A Comparison of Methods of Estimating Potential Evapotranspiration From Climatological Data in Arid and Subhumid Environments

By R. W. CRUFF *and* T. H. THOMPSON

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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A COMPARISON OF METHODS OF ESTIMATING POTENTIAL EVAPOTRANSPIRATION FROM CLIMATOLOGICAL DATA IN ARID AND SUBHUMID ENVIRONMENTS

By R. W. Cruff and T. H. Thompson

ABSTRACT

This study compared potential evapotranspiration, computed from climatological data by each of six empirical methods, with pan evaporation adjusted to equivalent lake evaporation by regional coefficients. The six methods tested were the Thornthwaite, U.S. Weather Bureau (a modification of the Penman method), Lowry-Johnson, Blaney-Criddle, Lane, and Hamon methods.

The test was limited to 25 sites in the arid and subhumid parts of Arizona, California, and Nevada, where pan evaporation and concurrent climatological data were available. However, some of the sites lacked complete climatological data for the application of all six methods. Average values of adjusted pan evaporation and computed potential evapotranspiration were compared for two periods—the calendar year and the 6-month period from May 1 through October 31.

The 25 sites sampled a wide range of climatic conditions. Ten sites (group 1) were in a highly arid environment and four (group 2) were in an arid environment that was modified by extensive irrigation. The remaining 11 sites (group 3) were in a subhumid environment.

Only the Weather Bureau method gave estimates of potential evapotranspiration that closely agreed with the adjusted pan evaporation at all sites where the method was used. However, lack of climatological data restricted the use of the Weather Bureau method to seven sites. Results obtained by use of the Thornthwaite, Lowry-Johnson, and Hamon methods were consistently low. Results obtained by use of the Lane method agreed with adjusted pan evaporation at the group 1 sites but were consistently high at the group 2 and 3 sites.

During the analysis it became apparent that adjusted pan evaporation in an arid environment (group 1 sites) was a spurious standard for evaluating the reliability of the methods that were tested. Group 1 data were accordingly not considered when making conclusions as to which of the six methods tested was best.

The results of this study for group 2 and 3 data indicated that the Blaney-Criddle method, which uses climatological data that can be readily obtained or deduced, was the most practical of the six methods for estimating potential evapotranspiration. At all 15 sites in the two environments, potential evapotranspiration computed by the Blaney-Criddle method checked the adjusted pan evaporation within ±22 percent. This percentage range is generally considered to be the range of reliability for estimating lake evaporation from evaporation pans.

INTRODUCTION

A study of the hydrologic balance for an area generally includes an analysis of the total water loss due to evaporation and transpiration from all surfaces of the area. This total of evaporation and transpiration is referred to as evapotranspiration or consumptive use. Potential evapotranspiration was defined by Langbein and Iseri (1960, p. 15) as the evapotranspiration that will occur if at no time there is a deficiency of water in the soil for use of vegetation.

The determination of potential evapotranspiration is of interest to agriculturists and hydrologists. A knowledge of the potential evapotranspiration is needed to determine irrigation requirements. In any given climatological regime potential evapotranspiration is affected by the type of soil and vegetative cover, but there is considerable agreement among hydrologists that lake evaporation may be used as a good average estimate of potential evapotranspiration.

The relation of evapotranspiration to climatic factors, geographic location, and vegetative cover has been studied by many hydrologists and has led to the development of various methods for estimating potential evapotranspiration. Most of the methods are based on empirical formulas. These formulas contain one or more climatological factors such as temperature, solar radiation, dewpoint, and windspeed, and they generally include empirically developed coefficients based on comparisons with actual evapotranspiration measured under conditions of ample water supply. The most commonly used methods for estimating potential evapotranspiration from climatological data are the Thornthwaite, U.S. Weather Bureau (a modification of the Penman method), Lowry-Johnson, Blaney-Criddle, Lane, and Hamon methods. These six methods were compared in this study.

PURPOSE AND SCOPE

The purpose of this study was to compare the potential evapotranspiration computed by each of the six methods with evaporation from a lake surface, as deduced from pan-evaporation data. The observed pan evaporation was adjusted to equivalent lake evaporation by the use of widely accepted regional coefficients. In general, the methods of computing potential evapotranspiration had been developed and tested in humid regions. Their applicability in arid and subhumid regions had not been adequately tested; thus, this study was confined to the arid and subhumid parts of Southwestern United States. Twenty-five test sites in Arizona, California, and Nevada were used (fig. 1).

