Delta Evapotranspiration of Applied Water – DETAW

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Introduction

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

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

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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.

Land Use

The goal of this effort was to develop historical land use for 168 Delta sub-areas for the water years 1922-2003, and to project land use for critically dry, and normal to wet water availability. Delta historical land use from 1992 through 2003 was obtained from the current CU model input files for both DSA54 and DSA55. Surveys are conducted every five to seven years, and the data are interpolated between survey years. The results are adjusted annually based on Agricultural Commissioner Reports. Projected level land-use data were developed by the CDWR-DPLA for Bulletin 160. 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 used by Mahmoud Mabrouk and Mary Serrato from the DWR Bay-Delta Office staff, 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.

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 agricultural 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 agricultural land for each sub-area using GIS distribution from step 5. Then, to distribute the assigned agricultural land among different crops, the intra crop distribution calculated in step 3 was used.
8) Assign and distribute any remaining unassigned area 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 file 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.

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 Delta 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.

Table 1. Components of the 15 land-use categories by source.

Land Use	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	Part of Grain and Hay	Non-Irrigated Grain	Non-Irrigated Grain
Native Vegetation	Native Vegetation, Native Classes Unsegregated, Idle, Barren Wasteland	Native Vegetation	Native Vegetation

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 (K_c) curves, but categories containing multiple crops or other surfaces do not have seasonal K_c curves. These multiple surface sub-categories, however, generally have one or two dominant surfaces. Therefore, it was possible to determine a weighted mean seasonal K_c 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. The sub-category percentages for each land-use category are provided in the DETAW Final Report.

Reference Evapotranspiration

Reference evapotranspiration (ET_o), an estimate of the evapotranspiration of a well-watered, improved pasture, is technically defined as the ET from a short 12 cm tall vegetation of large extent and not lacking for water. In practice, ET_o is approximately equal to the ET of a 12 cm tall, cool-season pasture grass. The DETAW program uses ET_o and crop coefficients to estimate the ET of various crops (ET_c). To estimate ET_o, 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 ET_o 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. Note that the ASCE-EWRI standardized ETo estimation method is described in the SIMETAW section of this bulletin.

ET_o Spatial Estimation

A fundamental problem with estimating ET_o 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 of them have only existed for 20 years or less. Prior to 1986, there were no CIMIS stations and only temperature data were available for estimating ET_o. 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 ET_o across the Delta. To resolve this problem, data from the nine CIMIS stations around the Delta were used to compute ET_o 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.

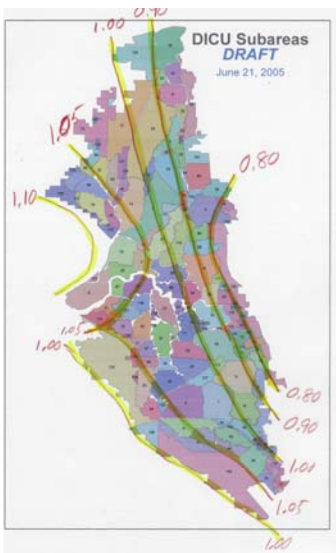
ET_o Corrrection Factors

The daily ET_o 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 ET_o versus the Lodi ET_o data was computed for each CIMIS station to determine the slope of the linear regressions through the origin. Then the PM-ET_o on any day at any CIMIS station was estimated as the product of the Lodi HS-ET_o and the slope. The derived slopes were used as correction factors to estimate PM-ET_o at the CIMIS stations using the HS-ET_o from the Lodi NCDC station. The derived slopes are given in the DETAW Final Report.

ET_o Correction Isolines

Using the annual slopes as correction factors for each CIMIS station, correction factor isolines were drawn by hand on a Delta map (Fig. 1.a). A scanned image of the hand-drawn isolines was geo-referenced and digitized into a GIS shape file (Fig. 1.b) using ArcGIS software. A weighted average of correction factors was derived, for each sub-area, by overlaying the sub-area GIS shape file on to the continuous surface and using the ArcGIS Spatial Analyst Zonal Statistic tool to extract the values.

