Final paper has a few slight changes WOP.

CHAPTER 5
CROP WATER USE

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INTRODUCTION

Two of the important parameters needing evaluation in development of irrigation and storage facilities for reclaimed water irrigation systems are losses through the process of evaporation and gains from precipitation. In fact this chapter could appropriately be titled "Net Losses in Surface-Atmosphere Interactions." In this chapter procedures are developed for estimating expected losses of water through transpiration (T) by plants and evaporation (E) from plant, soil, or pond surfaces. The combined loss for a cropped surface is commonly referred to as evapotranspiration (ET). Extensive precipitation records are already available.

In the past, well-watered, short green crops fully shading the ground have been used to evaluate the impact of climate on evapotranspiration. The term potential evapotranspiration (PET) was suggested by early researchers (Thornthwaite [1] and Penman [2]). More recently Doorenbos and Pruitt [3], expanding the Penman definition, described a "reference crop evapotranspiration, ET_o, as the "rate of evapotranspiration from an extended surface of 8 to 15 cm (3-6 inch) tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water." A term more commonly used is simply "reference evapotranspiration" with the crop specified. This term, with grass as the reference crop, was selected several years ago by an Interagency Group for use in California and was used by Pruitt et al. [4].

Values of ET_o are considered herein to provide direct estimates of water loss for a well-managed pasture. For other crops ET is estimated by multiplying ET_o values by recommended crop coefficients (k_c).

An analysis of storage needs for reclaimed water projects requires consideration not of ET alone, but of the annual (and monthly) excess of ET over P. The use of only normal or average values is not adequate due to the natural variation of both; hence

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In: Pettygrove, G.S. and T. Asano (editors). Irrigation with Reclaimed Municipal Wastewater. Report No. 84-1 wr. California State Water Resources Control Board. 1984. (In press).

long-term records of ET and P are required. Also, because the two are not independent[1/], a frequency distribution of (ET - P) cannot be developed by separate assessments of records of ET and of P; rather (ET - P) data for a number of years must be available or generated.

Since the records of measured ET_o are limited to a few locations in California the required long-term data for ET_o - P must be generated from year-by-year or even month-by-month estimates of ET_o. This could be accomplished using weather data and appropriate prediction equations, were it not for the paucity of required climatic data for equations that are sensitive enough to fully respond to temporal variations of ET_o.

Fortunately there are many locations in California with long term records of monthly pan evaporation (E_p). Except for 30 or so locations where pans were sited in an irrigated turfgrass environment, or in areas with continuously dry surroundings, selection of appropriate pan coefficients for estimating ET_o has been considered difficult[2/]. However, a procedure proposed herein should allow use of most of the evaporation pan records available in California to develop long-term estimates of ET_o.

In design of the irrigation system to handle the requirements of crops during midsummer, monthly values of ET (or ET - P for areas with summer rainfall) do not offer the necessary detail for developing peak demand information. This is especially true for shallow or sandy soils or shallow-rooted crops. Essentially, daily records of estimated ET for the months of June or July over a several-year period are needed to determine expected peak demand. Pan evaporation data on a

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1/ The cloudiness needed to produce precipitation reduces ET to lower than normal levels while ET is greatest during clear weather. A regression analysis of a 16-year record for Mar.-Apr. periods at Davis of measured ET for grass versus precipitation, P indicated ET = -0.469 P + 9.22 inches with a correlation coefficient r = 0.90. Annual data suggested ET = -0.231 P + 55.50 inches with r = 0.71.

2/ Several studies have shown the hazard of using pan evaporation data to estimate PET or ET_o without due regard to local pan environment (Ramdas [5], Pruitt [6], DWR [7], and Pruitt and Doorenbos [8], [9]).

daily basis are available from some local records; however, an approach adapted from Jensen and Criddle [10] and Doorenbos and Pruitt [3] is suggested. The design criteria are based upon published information on extreme maximum values of pan evaporation at a number of selected weather stations in California and adjacent states [11].

DEVELOPMENT OF REQUIRED BACKGROUND DATA

In this section we will present several methods for determining normal-year ET_o, discuss the availability and application of crop coeffcients to obtain ET(crop), and provide a reference source for obtaining necessary long-term precipitation records for California. These data are required for the ultimate development of long-term records (preferably twenty years or more) of net water loss (ET - P), and for use in subsequent frequency distribution analyses.

Reference Evapotranspiration, ET_o

Three alternative approaches are provided in this chapter for selecting normal-year values of ET_o for annual, seasonal, or monthly periods for any location in California. These ET_o values become the basis of development of expected losses, e.g., from pasture and other crops, fallow surfaces, and storage ponds. The approaches are as follows:

1. Bulletin 113-3, published by California's State Department of Water Resources (DWR [7]), provides tables of potential evapotranspiration (PET) for some ten regions of the state, each considered as a zone of similar evaporative demand. An equivalence of ET_o and PET can be assumed since most of the values of PET they report were based on actual ET by perennial ryegrass or tall fescue. Table 5-1 is a reproduction of their Table 6. Figure 5-9 (page 5-33, following the text) was also reproduced from Bulletin 113-3 [7]. It delineates so-called zones of similar evaporative demand. Data in Table 5-1 can be used for development of monthly, seasonal, or annual totals of ET_o, especially for locations well away (geographically) from the borders separating zones.

Table 5-1. Summary of estimated potential evapotranspiration in California inches.[a,b] After California DWR Bull. 113-3, [7].

	Northeastern Mountain Valleys	North Coast-Coastal Valleys and Plains	North Coast-Interior Valleys	Sacramento Valley	San Joaquin Valley	Central Coast-Coastal Valleys and Plains	Central Coast-Interior Valleys	South Coast-Coastal Valleys and Plains[c]	South Coast-Coastal Interior Valleys[c]	Southern California Desert[d]
Jan	0.6	0.5	0.8	1.1	0.9	1.8	1.6	1.8	1.7	2.7
Feb	1.0	1.0	1.2	1.8	1.7	2.1	2.1	2.4	2.4	3.6
Mar	2.1	2.0	2.4	3.0	3.2	3.1	3.3	3.1	3.3	5.9
Apr	3.7	2.5	3.4	4.4	4.5	3.9	4.3	3.8	4.2	7.6
May	5.0	3.3	5.0	5.8	6.5	4.7	5.7	4.5	5.1	10.1
Jun	5.8	3.6	5.9	7.3	7.5	4.9	6.2	5.1	6.0	11.4
Jul	7.9	3.5	7.1	7.9	7.8	5.3	6.7	5.5	6.9	11.6
Aug	7.0	3.4	6.2	6.7	6.6	4.8	6.0	5.5	6.7	9.6
Sep	4.9	2.8	4.6	5.2	4.8	3.8	4.8	4.5	5.2	8.5
Oct	2.8	1.7	2.7	3.4	3.3	3.2	3.8	3.4	3.8	6.3
Nov	0.9	1.1	1.2	1.6	1.5	2.2	2.3	2.6	2.3	3.5
Dec	0.5	0.7	0.7	1.0	0.7	1.5	1.5	2.2	1.8	2.0
M-O[e]	39.2	22.8	37.3	43.7	44.3	33.7	40.8	35.4	41.2	71.0
J-D[f]	42.2	26.1	41.2	49.2	49.0	41.3	48.3	44.4	49.4	82.8

a. Potential evapotranspiration (PET) = ET of grass = reference evapotranspiration, ET_o.

b. Calculated from area average pan evaporation (E_p) data and recommended statewide average monthly k_p values [7] except as noted.

c. No evaporation data (irrigated pasture environment) available. PET estimates based upon estimated evaporation.

d. An estimate of ET – grass for Imperial Valley. Calculated by first author from ET by alfalfa (excluding two weeks following cutting) as observed by Robert D. LeMert, USDA-ARS, Brawley. (A 10-15% lower ET by grass than by alfalfa was assumed.)

e. March through October (principal growing season).

f. January through December.

2. For other areas, estimates of ET_o (on an annual basis only) can be obtained for any location in California by multiplying a pan coefficient (K_p) of 0.80 by a value of annual evaporative demand E_o as obtained by interpolation from Plate No. 1 in DWR Bulletin 113-3 [7]. The term E_o as presented herein, represents the evaporation expected from a National Weather Service Class "A" pan located in an irrigated pasture (or comparable environment). (See Figure 5-10 on page 5-34 for a reduced copy of this plate.)
3. A third alternative is believed to offer improved overall accuracy for much of the State. The isoline maps in a UC Agricultural Sciences Bulletin by Pruitt et al. [4] can be used to obtain annual, seasonal, or monthly estimates of ET_o for normal-year conditions for any location in California. As illustrated later, estimates for periods shorter than one month can be developed. Copies (reduced in size) of the twelve isoline maps are included in this Chapter, one for each month of the year (Fig. 5-11, pages 5-35 through 5-46).

ET or E for Cropped and Noncropped Surfaces

Estimates of annual, seasonal, or monthly losses of water from cropped or noncropped soil or water surfaces can be obtained by applying crop coefficient (k_c) values to ET_o estimates. ET_o itself can serve as an estimate of ET losses by a well-managed pasture assuming $k_c = 1.0$. For most crops under full-cover conditions, and for water surfaces or wet bare soil, k_c values greater than 1.0 are appropriate[3/]. For fallow conditions, the soil surface is frequently not wet and for early stages of crop growth, ET is usually quite limited. Hence, k_c values well below 1.0 are common, unless frequent rain or irrigations are involved.

The sources of k_c values for various cropping patterns and for annual, monthly or shorter periods are outlined below:

3/ For a given climatic condition, the ET of many crops exceeds ET_o. Involved are their taller, aerodynamically rougher canopies, a slightly lower reflectance of incoming solar radiation, and a somewhat cooler canopy with lower long-wave radiation losses than for grass.

1. Annual k_c estimates: Table 5-2 provides recommended k_c values on an annual basis to be multiplied by annual ET_o estimates. Such data may be valuable for preliminary feasibility analysis.
2. Alternate sources of, and shorter-period estimates of k_c:
   a) Table 5-12 on page 5-29 at the end of the text provides estimates of monthly k_c data for a number of crops. This table is an adaptation of k_p coefficients published in Table 5 of DWR Bull. 113-3 [7].
   b) Table 5-13 (pp. 5-30 and 5-31) provides a sample of 10- to 11-day recommended k_c values for a number of crops grown in several areas of the State. These data were adopted, from a final report on Irrigation Management Programs by Fereres, et al. [12], and other studies cited in Table 5-13 footnotes. Copies of this report are available from the Dept. of Land, Air and Water Resources, University of California, Davis.
   c) A bulletin in preparation by Fereres et al. [13], includes more extensive crop coefficient data.

Precipitation

Long-term records of precipitation are available for hundreds of sites in California. An extensive and up-to-date record was published in a DWR Bulletin "California Rainfall Summary, Monthly Total Precipitation, 1949-1980 [14]. Other sources may be more convenient since the records of the cited reference are contained within microfiche frames.

NET WATER USE FOR CROPS WITH YEAR-LONG FULL COVER

In this section, procedures are described and examples given as follows: 1) development of estimates of yearly totals of net water loss for cases involving ET_o, ET(trees) and E(ponds), along with a frequency analysis; 2) same but for separate analyses of wet-season, dry season, and transition months; 3) a comparison of yearly totals based on 1) and 2) above; and 4) development of monthly net water-loss data at a particular probability level, with adjustment to provide agreement with yearly totals under 1) above.

Table 5-2. Recommended coefficient (k_c) values to be multiplied by ET_o for estimating ET and E_c losses for a range of air mass conditions ranging from humid to dry to dry and windy. Included are various perennial crops and evergreen shrubs and trees (nondeciduous) all providing green cover[a] with nearly full shading of the ground surface.

Description	k_c[b] Dry & Humid-Dry-Windy
Water surfaces (shallow ponds, storage reservoirs, etc)[c]	1.05-1.10-1.15
Dark bare soil (constantly moist on surface)	1.05-1.10-1.15
Lighter colored bare soil (constantly moist surface)	1.00-1.05-1.10
Grass pasture (well maintained with rotational grazing)[c]	0.80-0.90-1.00
Grass-clover (or alfalfa) pasture with >60% ground cover left after grazing[b]	1.00-1.05-1.10
Alfalfa (grown for hay with cuttings every 30-35 days)[c]	0.85-0.95-1.05
Shrubbery (various evergreen species – low stomatal control)[d]	1.05-1.15-1.20
Evergreen trees (various species – high soil moisture – low stomatal control)[e]	1.10-1.20-1.30

a. For mountainous regions and in northern California, pastures and alfalfa may go dormant in winter resulting in lowered k_c values.

b. Some regions of the State experience a range of conditions during the year making it difficult to select a single k_c for use in an analysis involving annual totals of ET. Since a large portion of the total annual ET takes place in Apr.-Sep., the column selected to represent general climate conditions should be based on conditions prevailing during Apr.-Sep.

c. Based on k_c values suggested by Doorenbos and Pruitt, [3].

d. Based on assumptions that some species of evergreen shrubs offer very little stomatal control when grown in constantly moist soil and that reflection and roughness characteristics would result in k_c values similar to those of a number of agricultural row crops when they are fully shading the ground, e.g., tomatoes, sugarbeets, corn, etc. [3, 15].

e. Assuming some species of evergreen trees need k_c values similar to those suggested for mature apple, cherry, and walnut orchards when grown with a cover crop (Middleton et al [16], and Doorenbos and Pruitt [3]. Many studies on salt cedar (Tamarix chinensis Lour) lead the authors to believe that these coefficients are conservative if anything. For example see Davenport et al. [17, 18], Gay and Sammis [19], and van Hylckama [20].

