2. New lands being prepared for crop production	0.55	0	33	67	1.00	0.20	1.00	1	366
Native	97.46	0	33	67	1.00	0.20	1.00	1	366
WS – Water Surface (2)	**%**								
Water	100	0	33	67	1.10	1.10	1.10	1	366
AL – Alfalfa (2)	**%**								
1. Alfalfa & Alfalfa Mixtures	100	0	33	67	1.00	1.00	1.00	105	304
PA – Pasture (2)	**%**								
2. Clover	0.29	0	33	67	0.95	0.95	0.95	1	366
3. Mixed Pasture	99.20	0	33	67	0.95	0.95	0.95	1	366
4. Native Pasture	0.51	0	33	67	0.95	0.95	0.95	1	366
RI – Rice (1)	**%**								
Rice	100	22	37	86	1.20	1.05	0.80	135	273
TO – Tomatoes (1)	**%**								
15. Tomatoes	100	25	50	80	0.30	1.10	0.65	91	243
TR – Truck (1)	**%**								
10. Onions & Garlic	0.99	10	26	75	0.80	1.00	0.75	60	274
12. Potatoes	9.24	20	45	78	0.80	1.10	0.70	105	227
17. Flowers & Nursery	2.26	20	45	78	0.80	1.10	0.70	105	227

Crop or Surface (type)	Category Area %	Growth Dates			Crop Coefficients			Dates	
OR – Orchards (3)	**%**	**B**	**C**	**D**	**Kc1**	**Kc2**	**Kc3**	**Beg**	**End**
18. Misc Truck	2.89	25	63	88	0.30	1.00	0.85	213	319
19. Bushberries	0.02	15	45	80	0.20	0.70	0.70	121	273
2. Asparagus	74.95	12	25	95	0.25	1.00	0.25	1	366
21. Peppers	0.58	20	45	85	0.80	1.00	0.85	60	243
3. Beans (green)	0.86	22	56	89	0.80	1.00	0.85	60	151
4. Cole Crops	0.92	25	63	88	0.30	1.00	0.85	213	319
7. Carrots	0.18	20	50	83	0.85	0.95	0.80	15	135
8. Lettuce (all types)	1.19	25	65	90	0.80	0.8	0.80	74	196
9. Melons, Squash, & Cucumbers (all types)	5.92	21	50	83	0.80	0.95	0.75	91	319
VI – Vineyards (3)	**%**								
Vineyards	100	0	25	75	0.45	0.80	0.35	91	305
U – Urban (3)	**%**								
Urban Hard Tops	41.46	0	33	67	0.00	0.00	0.00	1.00	366
Urban Vacant Lots	40.47	0	33	67	1.00	0.40	1.00	1.00	366
Urban Lawns	18.08	0	33	67	1.00	0.70	1.00	1.00	366