(a)



(b)

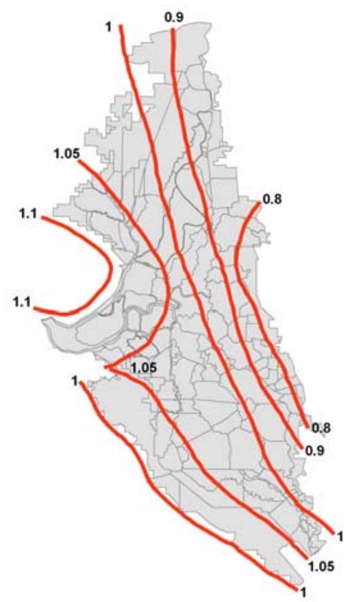


Figure 1. The Delta with hand-drawn isolines of ETo correction factors (a) and GIS digitized isolines of ET_o correction factors (b).

Spatial Rainfall Estimation

Rainfall data were unavailable for most of the Delta sub-areas, so 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 for seven stations: Davis, Stockton, Lodi, Tracy-Carbona, Rio Vista, Brentwood and Galt. Daily precipitation data were compiled, missing data were estimated, and the data were used to develop the daily time series for each sub-area. Thiessen Polygons were created to determine which precipitation stations can be used to estimate sub-area rainfall. Any sub-area that was completely within a Thiessen Polygon (Fig. 2) was represented by a single precipitation station, and sub-areas that fell in more than one Thiessen Polygon were 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 (Fig. 2).

Crop Coefficient Curves

In DETAW, seasonal K_c curves are used to estimate evapotranspiration for the 15 various land-use surfaces. There are actually two sets of K_c 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 K_c 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 K_c rather than the name “crop coefficient” for the factors that are multiplied by reference evapotranspiration (ET_o) to estimate the ET of a particular land-use category. We will use the symbol ET_c, 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:

$$ET_c = ET_o \times K_c \quad (1)$$

where K_c is a factor to convert ET_o to ET_c.