Yearly Totals Based on Annual Data

Preliminary evaluations for storage requirements of slow-rate reclaimed water systems can be based on estimates of yearly totals of evapotranspiration (ET) and/or of open water evaporation (E) from ponds, along with measured precipitation (P).

The EPA Process Design Manual [21] provides a map on page 2-11 with isolines of annual potential evapotranspiration minus precipitation (PET - P) for the entire contiguous USA. This map reproduced from Flach [22], although a valuable contribution, is not recommended for use in California for two reasons: (1) data developed within the state are likely to be more reliable; and (2) data for estimated or measured ET minus precipitation are needed for a number of years of record in order to develop design information related to a selected frequency of occurrence.

The simplest design procedure is for those systems which will involve the growing of some perennial crop which maintains year-round, full cover of green growth, e.g., pasture and evergreen shrubs or trees. As indicated earlier, reference evapotranspiration (ET_o) will be used herein as a foundation for calculating losses for various cropped or water storage areas with ET_o itself serving as an estimate for a well-managed pasture.

For system design based on annual data the following steps are recommended:

1. Develop an estimate of normal-year total annual ET_o for the geographical location of interest as described in an earlier section.
2. Using California's DWR Bulletin 73-79 [23], extract and tabulate annual pan evaporation data (E_p) for a location nearest the site of interest but with a record of 15 years or more of data. Do not combine the records of two or more types of pans for any given site since evaporation is very much a function of type of pan. If possible also avoid use of records involving a change of weather station siting. See U.S. Department of Commerce Bulletin [24].
3. After calculating a mean value of annual E_p divide this value into the estimated annual normal ET_o of (1) above to obtain an average pan coefficient, K_p.

4. Multiply the average K_p by each E_p value tabulated under (2) above to obtain an estimate of ET_o for each year for which pan data are available. If crops or surfaces other than pasture are involved, multiply the ET_o value by appropriate k_c values as given in Table 5-2; e.g., to obtain estimates of evaporation from storage ponds, E(pond) or evapotranspiration from trees, ET(trees).
5. Using California's DWR Bulletin "California Rainfall Summary" [14], extract from microfiche frames a record of the total annual rainfall for the same years of record as for the available E_p data tabulated under (2) above.
6. Subtract precipitation values from respective tabulated ET or E data under (4) above.
7. Run a frequency distribution analysis of estimated losses minus precipitation.

Data for 19 years from Davis, California are used in Example 5-1 to illustrate the steps outlined above with Steps 2-6 developed in Table 5-3a. Table 5-3b in Example 5-1 illustrates the development of the frequency distribution data. Figure 5-1, based on an assumed normal distribution, provides a plot of the results of the analysis developed in Example 5-1. The results of a separate frequency analysis of ET - P for a 16-year record of lysimeter measurements of ET for grass is also presented for comparison with the ET_o - P data. These measured data appear to validate the approach suggested under Steps 1 through 4, showing close agreement with the derived ET_o - P data except for the two years of highest losses.

The 90% probability level indicated in Fig. 5-1 is shown for illustration only, not necessarily a recommendation. Indicated is a 90% probability that net losses involving ET_o, E(pond), or ET(trees) should equal or exceed 20, 25, or 29 inches respectively (50.8, 63.5 or 73.7 cm), at Davis, California, in any given year. Of significance is the fact that for a reclaimed water system involving little, if any, deep percolation loss, the land acreage requirement for evergreen trees would be only 70% of that for a system involving grass pasture.

Example 5-1. E - P and ET - P for 19 years at Davis. (Yearly totals based on annual data)

Step 1. Normal-year ET_o (three alternative methods illustrated)

a) ET_o = 49.2 inch — Table 5-1 (Sacramento Valley)

or b) ET_o = 0.80 x 65 = 52.0 inch — Annual E map in Figure 5-10

or c) ET_o = 51.78 inch — 12-month summary, Isoline maps in Figure 5-11.

$$in/mo = \frac{\text{days in mo. x mm/day}}{25.4}$$

Step 2. Annual Epan (Oct.-Sep.) from SDWR Bull. 73-79 [23] pg. 28. Class A pan in an "A" environment. Missing data for years 1963, 1964, and 1975 obtained from local records to achieve a 19-year record.

Step 3. Divide normal-year ET_o (from Step 1) by Epan giving K_p = 51.78/70.79 = 0.731.

Step 4. Multiply each year's E_p by K_p to estimate ET_o. Multiply k_c values from Table 5-2 by ET_o to estimate ET(trees) and E(pond).

Step 5. Record precipitation, P obtained from SDWR Bull. "California rainfall summary" [14].

Step 6. Subtract Precipitation from ET and E totals.

Table 5-3a. Illustration for Davis, Ca. of Steps 2-6 using annual data.

Year	Epan(Oct-Sep) mm[a]	Epan(Oct-Sep) Inch	ET_o Inch[b]	ET(trees) Inch[b]	E(pond) Inch[b]	P Inch[c]	ET_o-P Inch[d]	ET(trees) - P Inch[d]	E(pond) - P Inch[d]
59-60	2029	79.9	58.4	70.1	64.2	10.7	47.4	59.4	53.5
60-61	1775	69.9	51.1	63.1	56.2	12.8	38.3	48.5	43.4
61-62	1712	67.4	49.3	59.2	54.2	15.0	34.3	44.2	39.2
62-63	1520	59.8	43.7	52.4	48.1	27.2	16.5	25.2	20.9
63-64	1786	70.3	51.4	61.7	56.5	11.1	40.3	50.6	45.4
64-65	1634	64.3	47.0	56.4	51.7	19.0	28.0	37.4	32.7
65-66	1732	68.2	49.9	59.9	54.9	11.1	38.8	48.8	43.8
66-67	1544	60.8	44.4	53.2	48.8	27.4	17.0	25.8	21.4
67-68	1867	73.5	53.7	64.4	59.1	11.6	42.1	52.8	47.5
68-69	1711	67.4	49.2	59.0	54.1	24.5	24.7	34.5	29.6
69-70	1872	73.7	53.9	64.7	59.3	17.0	36.9	47.7	42.3
70-71	1738	68.4	50.0	60.0	55.0	16.4	33.6	43.6	38.6
71-72	1820	71.7	52.4	62.9	57.6	9.4	43.0	53.5	48.2
72-73	1791	70.5	51.5	61.8	56.7	27.0	24.5	34.8	29.7
73-74	1848	72.8	53.2	63.8	58.5	21.4	31.8	42.4	37.1
74-75	1821	71.7	52.4	62.9	57.6	16.9	35.5	46.0	40.7
75-76	2036	80.2	58.6	70.3	64.5	6.8	51.8	63.5	57.7
76-77	1980	78.0	57.0	68.4	62.7	7.6	49.4	60.8	55.1
77-78	1945	76.6	56.0	67.2	61.6	27.0	29.0	40.2	34.6
Sum		1345.1	983.1	1179.6	1081.0	319.9	663.2	859.7	761.4
Average		70.79		62.1	56.9	16.84	34.91	45.3	40.1

a/ Step 2.
b/ Steps 3 and 4.
c/ Step 5. Note: Some discrepancies with SDWR [7] may be noted since local records were used in this example.
d/ Step 6.

Step 7. Illustration of Frequency Distribution Analysis.

a) Calculate probability level from 100 m/(n + 1) where m = ranking and n = years of record.

b) For systems involved, list data for water loss - P from Table 5-3a., ranked in order of descending magnitude.

c) Plot data on normal probability paper as in Figure 5-1.

Table 5-3b. Ranking of estimated annual totals of water loss - P.

m	$\frac{100m}{19+1}$	ET_o - P Inch	ET(trees) - P Inch	ET(pond) - P Inch
1	5	51.8	63.5	57.7
2	10	49.4	60.8	55.1
3	15	47.7	59.4	53.5
4	20	43.0	53.5	48.2
5	25	42.1	52.8	47.5
6	30	40.3	50.6	45.4
7	35	38.8	48.8	43.8
8	40	38.3	48.5	43.4
9	45	36.9	47.7	42.3
10	50	35.5	46.0	40.7
11	55	34.3	44.2	39.2
12	60	33.6	43.6	38.6
13	65	31.8	42.4	37.1
14	70	29.0	40.2	34.6
15	75	28.0	37.4	32.7
16	80	24.7	34.8	29.7
17	85	24.5	34.5	29.6
18	90	17.0	25.8	21.4
19	95	16.5	25.2	20.9

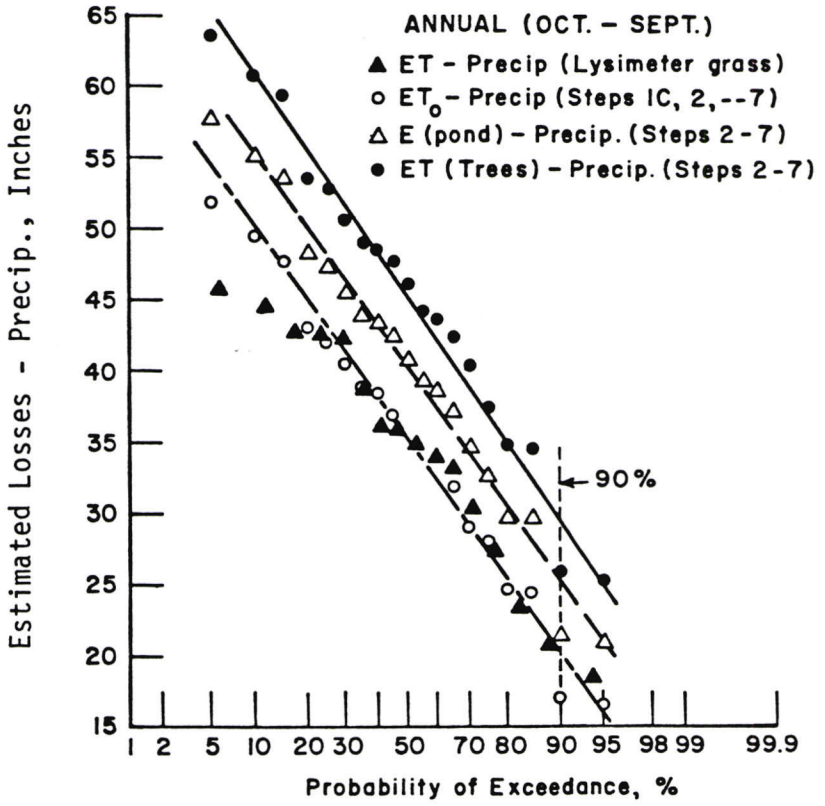

Figure 5-1. Frequency distribution analysis of data from Table 5-3b in Example 5-1 for ET_o, ET(trees), and E(pond), all minus precipitation. Yearly totals for hydrologic years (Oct.-Sept.), Davis, Calif. An analysis of measured ET(grass) - P (not tabulated in Table 5-3b) is shown for comparison with ET_o - P. Straight lines are from a fitting by eye.

Table 5-14a, b, and c following the text can be used to determine the risk (probability) that an event with a specified probability will occur during one or more, two or more, and three or more years within a selected design period. For example, ET - P has a 10% probability of being less than 20 inches (50.8 cm) in any given year (Figure 5-1). Using Table 5-14a, b, and c, one can calculate that the chances of ET - P being less than 20 inches on one or more, two or more and three

or more years during a 15-year design period, are 0.794, 0.451, and 0.184, respectively.

Seasonal Totals Based on Monthly Data

In many cases an analysis based on yearly totals may be inadequate to meet needs. The following section provides an example, again for a location in the Sacramento Valley (Davis, Ca.) of separate seasonal analyses with the year partitioned into a predominantly wet season (Nov.-Mar.), a predominantly dry season (May-Sept.), and two transition months (Oct. and Apr.). For many areas of California with its predominantly Mediterranean climate, such a grouping of months is recommended. For some areas of the state, however, other groupings may be desirable.

Wet Season

Example 5-2 provides a compilation of data and a frequency analysis for the predominantly wet season at Davis (Nov.-Mar.). Results of the measured ET(grass) are again shown to be in good agreement with the ET_o calculations using procedures proposed herein. Figure 5-2 indicates that in any given year, there is a 90% probability that the excess of P over ET would be equal to or less than 16 and 14 inches (40.6 and 35.6 cm) for systems involving ET_o and ET(trees), respectively. It would follow that, for storage ponds in this case, the excess would be around 15 inches (38 cm). Table 5-14 can again be used to determine risk of occurrence of excesses greater than the above for various design periods.