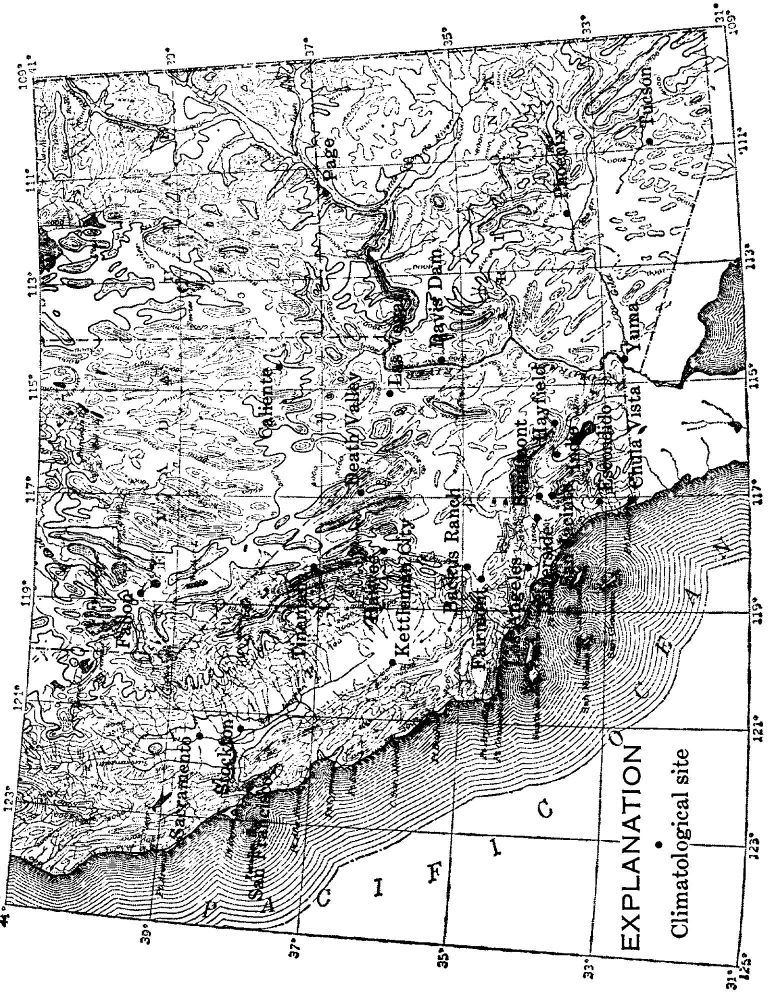


FIGURE 1.—Location of climatological sites used in this study.

The control for this study was the monthly pan-evaporation data collected by the U.S. Weather Bureau and other Federal, State, and local agencies. The requirement for inclusion of a site in the study was the availability of pan-evaporation data and concurrent climatological data at or near the pan site. Generally, the latest 10-year period of climatological and pan evaporation data were used at each site. Monthly values of adjusted pan evaporation (presumed lake evaporation) and potential evapotranspiration computed by each of the six methods were obtained for each year. From these monthly figures, average totals were computed for the calendar year and for the 6-month period of May 1 to October 31. This period is often referred to as the growing season in other parts of the United States and will be so designated in this report. Most of the annual evapotranspiration occurs during this growing season, and in the Southwestern United States this period is generally one of acute soil-moisture deficiency. By contrast, precipitation from November through April is sufficient to partly meet the demands of evapotranspiration in much of the region. At each site the average values of computed potential evapotranspiration for both the year and the growing season were compared with the average values of adjusted pan evaporation. Estimates of potential evapotranspiration for shorter periods of time would not be reliable.

ACKNOWLEDGMENTS

This study was made under the terms of a cooperative agreement between the U.S. Geological Survey and the California Department of Water Resources. The report was prepared by the Water Resources Division of the Geological Survey under the general supervision of Walter Hofmann, district chief for California. Technical supervision and guidance was given by S. E. Rantz, research hydrologist, U.S. Geological Survey, Menlo Park, Calif., who offered valuable suggestions and criticism throughout the study.

OTHER INVESTIGATIONS

An agriculturist or hydrologist interested in the potential evapotranspiration for an area generally must estimate values from climatological data by an empirically derived method. Many methods are available, and the investigator must determine the one most suitable for his area. Thus, investigations have been made in various parts of the world comparing some of the available methods of estimating potential evapotranspiration.

Stephens and Stewart (1963), using data for southern Florida, presented a comparison of correlation coefficients for measured pan evaporation versus computed monthly pan evaporation and for evapotranspiration measured by a lysimeter versus computed potential evapotranspiration. The methods of estimating potential evapotranspiration from climatological data used in their study were the Thornthwaite, Hamon, Blaney-Criddle, Penman, fractional evaporation equivalent, and U.S. Weather Bureau. Modifications of the Penman, Blaney-Criddle, and fractional evaporation equivalent methods were also used in their comparison study that was based on a 6-year period of record. Of the methods compared, the Weather Bureau method had the highest correlation, and the Thornthwaite method had the lowest.

Damagnez, Riou, DeVillele, and El Ammami (1963) compared the Thornthwaite, Blaney-Criddle, Turc, and Penman methods of estimating potential evapotranspiration from climatological data with evapotranspiration measured by nonweighing lysimeters. Their study used data from five sites in Tunisia. The climate at the five sites ranged from Mediterranean to hot desert, similar to the climate in this study. For the Tunisia areas, they found that only the Penman and Turc methods gave acceptable estimates of potential evapotranspiration.

Nixon, MacGillivray, and Lawless (1963) presented comparisons of the Blaney-Criddle and the Thornthwaite methods of estimating evapotranspiration from alfalfa with measured soil-moisture depletion. They used three California sites of differing climate—coastal fogbelt, coastal valley, and interior valley locations. All three sites were near lat 35° N. to eliminate the effect of latitude on the results. The study showed that neither method gave close estimates in these areas, but that the Blaney-Criddle method gave slightly closer estimates than the Thornthwaite method.

THE STUDY REGION

In this study 25 sites were used in arid and subhumid regions—5 in Arizona, 17 in California, and 3 in Nevada. The sites are listed in table 1, and their locations are shown in figure 1. Of these 25 sites, 23 were used for an entire year; pan evaporation is not measured at two of the sites during the winter.

Altitudes at the sites range from 200 feet below to 4,400 feet above mean sea level. Climatic conditions at the sites range from a desert environment with low annual precipitation and high summer temperature to a Mediterranean environment with moderate year-round temperatures, low summer precipitation, and high winter precipitation. Mean air temperatures for the growing season, May through October, range from 62° to 92° F. Mean annual precipitation ranges from 2 to 20 inches, but at all sites the average precipitation for the growing season is 6 inches or less. The climatalogical data for each test site are summarized in table 1.