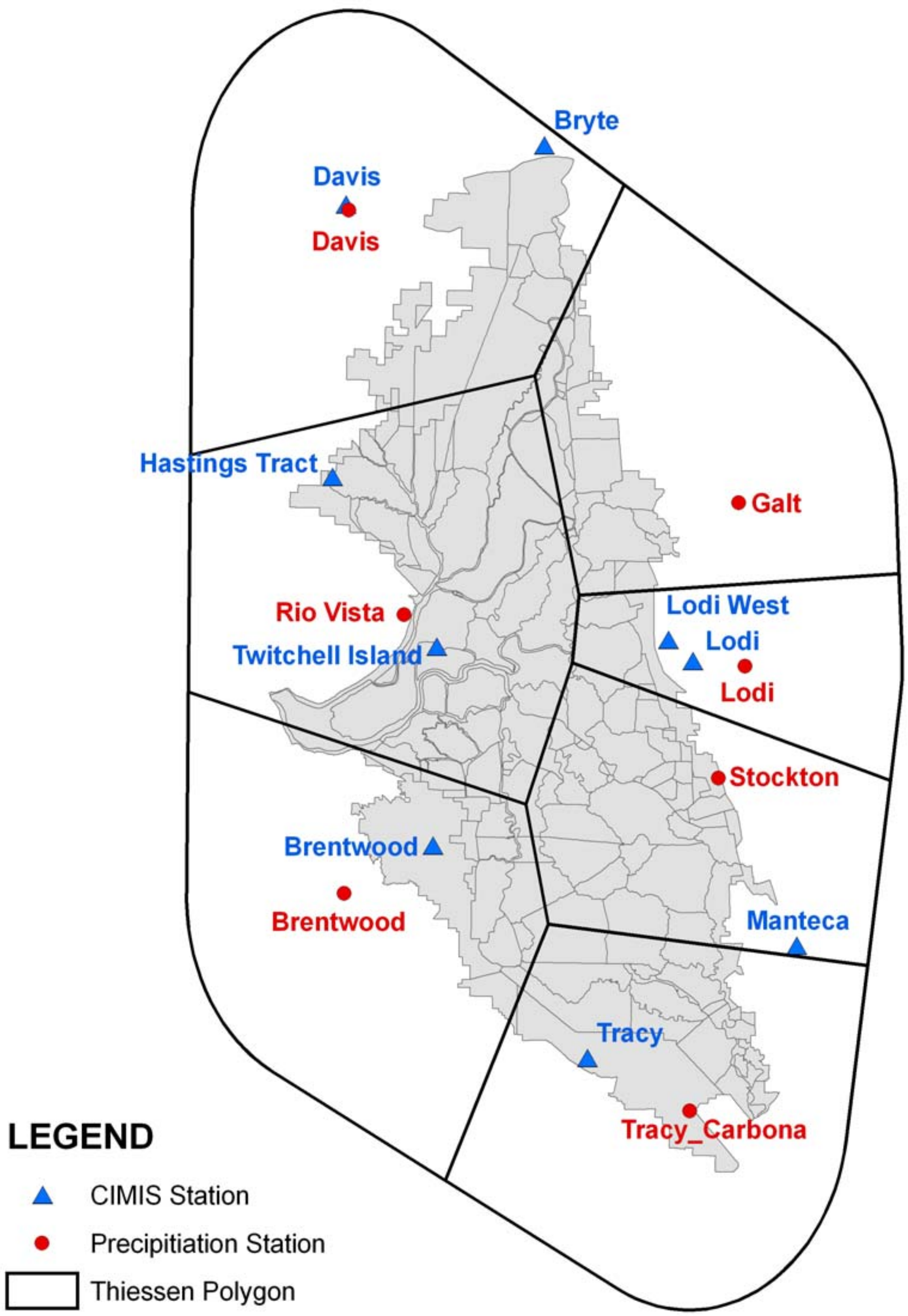


Figure 2. Thiessen Polygons for determining spatial distribution of precipitation.

One set of 15 K_c curves is used for ET calculations during non-critical water years and the other set of 15 K_c curves is used during critical water years. Samples of the critical and non-critical year Kc curves is shown for four land-use surfaces in Fig. 3. 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 Fig. 3, monthly mean in-season K_c values were computed for each land-use categories (Table 7). The crop K_c 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 K_c method, crop types, etc. are explained in the SIMETAW section of this Bulletin.