In areas where precipitation can greatly exceed the evaporative demand during the wet season of some years, a designer of wastewater systems would normally apply the water balance data to the storage pond areas only. The excess of P over ET in the cropped land area would merely go to deep percolation and directly into drainage channels. In areas where ET - P remains positive even during wet seasons, or in much wetter regions if deep percolation or run-off are restricted, water balance calculations would be required for both storage pond and cropped areas.

Example 5-2: ET - P for 19 years at Davis (wet-season analysis for November through March).

Step 1. Normal-year ET_o

a) ET_o = 8.5 inch Σ Nov.-Mar. Table 5-1,

b) Annual potential evaporation data not applicable.

or

c) ET_o = 8.68 inch Σ Nov.-Mar. from Isoline maps in Figure 5-11

Table 5-4. Example calculation for Davis, California for estimating November-March ET_o and ET (evergreen trees), and a frequency distribution analysis of expected water losses minus precipitation.

Year	Epan(Nov-Mar) mm[a]	Epan(Nov-Mar) Inch	ET_o Inch[b]	ET(trees) Inch[b]	P Inch[c]	ET_o-P Inch[d]	ET(trees) - P Inch[d]	$\frac{100m}{19+1}$[e]	ET_o-P Inch[e]	ET(trees) - P Inch[e]
59-60	419	16.4	11.5	13.8	9.3	2.2	4.5	5	8.9	11.2
60-61	305	12.0	8.4	10.1	12.0	-3.6	-1.9	10	4.6	6.7
61-62	318	12.5	8.7	10.4	14.8	-6.1	-4.4	15	2.8	4.8
62-63	265	10.4	7.3	8.8	14.5	-7.2	-5.7	20	2.2	4.5
63-64	366	14.4	10.1	12.1	9.1	1.0	3.0	25	1.0	3.0
64-65	278	10.9	7.6	9.1	13.9	-6.3	-4.8	30	-2.2	-0.6
65-66	286	11.2	7.8	9.4	10.0	-2.2	-0.6	35	-2.4	-0.7
66-67	249	9.8	6.9	8.3	22.5	-15.6	-14.2	40	-3.6	-1.9
67-68	295	11.9	8.3	10.0	10.7	-2.4	-0.7	45	-5.5	-3.8
68-69	274	11.2	7.8	9.4	22.3	-14.5	-12.9	50	-5.8	-3.9
69-70	356	14.0	9.8	11.8	15.6	5.8	-3.8	55	-6.1	-4.4
70-71	309	11.7	8.2	9.8	13.7	-5.5	-3.9	60	-6.3	-4.8
71-72	359	14.1	9.9	11.9	7.1	2.8	4.8	65	-7.0	-5.4
72-73	266	10.5	7.4	8.9	24.1	-16.7	-15.2	70	-7.2	-5.7
73-74	276	10.9	7.6	9.1	18.1	-10.5	-9.0	75	-10.5	-9.0
74-75	295	11.6	8.1	9.7	15.1	-7.0	-5.4	80	-14.5	-12.9
75-76	418	16.5	11.6	13.9	2.7	8.9	11.2	85	-15.6	-14.2
76-77	374	14.7	10.3	12.4	5.7	4.6	6.7	90	-16.2	-14.5
77-78	306	12.0	8.4	10.1	24.6	-16.2	14.5	95	-16.7	-15.2
Average		12.46		10.47	13.99	-5.27	-3.52			

a. Step 2 - From Bull. 73-79 [23], pp. 28. Class A pan in an "A" environment. Σ of Nov-Mar evaporation with missing data for years 1964 and 1975 obtained from local records.

b. Steps 3-4 - Using mean Kp = 8.68/12.46 = 0.70 for ET_o estimates and a k_c of 1.20 from Table 5-2 for evergreen trees (8.68" from Step 1c).

c. Step 5 - Precipitation data summed for Nov.-Mar. from microfiche frames of SDWR Bull. California rainfall summary [14].

d. Step 6 - Subtract precipitation from ET_o and ET(trees).

e. Step 7 - Distribution analysis.

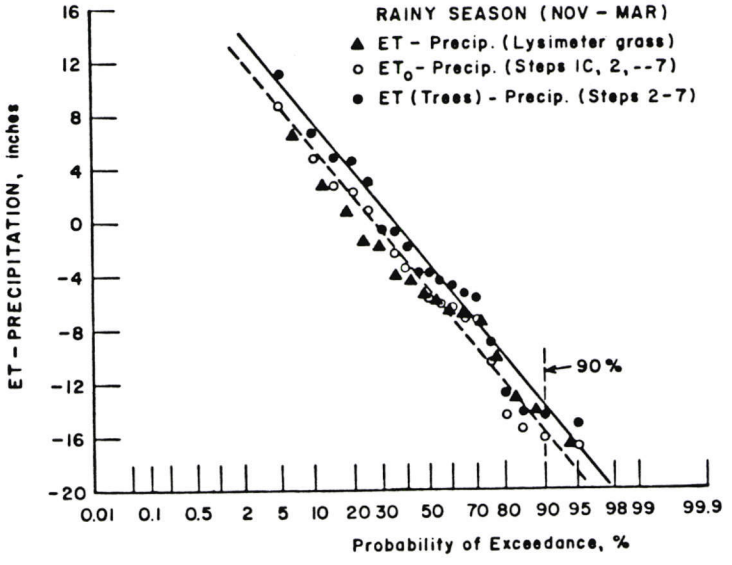

Figure 5-2. Frequency distribution analysis for ET_o - P and ET(trees) - P. An analysis of measured ET(grass) - P is shown for comparison. Davis, California. Rainy Season (November through March).

Dry Season and Transition Months

Specific examples of additional analyses are not laid out in detail although Tables 5-5 and 5-6 provide the necessary calculations for a dry season period (May through September) and for a combination of transition months (i.e., April and October).

Figure 5-3 presents the results of frequency distribution analyses for both sets of data. In any given year, there is a 90% probability that net losses by ET_o and ET(trees) for the dry season would be equal to or greater than 31 or 37 inches (78.7 or 93.9 cm), respectively. For the two transition months (April and October), corresponding values would be 4 and 5 inches (10.2 and 12.7 cm), respectively. It is obvious from the results of these two months, however, that there is a marked departure from a normal distribution for the wettest year (1962-63). Not only did this hydrologic year have the lowest ET_o for October and April, but the rain totaled some 11.87 inches. There have been, in a 110-year record, only two other years when P totaled greater than 5.8 inches (14.7 cm). In 1879-80 total P for Oct. and Apr. was 7.8 inches (19.8 cm) and in 1889-90 the total was 9.7 inches (24.6 cm).

The data to the far left in Figure 5-3 are useful for determining the supplemental water supply requirement to maintain good crop or tree growth during high demand years. The analysis suggests that for Davis there is, for example, only a 10% probability that the net demand for irrigation water for May through September would equal or exceed 38 or 46 inches (96.5 or 110.8 cm) for pasture or trees, respectively. The term "net irrigation supply" implies the need for use of an irrigation efficiency value to develop gross requirements (see Chapter 8).

Yearly Totals--Annual Data Versus Composite of Seasonal Data

Earlier a precautionary note was issued against using frequency distribution analyses for separate seasons. A comparison of yearly totals determined using the total annual and seasonal techniques is presented in Table 5-7. The yearly totals based on separate-season analyses are fairly close to those in Example 1 from Figure 5-1. In some climates larger differences might be found, and the trends noted do suggest increasing errors can be expected with consideration of

Table 5-5. Calculations for Davis estimating dry-season (May-Sep.) ET_o and ET (evergreen trees), and a frequency distribution analysis of expected water losses minus precipitation.

Year	Epan(May-Sep) mm[a]	Epan(May-Sep) Inch	ET_o Inch[b]	ET(trees) Inch[b]	P Inch[c]	ET_o-P Inch[d]	ET(trees) - P Inch[d]	100m/19+1[e]	Ranked ET_o-P Inch[e]	Ranked ET(trees) - P Inch[e]
59-60	1244	49.0	36.7	44.1	0.54	36.2	43.6	5	40.0	48.1
60-61	1139	44.8	33.6	40.3	0.27	33.3	40.0	10	37.8	45.5
61-62	1070	42.1	31.6	37.9	0.07	31.5	37.8	15	37.1	44.7
62-63	1041	41.0	30.8	36.9	0.87	29.9	36.0	20	36.2	43.6
63-64	1124	44.3	33.2	39.9	0.60	32.6	39.3	25	35.3	42.4
64-65	1113	43.8	32.8	39.4	0.58	32.2	38.8	30	35.3	42.4
65-66	1127	44.4	33.3	40.0	0.52	32.8	39.5	35	35.0	42.1
66-67	1073	42.2	31.6	38.0	1.01	30.6	37.0	40	34.8	41.8
67-68	1212	47.7	35.8	42.9	0.50	35.3	42.4	45	34.1	41.3
68-69	1158	45.6	34.2	41.0	0.19	34.0	40.8	50	34.0	40.8
69-70	1193	47.0	35.3	42.3	0.47	34.8	41.8	55	33.3	40.0
70-71	1141	44.9	33.7	40.4	1.29	32.4	39.1	60	32.8	39.5
71-72	1143	45.0	33.7	40.5	1.41	32.3	39.1	65	32.6	39.3
72-73	1193	47.0	35.2	42.3	0.16	35.0	42.1	70	32.4	39.1
73-74	1289	50.7	38.0	45.6	0.93	37.1	44.7	75	32.3	39.1
74-75	1198	47.2	35.4	42.5	0.12	35.3	42.4	80	32.2	38.8
75-76	1310	51.6	38.7	46.4	0.89	37.8	45.5	85	31.5	37.8
76-77	1217	47.9	35.9	43.1	1.83	34.1	41.3	90	30.6	37.0
77-78	1360	53.5	40.1	48.2	0.05	40.0	48.1	95	29.9	36.0
Ave.	1176	46.30	34.72	41.67	0.65	34.1	41.0			

Step 1 – Normal-year ET_o for May-Sept. = 34.72 inch (from Isoline maps, Figure 5-11)

a. Step 2 – Σ May through Sept. pan evaporation from DWR Bull. 73-79 [23].

b. Steps 3-4 – Using mean k_p = 34.72/46.30 = 0.750 for ET_o estimates and a k_c of 1.20 for evergreen trees.

c. Step 5 – Precipitation data summed for May-Sept. from microfiche frames of DWR Bull. "California rainfall summary" [14].

d. Step 6 – Subtract precipitation from ET_o and ET(trees).

e. Step 7 – Distribution analysis.

Table 5-6. Calculations for Davis of ET_o and ET (evergreen trees) for transition periods (Apr. and Oct.).

Year	Epan(Apr-Oct) mm[a]	Epan(Apr-Oct) Inch	ET_o Inch[b]	ET(trees) Inch[b]	P Inch[c]	ET_o-P Inch[d]	ET(trees) - P Inch[d]	100m/19+1[e]	Ranked ET_o-P Inch[e]	Ranked ET(trees) - P Inch[e]
59-60	366	14.4	10.0	12.0	0.90	9.1	11.1	5	10.6	12.7
60-61	331	13.0	9.1	10.9	0.53	8.6	10.4	10	9.4	11.4
61-62	324	12.8	8.9	10.7	0.11	8.8	10.6	15	9.1	11.1
62-63	214	8.4	5.9	7.0	11.87	-6.0	-4.9	20	8.8	10.6
63-64	296	11.7	8.2	9.8	1.45	6.7	8.3	25	8.6	10.4
64-65	243	9.6	6.7	8.0	4.56	2.1	3.4	30	8.2	9.9
65-66	319	12.6	8.8	10.5	0.58	8.2	9.9	35	8.0	9.7
66-67	222	8.7	6.1	7.3	3.93	2.2	3.4	40	7.7	9.5
67-68	360	14.2	9.9	11.9	0.47	9.4	11.4	45	7.4	9.2
68-69	279	11.0	7.7	9.2	1.51	6.2	7.7	50	6.7	8.3
69-70	323	12.7	8.9	10.6	0.93	8.0	9.7	55	6.6	8.3
70-71	288	11.3	7.9	9.5	1.29	6.6	8.2	60	6.4	8.2
71-72	318	12.5	8.7	10.5	0.96	7.7	9.5	65	6.2	7.7
72-73	332	13.1	9.1	11.0	2.69	6.4	8.3	70	5.4	7.0
73-74	283	11.1	7.7	9.3	2.33	5.4	7.0	75	5.4	6.9
74-75	328	12.9	9.9	10.8	1.63	7.4	9.2	80	5.2	6.9
75-76	308	12.1	8.4	10.1	3.20	5.2	6.9	85	2.2	3.4
76-77	389	15.3	10.7	12.8	0.12	10.6	12.7	90	2.1	3.4
77-78	279	11.0	7.7	9.2	2.32	5.4	6.9	95	-6.0	-4.9
Ave.	305	12.02	8.38	10.06	2.18	6.2	7.88			

Step 1 – Normal-year ET_o for Apr. and Oct. = 8.38 inch (from Isoline maps, Figure 5-11)

a. Step 2 – Σ Oct. and April pan evaporation from DWR Bull. 73-79 [23] for Hydrologic year beginning in October.

b. Steps 3-4 – Using mean k_p = 8.38/12.02 = 0.697 for ET_o estimates and a k_c of 1.20 for evergreen trees.

c. Step 5 – Precipitation data summed for Apr. and Oct. from microfiche frames of DWR Bull. "California rainfall summary" [14].

d. Step 6 – Subtract precipitation from ET_o and ET(trees).

e. Step 7 – Frequency distribution analysis.