TABLE 1.—*Climatological data for the test sites*

Site	Altitude above or below (−) mean sea level (feet)	Mean precipitation (inches)		Mean temperature (° F)		Mean annual windspeed (miles per day)
		Annual	May to Oct.	May to Oct.	Aug.	
Group 1. Arid environment						
Backus Ranch, Calif.	2,600	7	1	75	81	74
Davis Dam, Ariz.	700	2	1	86	93	109
Death Valley, Calif.	−200	2	1	92	99	73
Fairmont, Calif.	3,100	4	1	71	78	260
Haiwee, Calif.	3,800	6	1	72	79	208
Hayfield, Calif.	1,400	3	1	82	90	77
Kettleman City, Calif.	300	6	1	77	83	67
Las Vegas, Nev.	2,200	6	2	81	87	67
Page, Ariz.	4,300	4	1	74	80	43
Tinemaha, Calif.	3,900	6	1	70	77	224
Group 2. Modified arid environment						
Indio, Calif.	0	3	1	85	91	32
Phoenix, Ariz.	1,100	7	3	83	88	13
Tucson, Ariz.	2,400	10	6	80	83	29
Yuma, Ariz.	200	3	1	83	92	21
Group 3. Subhumid environment						
Beaumont, Calif.	3,000	20	3	69	75	26
Caliente, Nev.	4,400	9	4	67	74	82
Chula Vista, Calif.	0	10	1	65	68	83
Escondido, Calif.	700	16	2	72	73	------
Fallon, Nev.	4,000	5	2	65	70	37
Los Angeles, Calif.	100	13	1	65	72	30
Riverside, Calif.	1,000	11	1	71	75	49
Sacramento, Calif.	0	16	2	71	76	64
San Francisco, Calif.	0	19	2	62	63	66
San Jacinto, Calif.	1,500	13	2	70	77	29
Stockton, Calif.	0	13	1	71	75	40

On the basis of climatic characteristics, the test sites have been placed in three categories to facilitate later discussion. (See table 1.) Group 1 sites are in a highly arid environment of high temperatures, low precipitation, high windspeeds, and low humidity. Group 2 sites also have high temperatures and low precipitation, but windspeeds are low. Most important, however, is that the four test sites in group 2 are in an environment whose aridity has been modified locally by extensive irrigation and whose humidity is high relative to that at the sites in Group 1.

Group 3 sites include several whose proximity to the Pacific Ocean gives them a Mediterranean climate. All sites in this group have relatively low temperatures, high precipitation, and moderate windspeeds and humidity.

METHODS USED IN THIS STUDY TO ESTIMATE POTENTIAL EVAPOTRANSPIRATION

Six methods—Thornthwaite, Weather Bureau, Lowry-Johnson, Hamon, Blaney-Criddle, and Lane—were used in this study. The data required for use of these methods at each site were latitude; type of vegetative cover; and the climatological parameters of daily maximum temperature, mean monthly temperature, mean monthly solar radiation, mean monthly dewpoint, and mean monthly windspeed.

None of the methods required all the above parameters, but each method used one or a different combination of two or more of the parameters. In this section of the report, each of the six methods for estimating potential evapotranspiration from climatological data is briefly described.

THORNTHWAITE METHOD

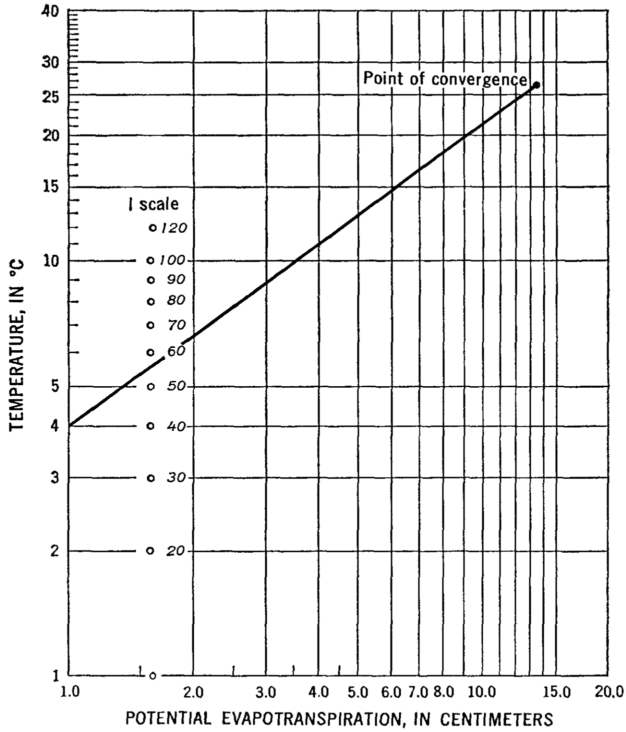
The method of estimating potential evapotranspiration from climatological data developed by Thornthwaite (1948, p. 89–94) was derived from the water budget for natural watersheds and from controlled experiments in the humid Northeastern United States. He derived the following general equation for estimating potential evapotranspiration:

$$e_T = 1.6(10T/I)^a \qquad (1)$$

where

e_T = unadjusted potential evapotranspiration, in centimeters, for a 30-day month;
T = mean monthly air temperature, in degrees centigrade;
I = heat index; and
a = cubic function of I.

To estimate potential evapotranspiration by this method, mean monthly temperature at the site and the latitude of the site must be known. Three steps are involved in the computation, and they are simplified by the use of a nomograph and tables. The first step is to compute the heat index, I. Thornthwaite (1948, p. 92) gives a table of monthly heat-index values corresponding to monthly mean temperature. Summation of the 12 monthly values gives the heat index, I. (See table 2). The next step is to determine the unadjusted monthly values of potential evapotranspiration from the nomograph given by Thornthwaite (1948, p. 94). This nomograph is a solution of equation 1. (See fig. 2.) Finally, these monthly values of unadjusted potential evapotranspiration are adjusted for possible hours of sunlight, in units of 30 days of 12 hours each. Thornthwaite (1948, p. 93) gives a table for possible hours of sunlight corresponding to latitude. (See table 3.)