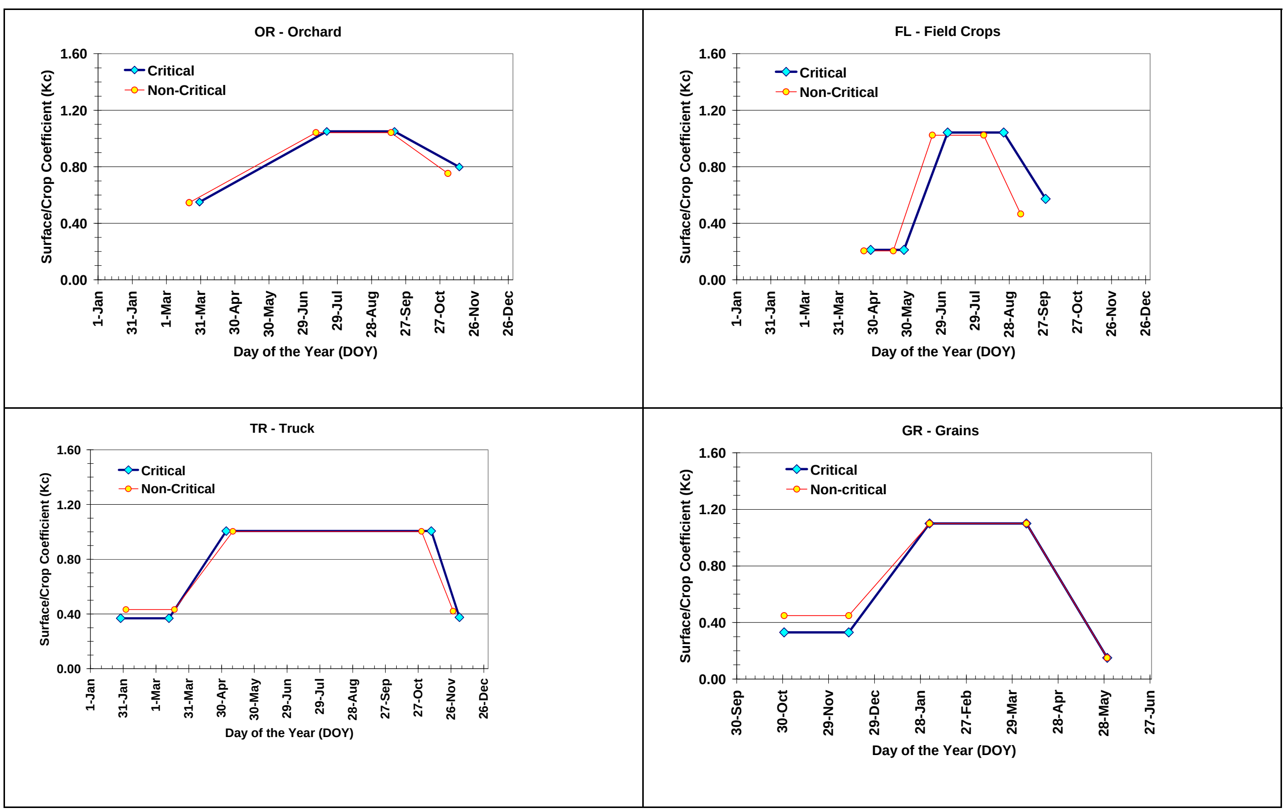


Figure 3. A set of charts showing the surface land-use category crop coefficient curves for critical and non-critical years.

Table 7. Monthly mean crop coefficient (K_c) factors for the 15 land-use surfaces during non-critical years 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

Crop and Soil Information

Crop and soil information are read from '.csv' comma-delimited data files that are specific to DELTA sub-areas. The variables and format for the non-critical and critical year '.csv' files are described in the DETAW Final Report. 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 information on pre-irrigation is unavailable.

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 depletion (SWD) does not exceed the yield threshold depletion (YTD), which is calculated as the product of the allowable depletion and the plant available water content within the crop rooting depth. The plant available water content is computed as the product of the soil available water-holding capacity and the effective rooting depth. The allowable depletion is a crop and soil specific factor that defines the fraction (or percentage) of the available water content within a rooting zone that can be depleted between irrigation events. For many crop and soil combinations, an allowable depletion of 50% is adequate. For drought tolerant crops with dense root systems, the allowable depletion can be increased by 10 to 15%. For drought sensitive crops, with sparse root systems, allowable depletions can be decreased byt 10 to 15%. . In the off-season, the maximum soil water depletion (SWD_x) is set equal to 50% of the available water content within the top 0.3 m. It is assumed that, without a crop, the soil in the top 0.3 m cannot lose more water than SWD_x.

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 allowable depletion (expressed as a fraction) 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 soil depth was set at 1524 mm. The maximum rooting depths in the Delta upland and lowland were obtained from Barnes (1979).