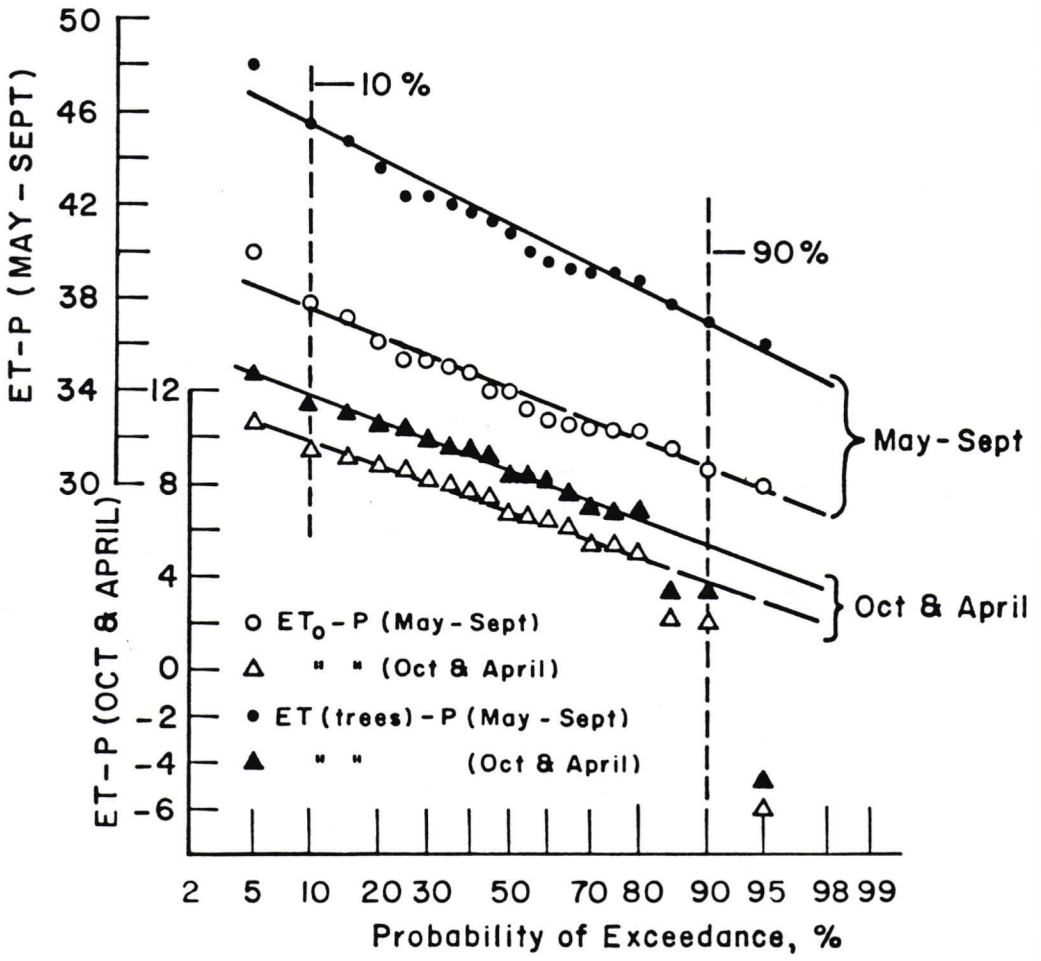

Figure 5-3. Frequency distribution analysis for ET_o - P and ET(trees) - P for dry season (May-Sept.) and transition months (Oct. and Apr.) at Davis, Calif.

even shorter periods, e.g., monthly. This will be shown later to be the case.

Month-by-Month Net Loss Estimates at a 90% Probability Level

Normally in design of wastewater systems a month-by-month water balance is developed. As indicated earlier, this should not be based on a summation of data from individual month-by-month frequency distribution analyses of expected net losses. Even division of the year into three separate periods as in Tables 5-4, 5-5, and 5-6 resulted in some discrepancy, e.g. in Table 5-7 at the 90% probability of exceedance level, values of annual net losses for ET_o and ET(trees)

Table 5-7. A comparison of predicted 12-month net water use at the 10% and 90% probability levels as indicated by frequency distribution analysis involving total annual (Example 5-1), and a summation of results from a breakdown into rainy season, dry season, and the transition months of October and April (Figures 5-2 and 5-3).

	Yearly total from annual data (Fig. 5-1)	Rainy-season total (Oct.-Mar.) (Fig. 5-2)	Dry-season total (May-Sept.) (Fig. 5-3)	Transition months total (Apr.-Oct.) (Fig. 5-3)	Yearly total from seasonal analysis	Difference for annual and seasonal analysis
	At 10% probability of exceedance level					
ET_o - P	50.3	5.5	37.6	9.8	52.9	-2.6
ET (trees) - P	61.0	7.5	45.6	11.8	64.9	-3.9
	At 90% probability of exceedance level					
ET_o - P	20.3	-15.7	30.8	3.8	18.9	+1.4
ET(trees) - P	29.5	-13.7	37.0	5.4	28.7	+0.8

are 1.4 and 0.8 inches lower, respectively, than for the analyses involving annual totals in Table 3b for the same 19-year period of record. Although these differences are small in the examples for Davis, this might not be true in some locations. Hence, the following example is given to provide a procedure whereby summaries of 12 monthly values of adjusted (ET - P) at a particular probability level (e.g., 90% or 0.9), will result in exactly the same value as that developed under Example 1 using annual totals. Distribution of monthly values for a particular season is based on the distribution of the dominant parameter during that season, i.e., on precipitation for the rainy season months and on ET - P during the other seasons.

Procedures are outlined in Example 5-3 with results tabulated in Table 5-8. Note in Table 5-8 that the sum of monthly values of $(ET_o - P)_{0.9}$ and $[ET(trees) - P]_{0.9}$ are in agreement with the 20.3 inch (51.56 cm) and 29.5 inch (76.07 cm) at the 90% probability level based on yearly totals using annual data for ET_o - P and ET(trees) - P, respectively (Table 5-7).

Example 5-3. Development of monthly values of net water loss at a particular probability level, adjusted such that the sum of 12 monthly values will agree with annual totals based on annual data.

Step 1. Listing of monthly normal-year ET_o
Table 5-1 (Sacramento Valley), or from Isoline maps of Figure 5-11 (Davis, Calif.).

Step 2. For crops other than pasture apply k_c values. Table 5-2.

Step 3. List normal monthly precipitation data for nearest location (Davis, Calif.)
Table 3, DWR Bull. "Calif. rainfall summary" [14], (1941-1970 mean).

Step 4. Calculate normal-year ET - P for each month.

Step 5a. For rainy-season: Develop monthly 90% probability values by partitioning a total rainy-season value of adjusted (ET - P) based on the distribution of total P between months.

Adjusted rainy-season $(ET - P)_{0.9}$ total = algebraic sum of $(ET - P)_{0.9}$ for rainy-season and the yearly difference of annual and seasonal analysis: Example with Table 5-7 data.

Adjusted rainy-season $(ET_o - P)_{0.9} = -15.7 + 1.4 = -14.3$

Development of monthly values of adjusted $(ET - P)_{0.9}$ by partition of adjusted rainy-season $(ET - P)_{0.9}$ total, in relation to the distribution of normal precipitation during the rainy-season: Example for month of January.

Adjusted monthly $(ET - P)_{0.9} = -14.3 \times (P_{Jan} \div \Sigma P_{Nov.-Mar.})$

$= -14.3 \times (3.88 \div 13.87) = -4.00"$

Step 5b. For transition and dry-season months develop 90% probability values for each month by application of a correction factor "C" to each month's normal-year value of ET - P, with "C" obtained from dividing the 90% probability value for that season by normal-year Σ (ET - P) for that season.

Example determination of C factor (using data in Table 5-7 and Table 5-8 below).

C(transition months) = 3.8 (from Table 5-7) ÷ (3.22 + 2.62) = 0.65

C(dry season months) = 30.8 (from Table 5-7) ÷ (5.96 + · + · + 5.27) = 0.91

Examples of adjusted monthly $(ET_o - P)_{0.9}$ for April and June:

$(ET_o - P)_{0.9} = 0.65 \times 3.22 = 2.10"$ (for April)

$(ET_o - P)_{0.9} = 0.91 \times 7.52 = 6.84"$ (for June)

Table 5-8. Illustration of development of monthly (ET - P) data for a 90% probability level at Davis.

	Normal-Year Data							90% Probability Level	
	ET_o (Isoline maps) mm/day a/	ET_o (Isoline maps) Inch/month a/	ET (trees) Inch/month b/	P Inch/month c/	ET_o-P Inch/month d/	ET-P (trees) Inch/month d/	Adj. Factor, "C" e/	$(ET_o-P)_{0.9}$ Inch/month e/	$(ET-P)_{0.9}$ (trees) Inch/month e/
Jan	0.85	1.04	1.25	3.88	-2.84	-2.63		-4.00	-3.61
Feb	1.65	1.84	2.21	2.79	-0.95	-0.58		-2.87	-2.59
Mar	2.60	3.17	3.80	1.95	1.22	1.85		-2.02	-1.82
Apr	4.00	4.72	5.66	1.50	3.22	4.16	0.65	2.10	2.99
May	5.30	6.47	7.76	0.51	5.96	7.25	0.91	5.42	6.57
Jun	6.50	7.68	9.22	0.16	7.52	9.06	0.91	6.84	8.22
Jul	6.70	8.18	9.82	0.01	8.17	9.81	0.91	7.43	8.90
Aug	5.70	6.96	8.35	0.03	6.93	8.32	0.91	6.31	7.55
Sep	4.60	5.43	6.52	0.16	5.27	6.36	0.91	4.80	5.77
Oct	3.00	3.66	4.39	1.04	2.62	3.35	0.65	1.71	2.41
Nov	1.40	1.65	1.98	2.04	-0.39	-0.06		-2.10	-1.90
Dec	0.80	0.98	1.18	3.21	-2.23	-2.03		-3.30	-2.98
Total		51.78	62.14	17.28	34.5	44.86		20.31	29.51

a/ Step 1 – in Example 5-3. Data from Isoline maps, Figure 5-11.

b/ Step 2 – k_c for evergreen trees x ET_o.

c/ Step 3 – Table 3 SDWR Bull. California rainfall summary [7].

d/ Step 4.

e/ Steps 5a. and 5b.

NET WATER USE FOR SYSTEMS INVOLVING ANNUAL CROPS

In the case of wastewater systems involving the growing of annual crops, the design in relation to water disposal becomes more complex due to the variation of ET with changing plant cover, stage of growth, maturity, etc. Clearly a development of normal-year ET on a month-by-month basis is needed. In fact, even shorter periods of time need to be considered during crop development. Once the ET data for a normal year are developed into monthly values, procedures proposed earlier are suggested to arrive at adjusted monthly (ET - P) values for a particular probability level.

Normal-Year ET for Annual Crops

Example 5-4 shows the development of monthly (or 10 to 11-day) ET_o and crop ET data for two annual crops including periods involving land preparation for planting, post harvest, etc. For one crop (tomatoes), two examples are offered, one involving infrequent irrigations during early crop stages and another with very frequent early irrigations. For the former case, and for all periods of full crop cover, crop coefficients as given in Table 5-13 were used in conjunction with ET_o data to estimate ET. For the latter case involving frequent early irrigations, k_c values during early growth stages were developed from a method suggested by Doorenbos and Pruitt [3]. The same method was also used for periods involving land preparation.

The results illustrated in Table 5-9 clearly reveal the reduced water use of annual crops as compared to full cover situations. For example, the estimated normal-year ET for corn (including pre-plant and post harvest periods) was 32.2 inch (81.79 cm) (Apr.-Oct.), whereas ET_o was estimated at 43.2 inch (109.7 cm). An ET of 39.5 inch (100 cm) is predicted for tomatoes (again including pre-plant and post-harvest periods) with a somewhat longer growing season, the use of frequent early irrigations, and with rather high k_c values right up to harvest. This is still almost 4 inches (10.2 cm) less than ET_o, and some 12 inches (20.5 cm) less than the expected ET for evergreen trees for the April through October period.

Example 5-4. Development of normal-year monthly and shorter-period ET_o and crop ET data. Example crops are field corn and processing tomatoes with planting around May 1, and harvest dates of Sept. 10 and 20, respectively.