Temperature (°C)	Potential evapotranspiration (cm)
26.5	13.50
27.0	13.95
27.5	14.37
28.0	14.78
28.5	15.17
29.0	15.54
29.5	15.89
30.0	16.21
30.5	16.52
31.0	16.80
31.5	17.07
32.0	17.31
32.5	17.53
33.0	17.72
33.5	17.90
34.0	18.05
34.5	18.18
35.0	18.29
35.5	18.37
36.0	18.43
36.5	18.47
37.0	18.49
37.5	18.50
38.0	18.50

FIGURE 2.—Nomograph for solution of Thornthwaite's general equation $e_T = 1.6(10T/I)^a$. From Thornthwaite (1948, p. 94)

TABLE 2.—*Monthly heat index*

[From Thornthwaite (1948, p. 92)]

Temperature (° C)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	--------	--------	0.01	0.01	0.02	0.03	0.04	0.05	0.06	0.07
1	0.09	0.10	.12	.13	.15	.16	.18	.20	.21	.23
2	.25	.27	.29	.31	.33	.35	.37	.39	.42	.44
3	.46	.48	.51	.53	.56	.58	.61	.63	.66	.69
4	.71	.74	.77	.80	.82	.85	.88	.91	.94	.97
5	1.00	1.03	1.06	1.09	1.12	1.16	1.19	1.22	1.25	1.29
6	1.32	1.35	1.39	1.42	1.45	1.49	1.52	1.56	1.59	1.63
7	1.66	1.70	1.74	1.77	1.81	1.85	1.89	1.92	1.96	2.00
8	2.04	2.08	2.12	2.15	2.19	2.23	2.27	2.31	2.35	2.39
9	2.44	2.48	2.52	2.56	2.60	2.64	2.69	2.73	2.77	2.81
10	2.86	2.90	2.94	2.99	3.03	3.08	3.12	3.16	3.21	3.25
11	3.30	3.34	3.39	3.44	3.48	3.53	3.58	3.62	3.67	3.72
12	3.76	3.81	3.86	3.91	3.96	4.00	4.05	4.10	4.15	4.20
13	4.25	4.30	4.35	4.40	4.45	4.50	4.55	4.60	4.65	4.70
14	4.75	4.81	4.86	4.91	4.96	5.01	5.07	5.12	5.17	5.22
15	5.28	5.33	5.38	5.44	5.49	5.55	5.60	5.65	5.71	5.76
16	5.82	5.87	5.93	5.98	6.04	6.10	6.15	6.21	6.26	6.32
17	6.38	6.44	6.49	6.55	6.61	6.66	6.72	6.78	6.84	6.90
18	6.95	7.01	7.07	7.13	7.19	7.25	7.31	7.37	7.43	7.49
19	7.55	7.61	7.67	7.73	7.79	7.85	7.91	7.97	8.03	8.10
20	8.16	8.22	8.28	8.34	8.41	8.47	8.53	8.59	8.66	8.72
21	8.78	8.85	8.91	8.97	9.04	9.10	9.17	9.23	9.29	9.36
22	9.42	9.49	9.55	9.62	9.68	9.75	9.82	9.88	9.95	10.01
23	10.08	10.15	10.21	10.28	10.35	10.41	10.48	10.55	10.62	10.68
24	10.75	10.82	10.89	10.95	11.02	11.09	11.16	11.23	11.30	11.37
25	11.44	11.50	11.57	11.64	11.71	11.78	11.85	11.92	11.99	12.06
26	12.13	12.21	12.28	12.35	12.42	12.49	12.56	12.63	12.70	12.78
27	12.85	12.92	12.99	13.07	13.14	13.21	13.28	13.36	13.43	13.50
28	13.58	13.65	13.72	13.80	13.87	13.94	14.02	14.09	14.17	14.24
29	14.32	14.39	14.47	14.54	14.62	14.69	14.77	14.84	14.92	14.99
30	15.07	15.15	15.22	15.30	15.38	15.45	15.53	15.61	15.68	15.76
31	15.84	15.92	15.99	16.07	16.15	16.23	16.30	16.38	16.46	16.54
32	16.62	16.70	16.78	16.85	16.93	17.01	17.09	17.17	17.25	17.33
33	17.41	17.49	17.57	17.65	17.73	17.81	17.89	17.97	18.05	18.13
34	18.22	18.30	18.38	18.46	18.54	18.62	18.70	18.79	18.87	18.95
35	19.03	19.11	19.20	19.38	19.36	19.45	19.53	19.61	19.69	19.78
36	19.86	19.95	20.03	20.11	20.20	20.28	20.36	20.45	20.53	20.62
37	20.70	20.79	20.87	20.96	21.04	21.13	21.21	21.30	21.38	21.47
38	21.56	21.65	21.73	21.81	21.90	21.99	22.07	22.16	22.25	22.33
39	22.42	22.51	22.59	22.68	22.77	22.86	22.95	23.03	23.12	23.21
40	23.30	--------	--------	--------	--------	--------	--------	--------	--------	--------

TABLE 3.—*Mean possible duration of sunlight, in units of 30 days of 12 hours each*

[From Thornthwaite (1948, p. 93)]