Water Balance Calculations

All input data and calculations in the DETAW application are in metric units. 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 a conversion factor of 0.008107.

$$\mathrm{mm} \times \frac{1\,\mathrm{m}}{10^3\,\mathrm{mm}} \times \mathrm{ha} \times \frac{10^4\,\mathrm{m}^2}{\mathrm{ha}} \times \frac{1\,\mathrm{A-ft}}{1233.482\,\mathrm{m}^3} = 0.0081071\ \mathrm{Ac-Ft}$$

Agricultural Crops

The daily change in soil water content is calculated as $D_{sw} = ET_c - E_{spg} - E_r$ for agricultural crops, where ET_c is the crop evapotranspiration, E_{spg} is the effective water contribution from seepage, and E_r is the effective rainfall. ET_c on every day of the year is computed as the product of ET_o and K_c value, which equals the higher of the off-season (OK_c) and in-season (IK_c) crop coefficient on the same date. The IK_c curves for each of the land-use surfaces were presented earlier in Figure 3 for critical and non-critical years. The OK_c values are computed as a function of the ET_o rate and soil wetting frequency. It is assumed that the K_c value on any given date cannot be lower than the OK_c value. Seepage (S_{pg}) is estimated as 0.3 inches per foot of maximum root depth per month, so $Spg = 0.025 \cdot RD_x / (days / month)$. Effective seepage ($E_{spg}$) is calculated from the S_{pg} and the soil water depletion. If the soil water depletion is greater than S_{pg}, then $E_{spg} = S_{pg}$. Otherwise, E_{spg} = SWD, the soil water depletion. Then the soil water depletion adjusted for seepage is calculated as SWD' = SWD – E_{spg}, which could be zero or some positive number if the ET_c is greater than the seepage.

Effective rainfall (E_r) is calculated in a similar manner as the effective seepage. If the precipitation (Pcp) is less than the SWD′, then E_r = Pcp. Otherwise, E_r = SWD′, and the daily change in soil water content is SWD = $ET_c - E_{spg} - E_r = 0$.

On every day of the year, the soil water depletion is calculated as SWD = SWD_p + Dsw, where SWD_p is the soil water depletion from the previous day and D_{sw} is the change in the soil water depletion on the current day. Irrigation dates and amounts are determined by comparing the SWD with the management allowable depletion.

Growers use a management allowable depletion (MAD) to help determine when and how much to irrigate. This is the amount of water that they want to deplete from the soil before irrigating, and it can depend on many crop, soil, and management factors. It is impossible for one to know how growers determine their MAD , but a main factor in determining a MAD is to estimate the yield threshold depletion (YTD), where the YTD is the soil water depletion that should not be exceeded to avoid yield reductions due to water stress. In DETAW, the YTD is estimated as 50% of the available soil water content in the crop root zone. The smaller of the maximum rooting depth and maximum soil depth is used to identify the effective rooting depth for a particular crop and soil combination. Values for maximum soil and root depth are read from the crop and soil '.csv' files. Then, the plant available water content for the effective rooting depth is calculated as the product of the effective rooting depth and the available water holding capacity. The plant available water content is computed and multiplied by 0.50 to obtain the YTD from the end of the crop rapid growth period to the end of the season. During initial growth period of field crops, the root depth is fixed at 0.3 m, but it increases to the maximum depth at the end of the initial growth. DETAW uses the YTD as the MAD except it is adjusted slightly to force the last irrigation to be applied so that the soil water content is low at the end of the season. In the program output, the column with the heading SWD_x contains the MAD data that are used for scheduling

When scheduling irrigation, if $SWD_p + D_{sw} > SWD_x$, then the net application is NA = $SWD_p + D_{sw}$. Otherwise, NA =0. On each date, the soil water depletion is calculated as SWD = $SWD_p + D_{sw} – NA$, so the SWD returns to SWD = 0 on an irrigation date. This procedure is followed throughout the in-season period.

During the off-season, there is no irrigation and, therefore, NA = 0 on all off-season dates. However, Dsw and SWD are computed in the same manner all year. During the off-season, the soil water depletion cannot exceed 50% depletion of the soil water content within the upper 0.3 m depth of soil (i.e., the off-season SWD_x). After the last day of the season, if SWD already exceeds SWD_x, the SWD will not increase. The SWD can decrease, however, if D_{sw} is negative as the result of seepage and/or rainfall. Once the SWD is less than the off-season SWD_x, it can increase again, but it cannot exceed the off-season maximum. Commonly, in California, the winter rainfall will decrease the SWD back to zero. Thus, the SWD prior to the next season is often close to field capacity.