Step 1. Plot monthly normal-year ET_o data for Mar.-Nov. as in Fig. 5-4 and draw smooth curve through the bar graph which provides a near balancing of areas above and below each monthly mean (ET_o data from Table 5-8).

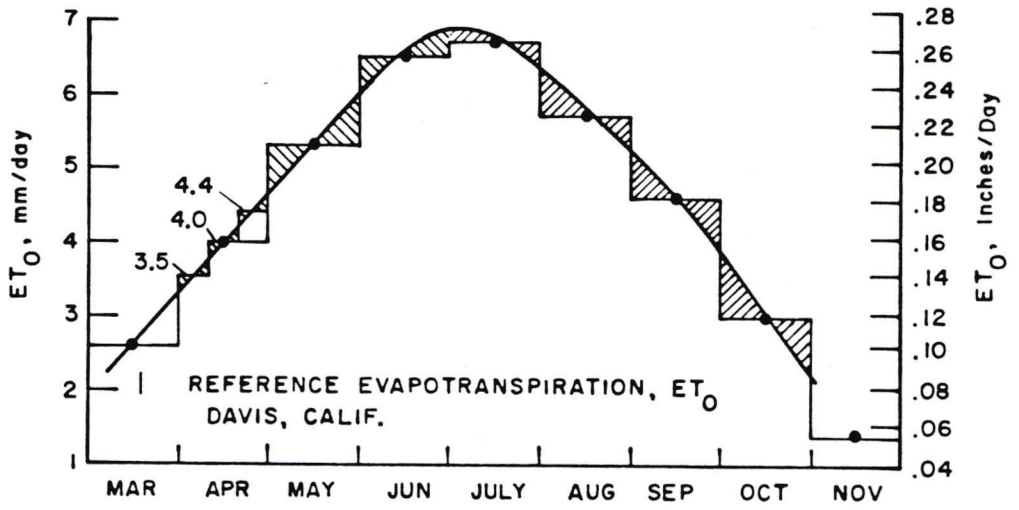

Figure 5-4. Plot of normal-year ET_o, and development of smooth curve (example for Davis).

Step 2. Select ET_o value at the midpoint of each 10 to 11 day period. Tabulate as in Table 5-9 and convert to equivalent total inches in each period.

Step 3. Prepare graph of k_c data as in Fig. 5-5 with data obtained as follows:

a) From Table 5-13 (or Fereres et al., [12, 13]), obtain 10-day planting to harvest k_c data and plot as in Fig. 5-5.

b) For frequent-irrigation cases (< 10-day schedule), select a k_c value for an initial Development Stage (Defined by Doorenbos and Pruitt [3] as "the time during germination or early growth when ground cover is less than 10%".) from Fig. 5-6, and plot as a horizontal line as illustrated in Fig. 5-5 (an estimate of the length in days of the period is obtained from Fig. 5-7). Draw a straight-line extrapolation on up to a tangential meeting with the k_c curve developed from Step 3a). Develop a new curvilinear relationship for k_c from the two straight-line segments.

c) For pre-planting periods, select values of k_c as illustrated in Fig. 5-6 and plot as in Fig. 5-5.

d) For post-harvest periods draw curves of k_c as in Fig. 5-5 reflecting a sharp drop to low values prior to pre-planting periods where soil surfaces are dry.

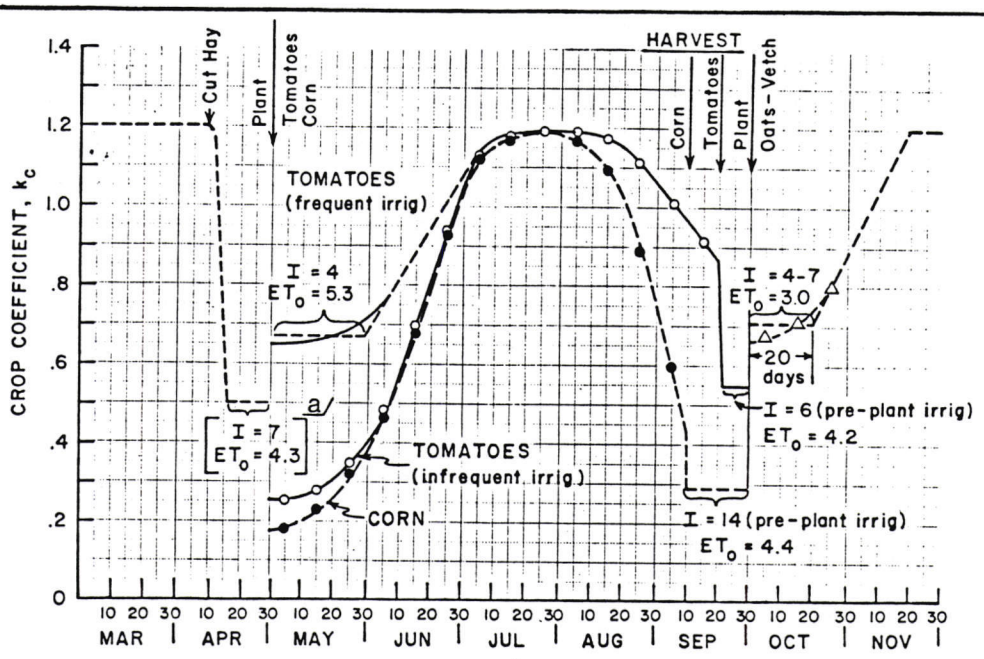

Figure 5-5. Development of crop coefficients for cropping sequences involving a Fall-Winter hay crop of oat and vetch with spring plantings of corn and tomatoes. Both frequent and infrequent early irrigation of tomatoes are illustrated.

a/ I = frequency of irrigation and/or precipitation during period (in days), and ET_o = normal ET_o rate expected midway through the period.

Step 4. From curves developed as in Fig. 5-5, select 10- to 11-day k_c data for each case and tabulate as in Table 5-9.

Step 5. Multiply k_c values by ET_o data to obtain estimates of crop ET and evaporation losses during non-cropped intervals as illustrated in Table 5-9.

Table 5-9. Example of development of normal year monthly and seasonal ET for annual crops. Location – Davis, California. Crops – processing tomatoes (May 1-Sep. 20) and field corn (May 1-Sep. 10) followed by an oat-vetch crop planted Oct. 1 to be harvested for hay around Apr. 5-10.

Month		Normal year ET_o mm/day a/	ET_o Inch a/	Oat - Corn - Oats k_c b/	ET Inch e/	Oats - Tomatoes - Oats k_c b/c/	ET Inch e/	k_c b/d/	ET Inch e/
Apr	1-10	3.5	1.38	1.10	1.52	1.10	1.52	1.10	1.52
	11-20	4.0	1.57	0.75	1.18	0.75	1.18	0.75	1.18
	21-30	4.4	1.73	0.50	0.86	0.50	0.86	0.50	0.86
May	1-10	4.8	1.89	0.18	0.34	0.25	0.47	0.65	1.23
	11-20	5.3	2.09	0.23	0.48	0.28	0.59	0.67	1.40
	21-31	5.8	2,52	0.32	0.81	0.35	0.88	0.69	1.74
Jun	1-10	6.2	2.44	0.47	1.15	0.49	1.20	0.77	1.88
	11-20	6.6	2.60	0.68	1.77	0.70	1.82	0.88	2.29
	21-30	6.7	2.64	0.93	2.45	0.94	2.48	1.01	2.67
Jul	1-10	6.8	2.68	1.12	3.00	1.13	3.03	1.13	3.03
	11-20	6.7	2.64	1.17	3.09	1.17	3.09	1.17	3.09
	21-31	6.5	2.80	1.19	3.33	1.19	3.33	1.19	3.33
Aug	1-10	6.2	2.44	1.16	2.83	1.19	2.90	1.19	2.90
	11-20	5.8	2.28	1.09	2.48	1.17	2.67	1.17	2.67
	21-31	5.4	2.32	0.89	2.06	1.11	2.58	1.11	2.58
Sep	1-10	5.0	1.97	0.60	1.18	1.01	1.99	1.01	1.99
	11-20	4.7	1.85	0.29	0.54	0.91	1.68	0.91	1.68
	21-30	4.2	1.65	0.29	0.69	0.55	0.91	0.55	0.91
Oct	1-10	3.6	1.42	0.68	0.97	0.68	0.97	0.68	0.97
	11-20	3.0	1.18	0.71	0.84	0.71	0.84	0.71	0.84
	21-31	2.5	1.08	0.80	0.86	0.80	0.86	0.80	0.86
Total			43.2"		32.2"		35.9"		39.5"

a/ Step 2.

b/ Step 4.

c/ Values of k_c for tomatoes based on infrequent irrigations during early stages of growth.

d/ Values for k_c for tomatoes based on an assumed four-day frequency of irrigation during early stages of growth.

e/ Step 5.

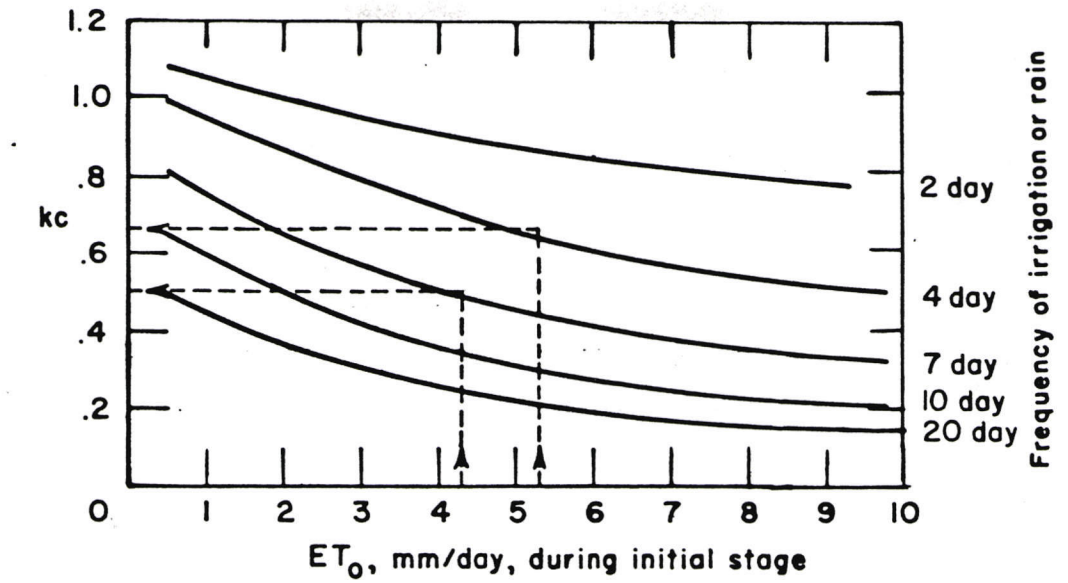

Figure 5-6. Average K_c value for Initial Development Stage as related to level of ET_o and the frequency of irrigation and/or significant rainfall (Adapted from Doorenbos and Pruitt [3]).

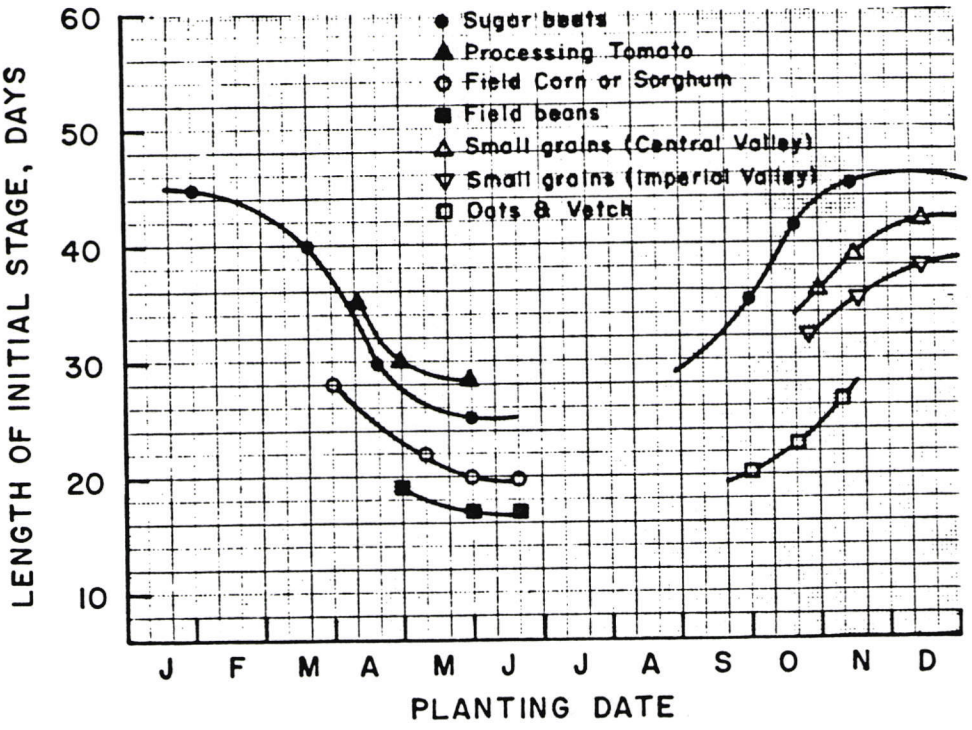

Figure 5-7. Length in days of Initial Development Stage for several annual crops in California as a function of planting date.