Latitude (degrees)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
North latitude												
0	1.04	0.94	1.04	1.01	1.04	1.01	1.04	1.04	1.01	1.04	1.01	1.04
5	1.02	.93	1.03	1.02	1.06	1.03	1.06	1.05	1.01	1.03	.99	1.02
10	1.00	.91	1.03	1.03	1.08	1.06	1.08	1.07	1.02	1.02	.98	.99
15	.97	.91	1.03	1.04	1.11	1.08	1.12	1.08	1.02	1.01	.95	.97
20	.95	.90	1.03	1.05	1.13	1.11	1.14	1.11	1.02	1.00	.93	.94
25	.93	.89	1.03	1.06	1.15	1.14	1.17	1.12	1.02	.99	.91	.91
26	.92	.88	1.03	1.06	1.15	1.15	1.17	1.12	1.02	.99	.91	.91
27	.92	.88	1.03	1.07	1.16	1.15	1.18	1.13	1.02	.99	.90	.90
28	.91	.88	1.03	1.07	1.16	1.16	1.18	1.13	1.02	.98	.90	.90
29	.91	.87	1.03	1.07	1.17	1.16	1.19	1.13	1.03	.98	.90	.89
30	.90	.87	1.03	1.08	1.18	1.17	1.20	1.14	1.03	.98	.89	.88
31	.90	.87	1.03	1.08	1.18	1.18	1.20	1.14	1.03	.98	.89	.88
32	.89	.86	1.03	1.08	1.19	1.19	1.21	1.15	1.03	.98	.88	.87
33	.88	.86	1.03	1.09	1.19	1.20	1.22	1.15	1.03	.97	.88	.86
34	.88	.85	1.03	1.09	1.20	1.20	1.22	1.16	1.03	.97	.87	.86
35	.87	.85	1.03	1.09	1.21	1.21	1.23	1.16	1.03	.97	.86	.85
36	.87	.85	1.03	1.10	1.21	1.22	1.24	1.16	1.03	.97	.86	.84
37	.86	.84	1.03	1.10	1.22	1.23	1.25	1.17	1.03	.97	.85	.83
38	.85	.84	1.03	1.10	1.23	1.24	1.25	1.17	1.04	.96	.84	.83
39	.85	.84	1.03	1.11	1.23	1.24	1.26	1.18	1.04	.96	.84	.82
40	.84	.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	.96	.83	.81
41	.83	.83	1.03	1.11	1.25	1.26	1.27	1.19	1.04	.96	.82	.80
42	.82	.83	1.03	1.12	1.26	1.27	1.28	1.19	1.04	.95	.82	.79
43	.81	.82	1.02	1.12	1.26	1.28	1.29	1.20	1.04	.95	.81	.77
44	.81	.82	1.02	1.13	1.27	1.29	1.30	1.20	1.04	.95	.80	.76
45	.80	.81	1.02	1.13	1.28	1.29	1.31	1.21	1.04	.94	.79	.75
46	.79	.81	1.02	1.13	1.29	1.31	1.32	1.22	1.04	.94	.79	.74
47	.77	.80	1.02	1.14	1.30	1.32	1.33	1.22	1.04	.93	.78	.73
48	.76	.80	1.02	1.14	1.31	1.33	1.34	1.23	1.05	.93	.77	.72
49	.75	.79	1.02	1.14	1.32	1.34	1.35	1.24	1.05	.93	.76	.71
50	.74	.78	1.02	1.15	1.33	1.36	1.37	1.25	1.06	.92	.76	.70
South latitude												
5	1.06	.95	1.04	1.00	1.02	.99	1.02	1.03	1.00	1.05	1.03	1.06
10	1.08	.97	1.05	.99	1.01	.96	1.00	1.01	1.00	1.06	1.05	1.10
15	1.12	.98	1.05	.98	.98	.94	.97	1.00	1.00	1.07	1.07	1.12
20	1.14	1.00	1.05	.97	.96	.91	.95	.99	1.00	1.08	1.09	1.15
25	1.17	1.01	1.05	.96	.94	.88	.93	.98	1.00	1.10	1.11	1.18
30	1.20	1.03	1.06	.95	.92	.85	.90	.96	1.00	1.12	1.14	1.21
35	1.23	1.04	1.06	.94	.89	.82	.87	.94	1.00	1.13	1.17	1.25
40	1.27	1.06	1.07	.93	.86	.78	.84	.92	1.00	1.15	1.20	1.29
42	1.28	1.07	1.07	.92	.85	.76	.82	.92	1.00	1.16	1.22	1.31
44	1.30	1.08	1.07	.92	.83	.74	.81	.91	.99	1.17	1.23	1.33
46	1.32	1.10	1.07	.91	.82	.72	.79	.90	.99	1.17	1.25	1.35
48	1.34	1.11	1.08	.90	.80	.70	.76	.89	.99	1.18	1.27	1.37
50	1.37	1.12	1.08	.89	.77	.67	.74	.88	.99	1.19	1.29	1.41

WEATHER BUREAU METHOD

The Weather Bureau method was developed by Kohler, Nordenson, and Fox (1955). It is a modification of the method developed by Penman (1948) and was derived by applying the Penman approach to a composite record of a number of weather stations in the United States and to the Lake Hefner studies by Kohler (1954). Estimation of lake evaporation, which, as previously stated, is assumed to approximate potential evapotranspiration, is determined from the equation:

$$E_L=0.70[(Q_n\delta+E_a\gamma)][(\delta+\gamma)], \qquad (2)$$

where

E_L=average daily lake evaporation, in inches;
Q_n=net radiant energy, in inches per day;
δ=slope of the curve relating saturation vapor pressure to temperature at the observed air temperature;
E_a=evaporation given by the aerodynamic equation (Kohler and others, 1955, p. 2) in which water temperatures are assumed equal to air temperature; and
γ=factor defined by the equation for Bowen's (1926) dimensionless ratio.

To simplify the computation, Kohler, Nordenson, and Fox (1955, p. 15) have presented nomographs (fig. 3) for the solution of equation 2.

The nomograph solution assumes a value of $\gamma=0.0105$. Data needed to use these nomographs for estimating mean daily lake evaporation are mean daily or monthly values of air temperature, dewpoint temperature, wind movement, and solar radiation. If daily values of the climatic parameters are used, monthly lake evaporation is obtained by adding the values of daily lake evaporation for each day of the month. More commonly, as in this report, monthly values of lake evaporation are obtained by entering the nomograph with mean monthly values of the climatic parameters, after which the value obtained for mean daily lake evaporation is multiplied by the number of days in the month.