Rice

Because rice is grown in paddies with continuous standing water, the water balance requires different calibration. For the other crops, we calculate the change in soil water content as: D_{sw} =

ET_c – E_{spg} – E_r on each day. However, water is continuously applied, so the crop is irrigated each day. We assume that all seepage is effective, so $E_{spg} = S_{pg}$. For calculation purposes, it is assumed that the daily change in soil water content (D_{sw}) is replaced by a net application (NA) on each day of the growing season up to 20 days prior to the end of the season. Growers typically drain their fields about 20 days before the end of the season, so there are no net applications during that period. The losses to evapotranspiration during that 20-day period are assumed to come from soil water stored prior to the beginning of the season. Since rice is growing mainly in standing water, it is not possible to compute a daily SWD or to determine when to apply irrigation. Therefore, it is assumed that NA=ET_c on each day of the season. Rainfall is not included in the daily water balance calculations for rice. The annual total rice ET_{aw}, however, can be improved by adding the NA values during the season and subtracting the total seasonal precipitation. This assumes that all of the rainfall is effective and the contribution decreases the need for an equal amount of net application (NA).

Riparian Vegetation

Riparian vegetation grows near sources of surface and ground water and receives much of its water needs from seepage. Since riparian vegetation is believed to receive sufficient water from seepage to avoid transpiration reducing water stress, the contribution of seepage was set equal to the ET_c on each day of the year. Thus, the daily change in soil water content was calculated as $D_{sw} = ET_c – E_{spg} =0$. Riparian vegetation is not irrigated and, therefore, there is no ET of applied water for surfaces covered with riparian vegetation. Precipitation is ignored in the riparian vegetation water balance calculations because effective rainfall cannot be calculated when the soil water content is not allowed to drop.

Open Water Surfaces

For open water surfaces, the seepage is lost rather than gained, so, unlike the other surfaces, $D_{sw} = ET_c + E_{spg}$ on each day. In this case, however, the E_{spg} is equal to the sum of the E_{spg} going to all other surfaces in the sub-area. Precipitation is ignored in the water balance calculations because effective rainfall cannot be calculated when the soil water content is not allowed to drop. Actually, all precipitation on water surfaces is effective.

Native Vegetation

Native vegetation differs from riparian vegetation in that seepage does not supply sufficient water to the plants to match ET_c and avoid transpiration reducing water stress. For native vegetation, the daily change in soil water content is calculated as $D_{sw} = ET_c – E_{spg} – E_r$, which is exactly the same procedure used for agricultural crops. The difference is that there are not applications of irrigation water so NA = 0 always. Native vegetation typically goes dormant during the summer months, which reduces the K_c value to near zero and hence ET_c is very low. The ET_c increases again in the fall after the rains begin and the soil water content increases.

ET of Applied Water

Definition

ET_{aw} 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 fraction of GA that contributes to crop evapotranspiration (ET_c). The method used to determine ET_{aw} is explained below using the example of a tomato crop grown in Sub-area 104, Acker Island, in the Sacramento – San Joaquin River Delta. The ET_o, ET_c, and K_c values for two sample years are shown in Figure 4.