Frequency Distribution of Monthly Net Losses

As indicated earlier, development of a month-by-month water balance is usually desirable, and yet the summation of individual month-by-month frequency distribution analyses can be misleading. For cropping patterns involving annual crops, the same procedures as those used in Example 5-3 are suggested for development of adjusted monthly values of (ET - P) at any particular probability level. Thus, in the example for Davis, a "C" of 0.65 would be applied to the transition months of April and October and a "C" of 0.91 for the months of May through September, as in Table 5-8.

Table 5-10 provides an example of cropping sequences using the cases of Example 5-4 but excluding the case for infrequently-irrigated tomatoes. The results depend upon the assumption of a k_c value for December through March of 1.20 for the oat-vetch winter-cover hay crop. Hence, the normal-year and 90% probability data for those months coincide with the data developed in Table 5-8 for evergreen

Table 5-10. Estimated monthly (Losses - Precipitation) at a probability level of 90% (adjusted to provide realistic seasonal and annual levels). Cropping patterns include annual crops with a mix of oats and vetch for winter cover crop, harvested for hay in April.

	Normal Year				Normal Year		Adj.	90% Probability	
	ET_o	ET (Oats, Tomato, Oats)	ET (Oats, Corn, Oats)	P	ET - P (Oats, Tomato, Oats)	ET - P (Oats, Corn, Oats)	Factor "C" for 90% prob.	$(ET - P)_{0.9}$ (Oats, Tomato, Oats)	$(ET - P)_{0.9}$ (Oats, Corn, Oats)
Month	Inch[a]	Inch[b]	Inch[b]	Inch	Inch	Inch	c	Inch	Inch
Jan	1.04	1.25	1.25	3.88	-2.63	-2.63	-	-3.61	-3.61
Feb	1.84	2.21	2.21	2.79	-0.58	-0.58	-	-2.59	-2.59
Mar	3.17	3.80	3.80	1.95	1.85	1.85	-	-1.82	-1.82
Apr	4.72	3.56	3.56	1.50	2.06	2.06	0.65	1.34	1.34
May	6.47	4.37	1.63	0.51	3.86	1.12	0.91	3.51	1.02
Jun	7.68	6.84	5.37	0.16	6.68	5.21	0.91	6.08	4.74
Jul	8.18	9.45	9.42	0.01	9.44	9.41	0.91	8.59	8.56
Aug	6.96	8.15	7.37	0.03	8.12	7.34	0.91	7.39	6.68
Sep	5.43	4.58	2.41	0.16	4.42	2.25	0.91	4.02	2.05
Oct	3.66	2.67	2.67	1.04	1.63	1.63	0.65	1.06	1.06
Nov	1.65	1.65	1.65	2.04	-0.39	-0.39	-	-2.10	-2.10
Dec	0.98	1.18	1.18	3.21	-2.03	-2.03	-	-2.98	-2.98
Total								18.90	12.30

a. From Table 5-8.

b. For Apr.-Oct. list monthly totals obtained from 10-11 day data in Table 5-9. For Nov. assume ET for oats-vetch is equivalent to ET_o, and for Dec.-Mar., that ET is equivalent to ET(trees) as in Table 5-8.

c. Same as in Table 5-8.

trees. For November, Figure 5-5 reveals an average k_c for the month a little above 1.0. A conservative estimate would be the use of 1.0 for k_c; hence for November, the ET_o value for that month is used directly in Table 5-10.

The annual summary of the 90% probability level for ET - P indicates values of 18.9 and 12.3 inches (48.0 and 32.2 cm) for the frequently-irrigated tomato and corn crops, respectively, when a winter cover crop of oats and vetch are involved. This compares with 29.5 and 20.3 inches for continuous cropping of evergreen trees and well-managed pasture, respectively, at the 90% probability of exceedance level (See Table 5-7).

PEAK ET DEMAND FOR IRRIGATION SYSTEM DESIGN

For optimal crop production, irrigation systems should be designed to meet crop needs during expected levels of peak ET. Prior discussion has revealed the wide year-by-year variation of actual ET_o. The variation of ET during peak demand months is expected to be even greater. For example, the frequency analysis of lysimeter records for Davis indicates that a monthly total for June as great as 8.85 inches (22.48 cm) is expected with a 90% probability in any one year, 14% higher than the mean monthly loss for June of 7.76 inches (19.71 cm) . However, except for very deep-rooted crops growing in medium- to heavy-textured soils, the level of depletion allowable under peak-demand conditions would normally be much less than this. More typical for optimal crop production would be 3 to 5 inches (7.62 to 12.7 cm) of depletion, or even less for shallower-rooted crops, lighter-textured soils, or crops otherwise benefitting from frequent irrigations. Hence, for the shorter consecutive-day periods involved, peak loss design rates can be expected to run well above long-time monthly means for peak demand months.

Jensen and Criddle [10] provided a design approach involving the selection of a multiplying factor to use with the long-time mean monthly ET to obtain a peak design value for any given level of soil water depletion. This approach was later adapted by Doorenbos and Pruitt [3] and still later by Pruitt et al. [4] for California. Procedures in the last report were based on data for extreme maximum values of evaporation (or E_o) at selected stations in California and

adjacent states as published by Bassett and Jensen [11]. Extreme maximum values of ET_o were derived by normalizing E_o data for a two-year occurrence frequency against the normal-year July ET_o as obtained from the ET_o isoline maps of Pruitt et al. [3]. Figure 5-8 in Example 5-5 reproduces the results for several locations in California representing a wide range of climatic conditions. By locating the desired level of soil moisture depletion on the x-axis, one can select a ratio which when multiplied by the normal-year ET_o for the peak demand month, will provide peak ET_o data for either an average 5-year or 10-year expected occurrence frequency. For crops other than grass and if they are under full-cover conditions during peak demand periods, the k_c for that crop should also be applied (See Table 5-2 or 5-13).

Example 5-5 outlines the use of Figure 5-8 in development of design peak ET rates (based on a 10-year frequency). In addition to the use of Figure 5-8, important input data related to the time of expected peak ET include the following: 1) effective rooting depth of crop; 2) an estimate of total available water (TAW) in effective root zone; and 3) an estimate of readily available water (RAW), or of management allowed deficit (MAD) in the effective root zone. TAW, RAW and MAD represent terminology proposed by Merriam and Keller [25].

While the design data developed in Table 5-11 would provide an irrigation system with full capacity to meet possible short-term peak ET demand with a 90% probability (on the average for nine out of ten years), economic considerations may call for a reduction in the design estimates. This would be particularly true for soils with moderate to high values of TAW and RAW. Water stored in the root zone beyond that normally described as "readily available", may, for such soils, contribute substantially in coping with unusual ET demands. Hence, a system with a capacity to meet ET demands somewhat less than the design values of Table 5-11 may be considered. If, however, the designer chooses such an option, special attention will be needed in irrigation operations, to ensure that the peak demand periods are entered into with a fully recharged soil profile.

Example 5-5. Illustration for Davis, California of Development of design peak ET rates for several crops.

Step 1. From local soils and crop data, e.g., as obtained from Cooperative Extension Farm Advisors or Soil Conservation Service technicians, list values of effective rooting zone, TAW, and RAW (as defined earlier) for period of peak evaporative demand.

Step 2. Enter Fig. 5-8 on the X-axis at a value equal to the RAW or MAD in mm and project vertically to intersect a curve most likely to represent the project site involved.

Obtain a value for the Ratio of mean peak ET_o to normal-year mean monthly ET_o by projecting horizontally from the intersect point back to the Y-axis.

Step 3. For crops involved, list as in Table 5-11, the normal-year mean monthly ET values for the month of peak use (normally July in California). ET_o is assumed to be equivalent to pasture ET (Data obtained directly from Table 5-9, or calculated from data contained therein).

Step 4. Multiply "Ratio" by July normal-year ET values.

Table 5-11. Example development of design peak ET rates for several crops (10-year frequency).

Crop	Effective rooting depth, ft.[a]	TAW in.[a]	RAW or MAD[a] at peak-demand period in.	RAW or MAD[a] at peak-demand period mm	Ratio, Fig. 5-8 b	Normal-Year[c] July mean monthly ET mm/day	Normal-Year[c] July mean monthly ET inch/day	Design ET[d] (10-year frequency) inch/day
Pasture	3.0	6.0	3.0	75	1.30	6.7	.264	.343
Tomatoes	5.0	10.0	5.0	125	1.22	8.0	.315	.384
Corn	4.0	8.0	4.0	100	1.25	7.8	.307	.384

a. Step 1.

b. Step 2 - From Figure 5-8.

c. Step 3 - Data from Table 5-9.

d. Step 4.

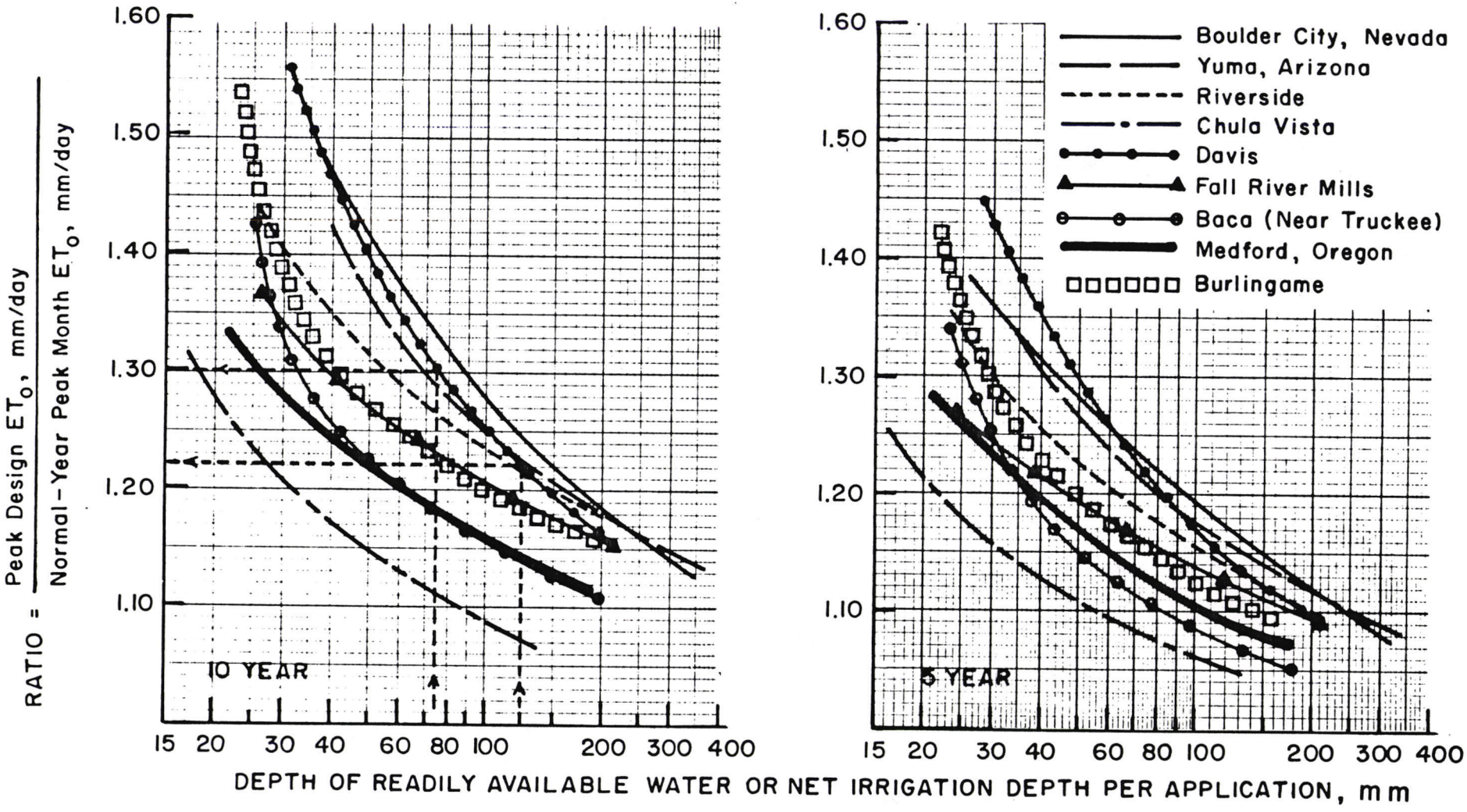

Figure 5-8. Examples for California and bordering state locations of the ratio of design peak ET_o to normal-year ET_o (July) as a function of readily available soil water or net irrigation application based on analyses of Bassett and Jensen [11].