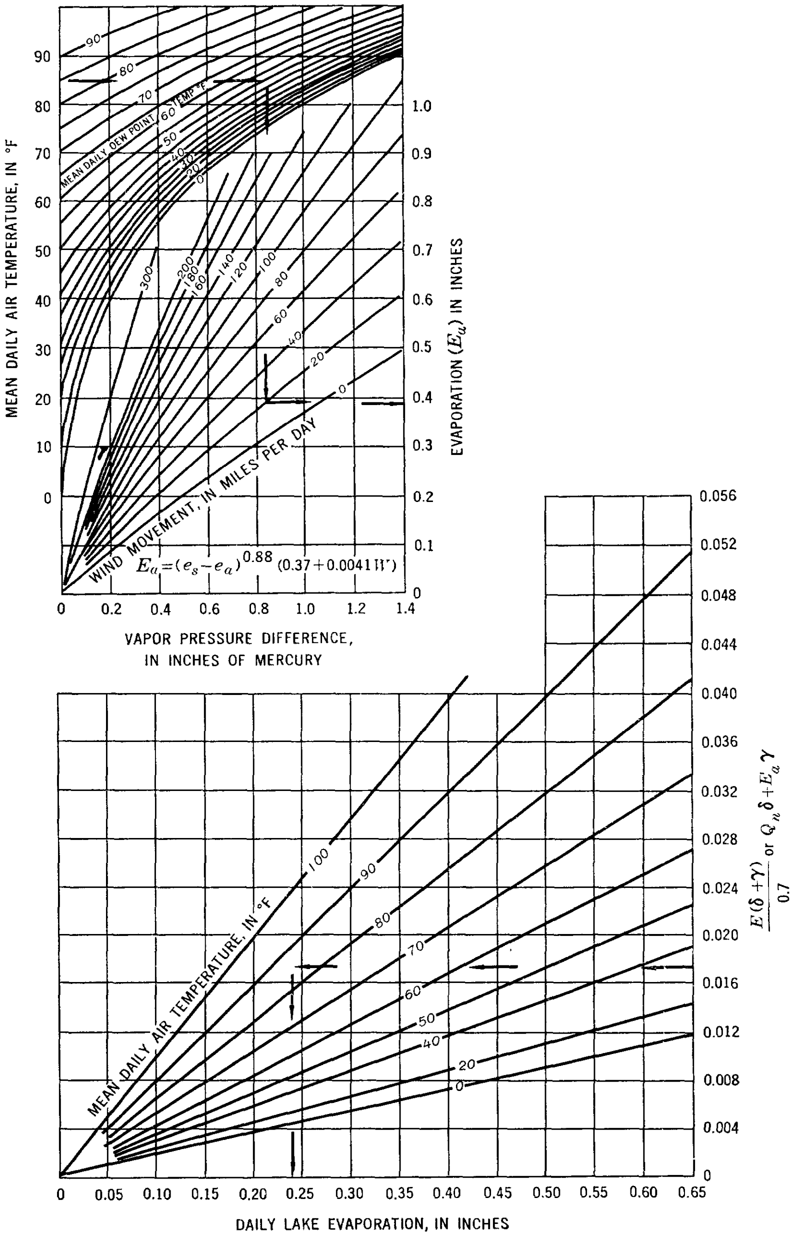


FIGURE 3.—Nomographs for solution of equation 2 for daily lake evaporation. From Kohler, Nordenson, and Fox (1955, p. 15).

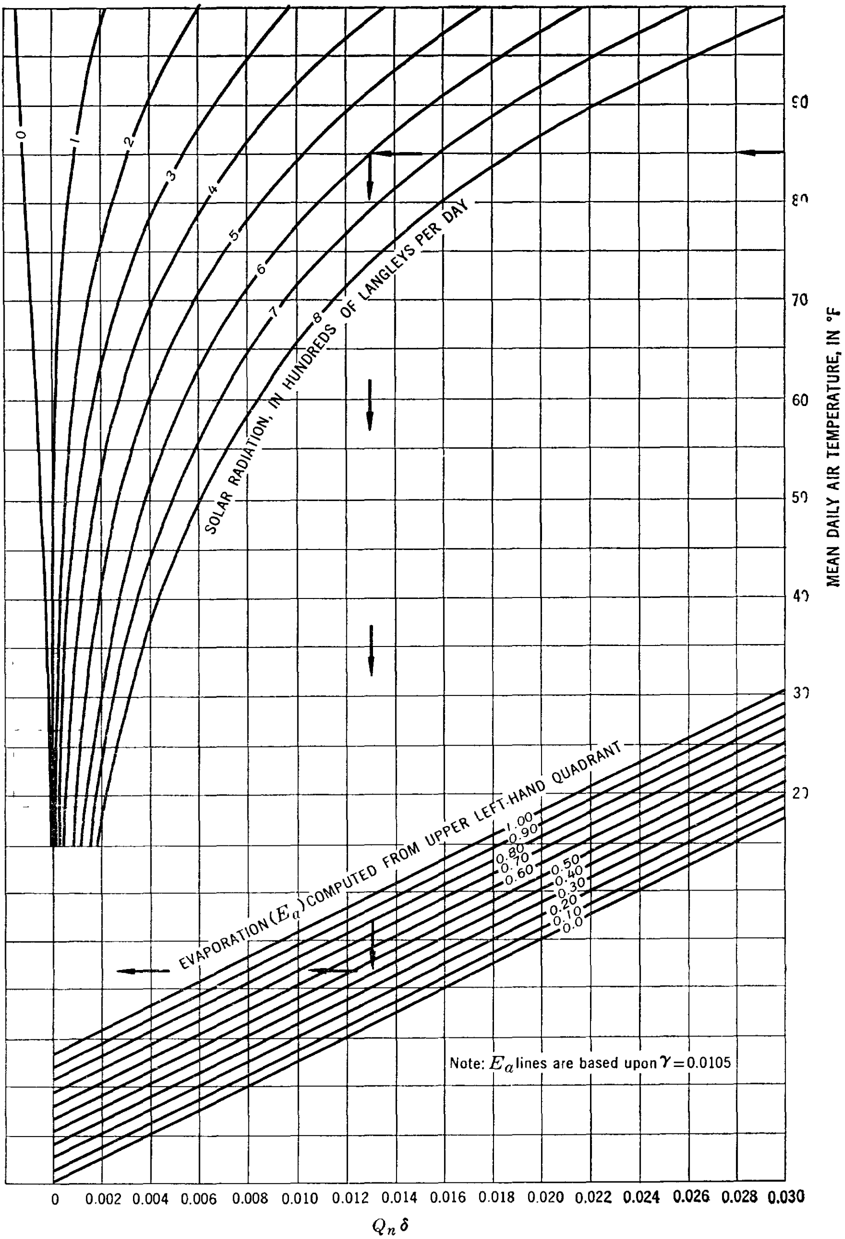


FIGURE 3.—Continued.