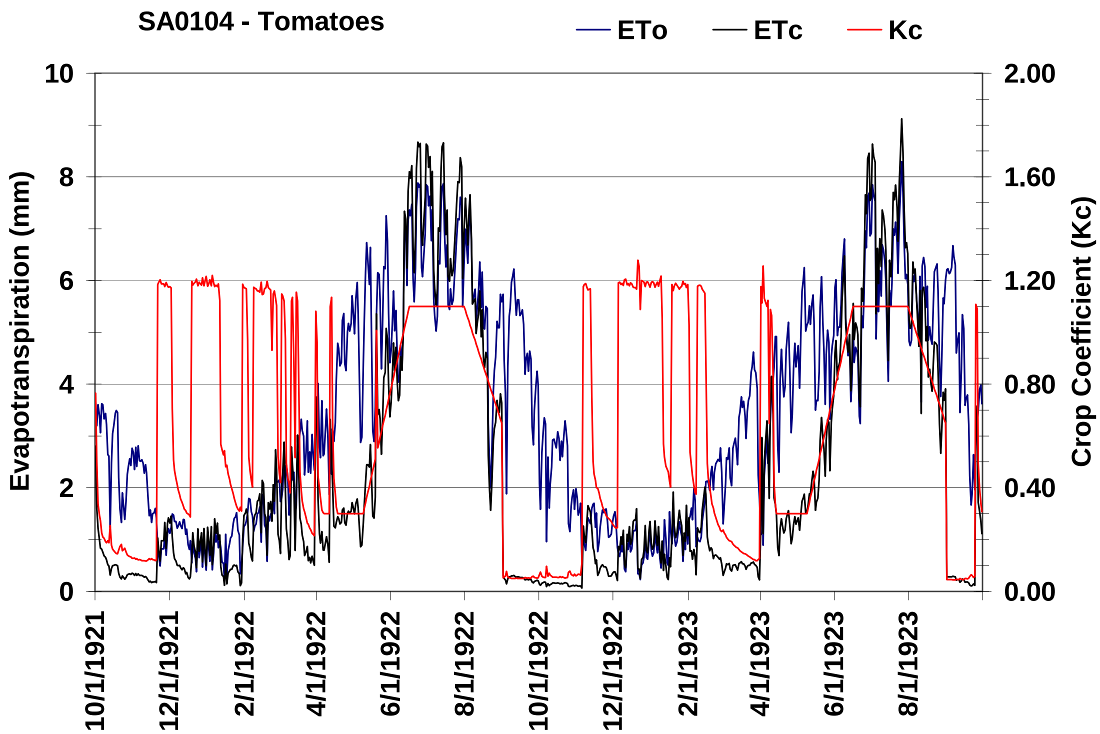


Figure 4. Crop (ET_c) and reference (ET_o) evapotranspiration and crop coefficient factors for 1921 – 1922 water years for a tomato crop grown in Sub-area 104 of the Delta.

For all surfaces except open water and riparian vegetation, daily water balance calculations start with the soil water content on the previous day (SWC_o). Then the water losses to ET_c are subtracted to determine the soil water content on the current day as $SWC_1 = SWC_o - ET_c$. This is the soil water depletion adjusted for ET_c. Next, the effective seepage (E_{spg}) contribution to the water balance is computed by comparing the seepage (S_{pg}) with SWC_1. If $S_{pg} < SWC_1$, then $E_{spg} = S_{pg}$, otherwise, $E_{spg} = SWC_1$. Then the soil water content based on ET_c and effective seepage is calculated as $SWC_2 = SWC_1 + Espg$. Then, the soil water content is adjusted for effective rainfall by comparing the precipitation (P) with SWC_2. If $P < SWC_2$, then the effective rainfall is calculated as $E_r = P$. Otherwise, $E_r = SWC_2$. Then, the soil water content based on ET_c, effective seepage, and effective rainfall is calculated as $SWC_3 = SWC_2 + Er$. Therefore, the final estimate of soil water content without considering irrigation, is given in terms of the daily change in soil water content (D_{sw}) as

$$SWC_3 = SWC_o - D_{sw} = SWC_o - (ET_c - E_{spg} - E_r)$$

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_3) back to field capacity (FC) on the irrigation date. On each irrigation date, the NA is equal to SWC_3, so the actual soil water content on each day of the season is calculated as

$$SWC = SWC_o - D_{sw} + NA$$

where SWC_o is the soil water content on the previous day, NA is the net application, which is zero on non-irrigation days, and D_{sw} is the daily change in soil water content expressed as

$$D_{sw} = ET_c - E_{spg} - E_r .$$

By definition, ET_{aw} is the amount of applied irrigation water that contributes to ET_c; therefore, ET_{aw} is the sum of the net irrigation applications during a cropping season. The ET_{aw} for *n* irrigation events is therefore calculated as:

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

This is the method used to determine the ET_{aw} in DETAW. Although not computed in DETAW, 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} irrigation date of the season. Assuming AE is the apparent, seasonal application efficiency, the seasonal irrigation water diversion can be calculated as:

$$D = \frac{ET_{aw}}{AE}$$

where AE is the apparent, application efficiency fraction for the season.

Off-Season 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 from the rivers and canals to the ground water and into the effective 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 decreases by the rainfall amount but the SWD can never be 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. 7).

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 the water balance during the off-season before planting or leaf-out. It is assumed that the initial SWD equals zero on September 30, 1921. After that the SWD is calculated using water balance for the entire period of record.

In-season Calculations

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. 7). If rainfall occurs, SWD is reduced by an amount equal to the rainfall. However, the SWD is not allowed to fall to less than zero. This procedure 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. The method ignores runoff and water running onto the field, but this is a minor problem in most irrigated fields in California. Irrigation events occur 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.

Summary

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 ET_c and ET_{aw} based on the daily water

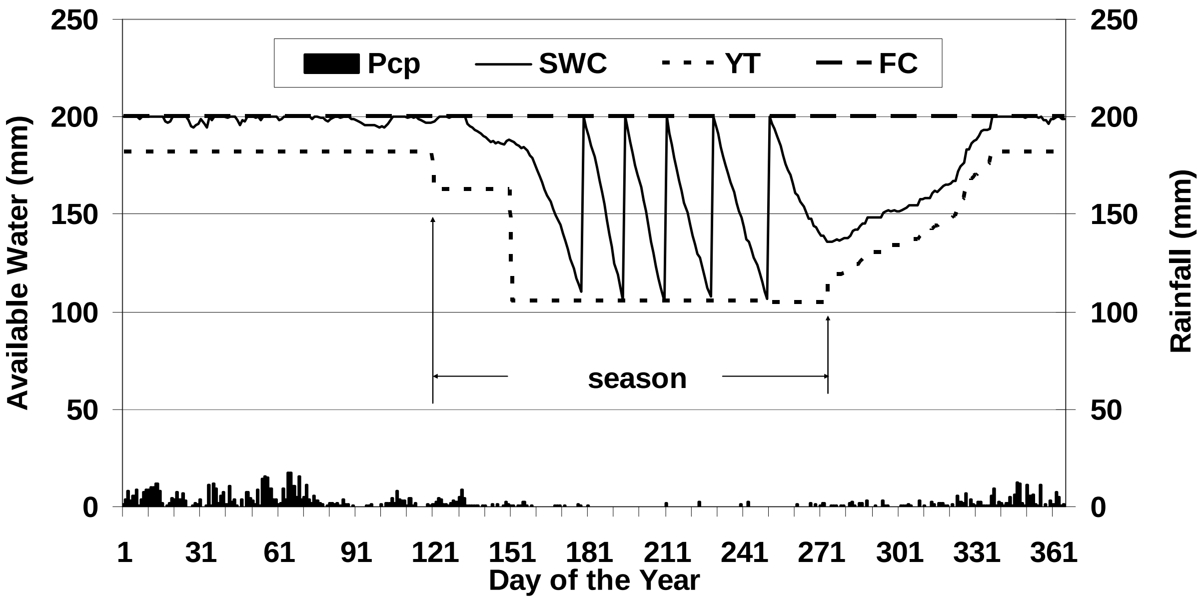


Fig. 7. An annual water balance for maize showing fluctuations in soil water content (SWC) between field capacity (FC) and the yield threshold (YT) and precipitation (Pcp).

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 usageis 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.

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