ADDITIONAL TABLES AND FIGURES

Table 5-12. Recommended monthly crop coefficients, k_c for principal crops grown in California, as adapted from Table 5 of DWR Bull. 113-3 [7][a]. Values of k_c for relating to ET_o were derived by dividing DWR's monthly k_p data for the month and crop of interest, by the k_p for pasture for the same month. Example: Cantaloupes in June; k_c = 0.86/0.78 = 1.10.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Field Crops												
Alfalfa (hay)	1.00	1.00	0.92	0.91	0.91	0.94	0.97	1.03	1.04	1.03	1.00	1.00
Barley (fall)	0.94	1.28	1.08	0.65	0.26	-	-	-	-	-	0.14	0.43
Barley (winter)	0.42	0.91	1.25	1.06	0.64	0.26	-	-	-	-	-	-
Beans (dry)	-	-	-	-	-	-	0.54	1.09	0.56	-	-	-
Cantaloupes	-	-	-	0.19	0.41	1.10	0.17	-	-	-	-	-
Corn (field)	-	-	-	-	0.15	0.62	1.20	1.08	0.65	-	-	-
Cotton (solid)	-	-	-	-	0.13	0.69	1.31	1.29	1.13	0.65	-	-
Cotton (2 x 1)	-	-	-	-	0.13	0.63	1.17	1.36	1.13	1.01	-	-
Cotton (2 x 2)	-	-	-	-	0.13	0.47	1.13	1.18	1.08	0.55	-	-
Cotton (2 x 2)[b]	-	-	-	-	0.13	0.19	0.87	1.13	0.81	0.35	-	-
Grain sorghum	-	-	-	-	0.13	0.32	1.15	1.05	0.52	-	-	-
Pasture (improved)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rice	-	-	-	1.04[c]	1.15	1.28	1.28	1.28	1.17	0.40	-	-
Sugar beets (annual)	-	-	-	0.20[d]	0.50	1.00	1.18	1.03	1.04	0.79	0.55	-
Sugar beets (overwintered)	1.00	1.00	1.00	0.49	0.20[d]	0.50	1.00	1.18	1.04	1.07	1.00	1.00
Tomatoes (Machine harvested)	-	-	-	0.29	0.77	1.13	1.06	0.79	-	-	-	-
Trees and Vines												
Deciduous orchard[e]	-	-	0.59	0.71	0.83	0.90	0.96	0.96	0.91	0.80	-	-
Subtropical orchard[f]	-	-	0.59	0.58	0.64	0.64	0.64	0.64	0.58	0.60	-	-
Vineyard (table grapes)	-	-	-	0.16	0.58	0.77	0.85	0.83	0.71	0.40	-	-
Vineyard (wine grapes)[f]	-	-	-	0.16	0.58	0.71	0.64	0.45	0.26	0.07	-	-
Truck Crops												
Potatoes (Spring crop)	-	-	0.66	1.08	1.20	0.64	-	-	-	-	-	-
Tomatoes (hand-picked)	-	-	0.29	0.78	1.13	1.13	0.96	0.64	0.39	-	-	-

a. Relate mainly to Central Valley (California) growing seasons. Modifications may be needed for use in areas or situations with different planting dates.

b. For extremely fine textured (clay) soils.

c. Planted or harvested at mid-month. ET_o for partial month should be used with ratio.

d. Adjusted upward from original values which appeared to be unreasonable.

e. Deciduous trees except almonds (Presumably clean cultivated orchards). Coefficients should likely be 10-25% lower for almonds during the last one-third of the season if cultural practices involve no post-harvest irrigations.

f. No ET data available (in 1974). Original k_p ratios reported were estimated from PET data modified to reflect prevalent irrigation and cultural practices.

Table 5-13. Recommended 10-day crop coefficients, k_c for a number of selected crops grown in various regions of the State[a/]. (See Figure 5-9 for a delineation of regions.)

	Processing tomatoes					Sugar beets[b/]				Grain corn			Milo
Plant Date	2/1	3/1	4/1	5/1	6/1	4/1	5/1	6/15	10/1	3/15	5/1	6/15	5/15
Harvest Date	6/30	8/10	9/10	9/30	11/20	10/20	11/20	3/20	6/30	8/15	9/10	10/15	9/30
Jan 1-10								1.17	1.16				
11-20								1.16	1.17				
21-31								1.15	1.17				
Feb 1-10	0.36							1.14	1.17				
11-20	0.40							1.13	1.17				
21-28	0.42							1.12	1.17				
Mar 1-10	0.48	0.26						1.11	1.16				
11-20	0.57	0.26						1.10	1.15	0.17			
21-31	0.72	0.26							1.14	0.19			
Apr 1-10	0.92	0.27	0.26			0.15			1.13	0.23			
11-20	1.03	0.29	0.26			0.18			1.11	0.32			
21-30	1.08	0.34	0.27			0.25			1.09	0.46			
May 1-10	1.10	0.46	0.29	0.25		0.34	0.21		1.05	0.65	0.18		
11-20	1.10	0.65	0.35	0.28		0.49	0.23		1.02	0.99	0.23		0.13
21-31	1.06	0.92	0.47	0.35		0.74	0.28		0.97	1.15	0.32		0.17
Jun 1-10	0.98	1.10	0.67	0.49	0.22	0.97	0.44		0.91	1.19	0.47		0.21
11-20	0.88	1.17	0.93	0.70	0.24	1.08	0.65	0.22	0.84	1.20	0.68	0.30	0.28
21-30	0.76	1.19	1.12	0.94	0.27	1.13	0.87	0.24	0.80	1.19	0.93	0.35	0.40
Jul 1-10		1.16	1.17	1.13	0.30	1.16	1.06	0.30		1.05	1.12	0.58	0.82
11-20		1.09	1.19	1.17	0.40	1.17	1.11	0.47		1.04	1.17	1.01	1.08
21-31		0.97	1.16	1.19	0.54	1.17	1.16	0.80		0.87	1.19	1.18	1.12
Aug 1-10		0.86	1.07	1.19	0.72	1.17	1.17	1.09		0.65	1.16	1.20	1.12
11-20			0.97	1.17	0.93	1.16	1.18	1.15		0.52	1.09	1.21	1.10
21-31			0.86	1.11	1.03	1.14	1.18	1.18			0.89	1.21	1.06
Sep 1-10			0.73	1.01	1.12	1.12	1.18	1.19			0.60	1.04	0.95
11-20				0.91	1.16	1.10	1.18	1.20				0.95	0.85
21-30				0.60	1.19	1.08	1.18	1.21				0.78	0.72
Oct 1-10					1.19	1.06	1.18	1.21	0.36			0.56	
11-20					1.15	1.03	1.18	1.21	0.40			0.35	
21-31					1.07		1.17	1.21	0.44				
Nov 1-10					0.96		1.16	1.21	0.55				
11-20					0.82		1.15	1.21	0.70				
21-30								1.20	0.90				
Dec 1-10								1.19	1.04				
11-20								1.18	1.10				
21-31								1.18	1.15				
Regions where applicable	10,11	4,5,6,8,9,10			9,10	4,5,6,8			11	5	4,5, 6[c/],8[c/]	5	4,5, 6[c/],8[c/]

a. Adapted from recommendations for the Sacramento and San Joaquin Valleys as developed from many studies including those cited herein [3, 6, 7, 15, 16]. Extension to other regions (as delineated in Figure 5-9) assume that during growth stages involving full ground cover, k_c values would be similar in all areas of the state except for the Imperial Valley in Region 11 where soil salinity and very high evaporative demands apparently combine to produce lower than expected k_c's at least for cotton. Region 11 coefficients were largely adapted from studies conducted by the Imperial Valley Conservation Research Center at Brawley [26, 27].

b. Planting and harvest dates vary widely for sugar beets.

c. Season can extend 20-40 days longer in Regions 6 and 8 than that indicated.

Table 5-13. Continued

Plant Date / Harvest Date	Cotton			Field beans		Wheat & Barley			Sudan grass	Deciduous orchards with cover		Rice	
	4/1 / 9/30	4/20 / 10/15	4/1 / 10/31	5/1 / 8/20	6/1 / 9/20	11/20 / 6/20	12/1 / 5/31		4/1 / 8/20			4/1 / 9/30	4/1 / 8/31
Jan 1-10						0.60	0.45						
11-20						0.77	0.54			0.90	0.50		
21-31						0.93	0.62						
Feb 1-10						1.05	0.76						
11-20						1.13	0.90			0.95	0.45		
21-28						1.17	0.98						
Mar 1-10						1.19	1.04						
11-20						1.20	1.07			1.05	0.60		
21-31						1.20	1.10						
Apr 1-10	0.12		0.27			1.20	1.10		0.58				1.00
11-20	0.15		0.30			1.19	1.09		0.68	1.15	1.00		1.02
21-30	0.17	0.15	0.34			1.18	1.05		0.80				1.04
May 1-10	0.21	0.17	0.38	0.17		1.15	0.85	0.35	0.91			1.00	1.06
11-20	0.28	0.20	0.43	0.21		1.10	0.58	0.51	1.04	1.20	1.10	1.02	1.12
21-31	0.41	0.26	0.48	0.40		1.00	0.35	0.67	1.08			1.05	1.18
Jun 1-10	0.59	0.41	0.55	0.80	0.12	0.87		0.98	1.10			1.08	1.20
11-20	0.79	0.62	0.63	1.10	0.17	0.57		1.09	1.10	1.20	1.20	1.14	1.20
21-30	1.05	0.82	0.67	1.15	0.41			1.18	1.10			1.18	1.20
Jul 1-10	1.18	1.08	0.70	1.14	0.83			1.19	1.10			1.20	1.20
11-20	1.22	1.18	0.73	1.08	1.09			1.15	1.10	1.20	1.20	1.20	1.20
21-31	1.22	1.22	0.74	0.95	1.14			1.02	1.10			1.20	1.20
Aug 1-10	1.22	1.22	0.74	0.75	1.15			0.82	1.10			1.20	1.15
11-20	1.22	1.22	0.75	0.52	1.14			0.58	1.10	1.20	1.20	1.20	1.10
21-31	1.15	1.18	0.76		1.06							1.18	1.00
Sep 1-10	1.00	1.13	0.76		0.78							1.12	
11-20	0.83	0.96	0.76		0.45					1.15	1.15	1.00	
21-30	0.65	0.82	0.74									0.90	
Oct 1-10		0.62	0.62										
11-20		0.46	0.50							1.05	1.00		
21-31			0.45										
Nov 1-10													
11-20										1.00	0.85		
21-30						0.24							
Dec 1-10						0.30	0.31						
11-20						0.38	0.35			0.95	0.60		
21-31						0.49	0.40						
Regions where applicable	5	5	11[d]	5	4,5	4,5	11[d]	3[e]	11[d]	4,5[f]	2,3, 7[g]	4[h]	5[h]

d. k_c data suggest significant control of transpiration for cotton grown at Brawley. As compared to cotton grown in the San Joaquin Valley [7], in Arizona [28, 29], and in Israel [30, 31], coefficients in July and August are very low. Somewhat lower k_c's are also suggested for grains and Sudan grass.

e. Would also apply to Regions 2 and 7 in mountain valley areas where small grains are grown.

f. Mature trees with year-around dense green cover crop.

g. Same as f., but with dormant cover crop during winter months due to heavy frosts.

h. Rice grown in areas with a very high percentage of surrounding land also planted to rice, may need 10-15% lower k_c values (Lourence et al. [32]).

Table 5-14a. Risk of at least one occurrence of a rare event for various design periods in years versus probabilities of occurrence within a year.

Probability %	Design Period (years) 5	10	15	20	25	30	35	40	45
95	0.226	0.401	0.537	0.642	0.723	0.785	0.834	0.871	0.901
90	0.409	0.651	0.794	0.878	0.928	0.958	0.975	0.985	0.991
85	0.556	0.803	0.913	0.961	0.983	0.992	0.994	0.997	0.999
80	0.672	0.893	0.965	0.988	0.996	0.999			
75	0.763	0.944	0.987	0.997	0.999				
70	0.832	0.972	0.995	0.999					
65	0.884	0.987	0.998						
60	0.922	0.994							
55	0.950	0.997							

Table 5-14b. Risk of at least two occurrences of a rare event for various design periods in years versus probabilities of occurrence within a year.

Probability %	Design Period (years) 5	10	15	20	25	30	35	40	45
95	0.023	0.086	0.171	0.264	0.358	0.446	0.528	0.601	0.665
90	0.081	0.264	0.451	0.608	0.729	0.816	0.878	0.920	0.948
85	0.165	0.456	0.681	0.824	0.907	0.952	0.976	0.988	0.994
80	0.263	0.624	0.833	0.931	0.973	0.989	0.996	0.999	1.000
75	0.367	0.756	0.920	0.976	0.993	0.998	1.000		
70	0.472	0.851	0.965	0.992	0.998	1.000			
65	0.572	0.914	0.986	0.998	1.000				
60	0.663	0.954	0.995	0.999	1.000				
55	0.744	0.977	0.998	1.000					

Table 5-14c. Risk of at least three occurrences of a rare event for various design periods in years versus probabilities of occurrence within a year.