LOWRY-JOHNSON METHOD

Lowry and Johnson (1942) noted a high correlation between consumptive use (evapotranspiration) and effective heat (accumulated degree-days of daily maximum temperature above 32 °F). The linear relation they developed is expressed by the following equation:

$$CU = 0.00185\, H_E + 10.4 \tag{3}$$

where

CU = annual consumptive use, in inches; and

H_E = effective heat, in degree-days above 32 °F.

Monthly estimates of consumptive use are determined by using a ratio of the monthly degree-days to the annual degree-days multiplied by the annual consumptive use. Equation 3 is expressed in graphical form on figure 4.

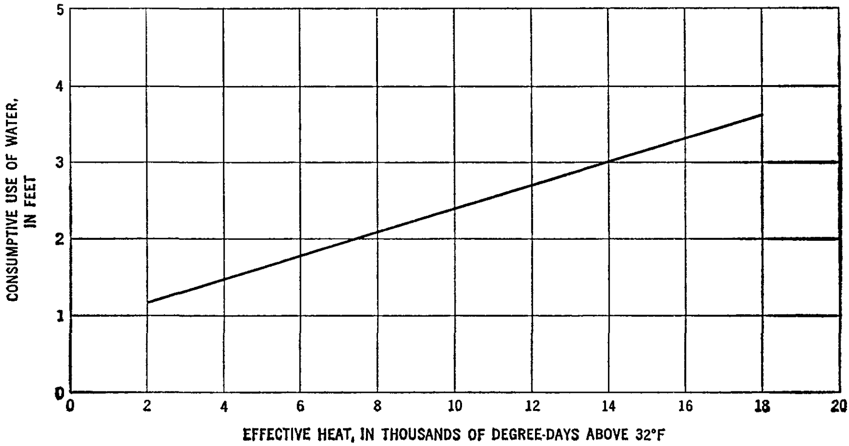


FIGURE 4.—Graphical solution of equation 3 for consumptive use versus effective heat.

The relation expressed in equation 3 was determined from basin-wide studies of the hydrologic budget using inflow, outflow, precipitation, and change in the quantity of ground water in storage. Of the 20 sites in the United States used by Lowry and Johnson to determine consumptive use, only 2 were in arid regions.

HAMON METHOD

Hamon (1961) formulated a simplified expression for estimating potential evapotranspiration. The expression is represented by the equation:

$$E_T = CD^2P_t, \tag{4}$$

where

E_T=average potential evapotranspiration, in inches per day;

D=possible hours of sunlight, in units of 30 days of 12 hours each;

P_t=saturated water-vapor density (absolute humidity at saturation) at the daily mean temperature, in centigrams per cubic meter; and

C=coefficient chosen to give appropriate yearly values of potential evapotranspiration.

Hamon empirically determined the value of C to be 0.55 from comparisons with the results of the complex Thornthwaite method and the Lowry-Johnson study.

The Hamon method is based on the relation between potential evapotranspiration, maximum possible incoming radiant energy, and the moisture-holding capacity of the air at the prevailing air temperature. In equation 4 the possible hours of sunlight were used as an index of the maximum possible incoming radiant energy, and the absolute humidity at saturation is the moisture-holding capacity of the air. In using this method values of mean monthly temperature and the latitude of the site are required. The absolute humidity at saturation, P_t, is then determined directly from mean air temperature (table 4). The possible hours of sunlight, D, are determined for the latitude of the site (table 3).

TABLE 4.—*Density of saturated water vapor*

Temperature		Density (grams per cubic meter)	Temperature		Density (grams per cubic meter)
°C	°F		°C	°F	
−40	−40	0.12	30	86	30.4
−30	−22	.4	35	95	39.6
−20	−4	.89	40	104	51.1
−10	14	2.2	50	122	83.2
0	32	4.8	60	140	130.5
5	41	6.8	70	158	198.4
10	50	9.3	80	176	293.8
15	59	12.7	90	194	424.1
20	68	17.1	100	212	598.7
25	77	22.8			

BLANEY-CRIDDLE METHOD

In experimental studies throughout Western United States, Blaney and Criddle (1950) developed a method for estimating consumptive use (evapotranspiration) by various crops. They found that evapotranspiration varies with temperature, daytime hours, and available moisture for various crops. With ample moisture available, the relation between evapotranspiration and the above mentioned parameters is expressed by the equation:

$$U=K\sum\frac{T\times p}{100}, \tag{5}$$

where

U=consumptive use, in inches, during growth of the crop;
K=empirical consumptive-use coefficient that is dependent on the type and location of crop;
p=monthly percentage of total daytime hours in the year; and
T=mean monthly temperature, in degrees Fahrenheit.

Blaney (1956, p. 46) stated that evapotranspiration from an alfalfa field was approximately equal to lake evaporation. In a later study, Blaney and Criddle (1962, p. 49) suggested values for K in equation 5 for alfalfa at a few selected locations. In written communications with the authors, Blaney suggested values for K of 0.85 for the entire year and 1.00 for the growing season at the sites in groups 1 and 2 for estimating potential evapotranspiration by the Blaney-Criddle method. He also suggested values for K of 0.75 for the entire year and 0.90 for the growing season at the sites in group 3. These values are approximately the same as those given by Blaney and Criddle (1962, p. 49) for alfalfa and were used in this study.

Table 5 from a report by Blaney and Criddle (1950) gives values of p, the percentage of daytime hours in each month between lat 24° and 50° N. The appropriate value of p and the mean monthly temperature, T, are used in equation 5 to compute monthly values of potential evapotranspiration.

LANE METHOD

Lane (1964), using 551 sets of monthly data for pan evaporation, solar radiation, and air temperatures at various sites in the United States, developed the following equation to express the relation between lake evaporation, solar radiation, and temperature:

$$10^4\frac{E_L}{Q_S}=2.67T-51.46, \tag{6}$$

where

E_L=average monthly lake evaporation, in inches;
Q_s=average monthly incoming solar radiation, in langleys per day;
T=average monthly air temperature, in degrees Fahrenheit.