Probability %	Design Period (years) 5	10	15	20	25	30	35	40	45
95	0.002	0.011	0.036	0.075	0.127	0.187	0.254	0.323	0.392
90	0.008	0.070	0.184	0.323	0.463	0.588	0.694	0.778	0.841
85	0.027	0.180	0.395	0.595	0.746	0.849	0.913	0.952	0.973
80	0.058	0.322	0.602	0.794	0.902	0.955	0.981	0.993	0.997
75	0.103	0.474	0.764	0.909	0.968	0.989	0.997		
70	0.163	0.618	0.873	0.964	0.991	0.998			
65	0.236	0.738	0.938	0.988	0.998				
60	0.317	0.833	0.973	0.996	1.000				
55	0.407	0.901	0.989	0.999					

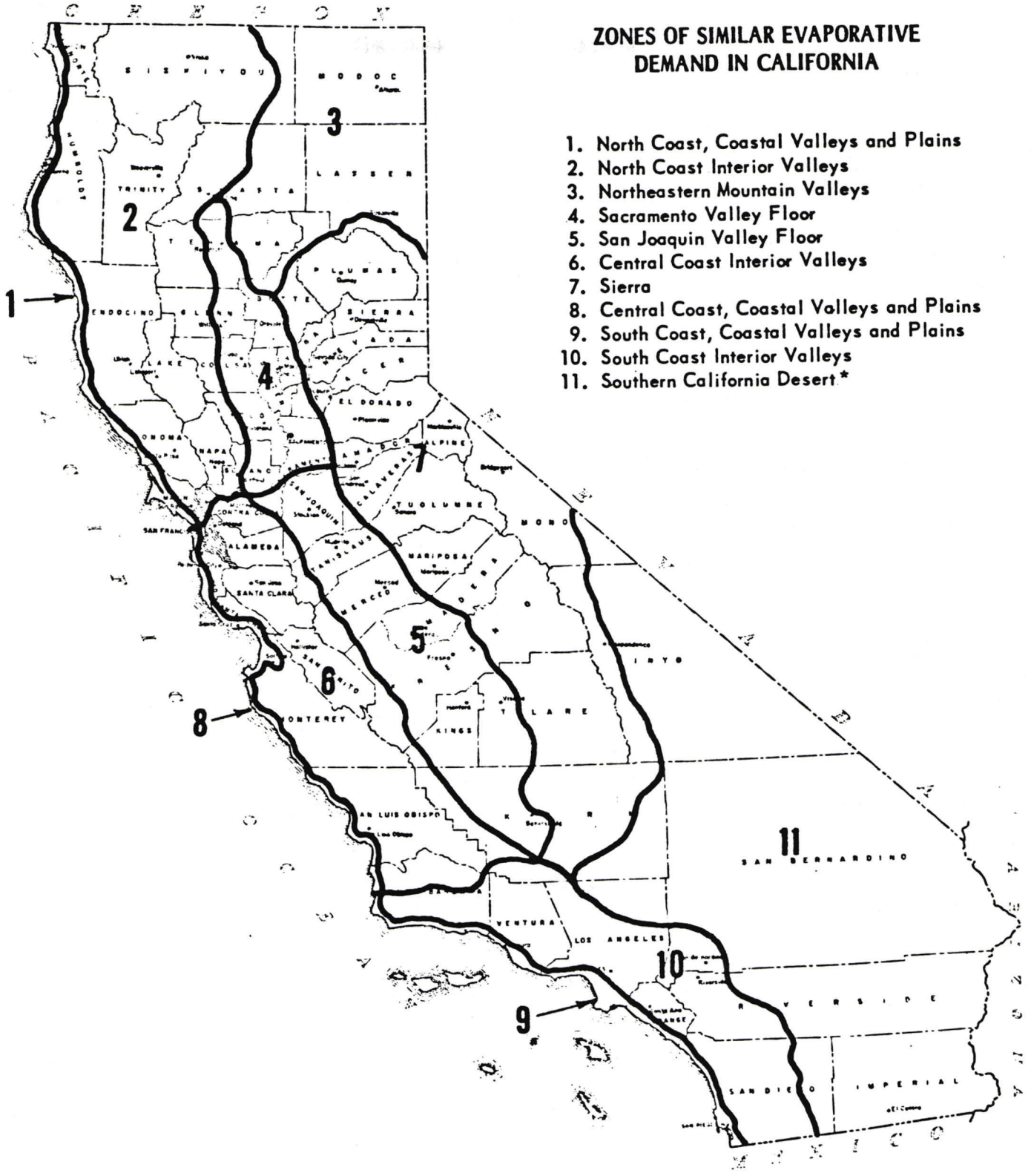

Figure 5-9. Zones of similar evaporative demand. After California DWR Bull. 113-3 [7].



Figure 5-10. Annual evaporative demand in California, the expected evaporation loss in inches (for normal conditions) from a National Weather Service Class "A" pan located in an irrigated pasture (or comparable environment). After California DWR Bull. 113-3 [7].

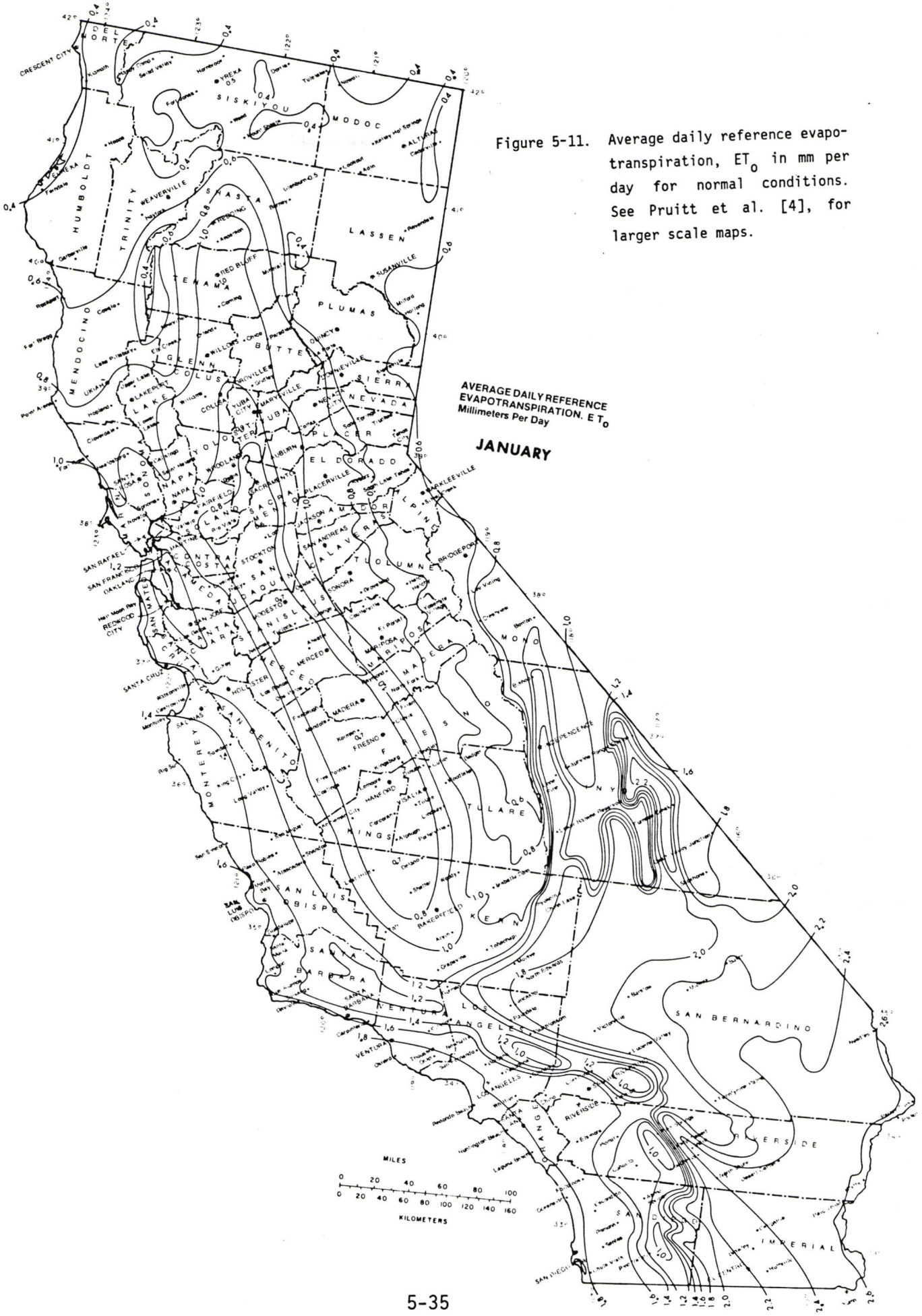

Figure 5-11. Average daily reference evapotranspiration, ET_o in mm per day for normal conditions. See Pruitt et al. [4], for larger scale maps.

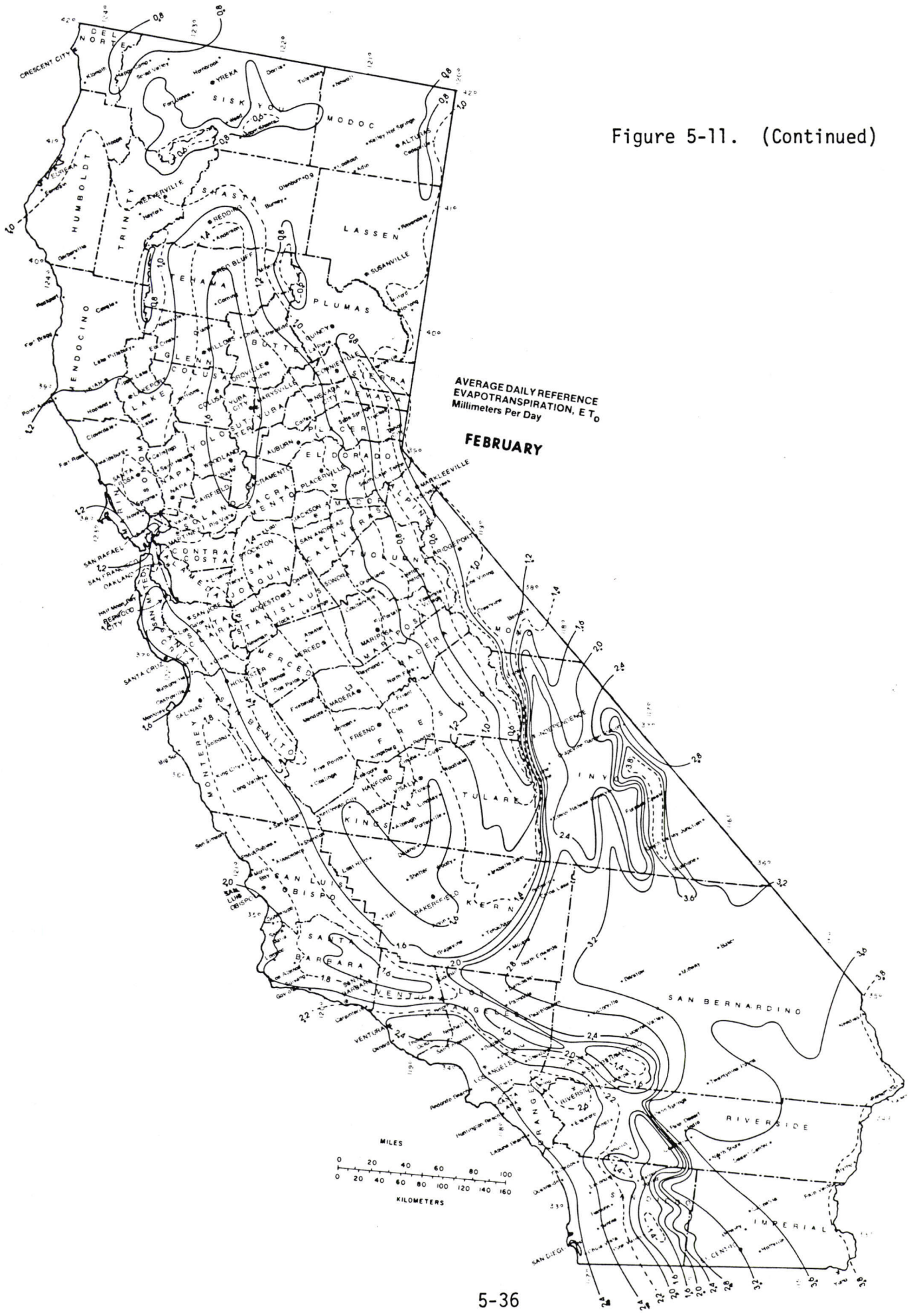

Figure 5-11. (Continued)



Figure 5-11. (Continued)



Figure 5-11. (Continued)



Figure 5-11 (Continued)



Figure 5-11 (Continued)



Figure 5-11 (Continued)



Figure 5-11. (Continued)



Figure 5-11 (Continued)



Figure 5-11 (Continued)



Figure 5-11 (Continued)



Figure 5-11 (Continued)

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