Lane used a coefficient of 0.70 to adjust observed pan evaporation to the values he used for lake evaporation. A comparison of results obtained by equation 6 with published lake evaporation at various

TABLE 5.—*Daytime hour percentages for each month of the year for lat 24° to 50° N*

[From Blaney and Criddle (1950 p. 48)]

Month	Percentages for indicated degrees of latitude													
	24	26	28	30	32	34	36	38	40	42	44	46	48	50
January	7.58	7.49	7.40	7.30	7.20	7.10	6.99	6.87	6.76	6.62	6.49	6.33	6.17	5.98
February	7.17	7.12	7.07	7.03	6.97	6.91	6.86	6.79	6.73	6.65	6.58	6.50	6.42	6.32
March	8.40	8.40	8.39	8.38	8.37	8.36	8.35	8.34	8.33	8.31	8.30	8.29	8.27	8.25
April	8.60	8.64	8.68	8.72	8.75	8.80	8.85	8.90	8.95	9.00	9.05	9.12	9.18	9.25
May	9.30	9.38	9.46	9.53	9.63	9.72	9.81	9.92	10.02	10.14	10.26	10.39	10.53	10.69
June	9.20	9.30	9.38	9.49	9.60	9.70	9.83	9.95	10.08	10.21	10.38	10.54	10.71	10.93
July	9.41	9.49	9.58	9.67	9.77	9.88	9.99	10.10	10.22	10.35	10.49	10.64	10.80	10.99
August	9.05	9.10	9.16	9.22	9.28	9.33	9.40	9.47	9.54	9.62	9.70	9.79	9.89	10.00
September	8.31	8.31	8.32	8.34	8.34	8.36	8.36	8.38	8.38	8.40	8.41	8.42	8.44	8.44
October	8.09	8.06	8.02	7.99	7.93	7.90	7.85	7.80	7.75	7.70	7.63	7.58	7.51	7.43
November	7.43	7.36	7.27	7.19	7.11	7.02	6.92	6.82	6.72	6.62	6.49	6.36	6.22	6.07
December	7.46	7.35	7.27	7.14	7.05	6.92	6.79	6.66	6.52	6.38	6.22	6.04	5.86	5.65
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

sites in the United States indicated to him that a coefficient of 0.92 should be applied to his results. This reduced equation 6 to the following form for estimating lake evaporation:

$$E_L=0.92\times10^{-4}Q_s(2.67T-51.46). \qquad (7)$$

Values of mean monthly solar radiation and mean monthly air temperature are required for use of this method.

ANALYSIS OF ESTIMATED POTENTIAL EVAPOTRANSPIRATION

Pan evaporation when adjusted by the proper coefficients approximates the evaporation from a shallow lake; and lake evaporation, in turn, is approximately equivalent to potential evapotranspiration. Adjusted pan-evaporation data were therefore used as the standard for comparing and evaluating the effectiveness of each of the six methods of computing evapotranspiration on the basis of climatological data for both the calendar year and the growing season.

All six methods were used at each site except where required climatological data were lacking. The latest 10 years of available record was used for the comparisons. A site with less than 10 years of record was used only if its record was sufficiently long to give reliable results and its use was needed to enhance areal coverage. Where two climatological stations were in close proximity and neither had complete data, the data from the two sites were combined if the two sites had the same general climate and if an increased number of methods could be used by combining the data. For example, the site at Phoenix, Ariz., had all the required climatological data for the six-methods, but no pan-evaporation data. At Tempe, 6 miles away, pan-evaporation data were available, but only part of the required climatological data was available. A check of the available data showed the climate at both sites to be approximately equivalent, and the two sets of data were therefore combined and used under the site name, Phoenix.

Most of the data used in the computations—monthly mean values of pan evaporation, air temperature, solar radiation, wind movement, and dewpoint and daily maximum values of air temperature (for computing degree-days)—were obtained from the monthly series of U.S. Weather Bureau publications entitled "Climatological Data." Solar radiation is not measured at most of the sites used in this study. The mean monthly values were obtained from maps in the climatological data report series that show isopleths of mean monthly solar radiation. Pan-evaporation data for a few of the sites were obtained from reports by the California Department of Public Works (1947, 1948, and 1955). An analysis of the potential evapotranspiration estimated by each of the methods previously discussed is described on the pages that follow.

ADJUSTED PAN EVAPORATION

All but 4 of the 25 sites were equipped with Weather Bureau class A pans. Four sites—Fairmont, Haiwee, Tinemaha, and Escondido, Calif.—were equipped with Colorado-type pans. Descriptions of these two pans are in most standard hydrology texts (for example, Linsley and others, 1958, p. 99). The coefficients used to adjust observed class A pan evaporation to equivalent lake evaporation were obtained from a Weather Bureau map (Kohler and others, 1959, pl. 3) showing isopleths of the coefficients. For the 21 sites equipped with class A pans the coefficients ranged from 0.60 to 0.78. Coefficients for use with the Colorado pans were based on values presented in a table by Linsley and others (1958, p. 104). Three of the four Colorado pans were standard installations and a coefficient of 0.90 was used. The fourth Colorado pan, at Escondido, Calif., is set in concrete and a coefficient of 0.92 was used.

The average annual values of observed and adjusted pan evaporation are listed in table 6. Similar evaporation figures for the growing season are listed in table 7. The adjusted values of pan evaporation in each table were used as standards to compare results of the six methods of estimating potential evapotranspiration from climatological data. The computed value is shown in the first column under each method in the two tables. The percentage difference between computed values and values of adjusted pan evaporation is shown in italic type in the second column under each method.

EMPIRICAL METHODS

Thornthwaite method.—Values of potential evapotranspiration computed by the Thornthwaite method were less than the adjusted pan evaporation at all sites used in the study. The differences ranged from −21 to −66 percent for the entire year and from −10 to −63 percent for the growing season. The median differences were −39 and −33 percent, respectively.

Weather Bureau method.—Potential evapotranspiration was computed by the Weather Bureau method for only 7 of the sites because dewpoint data were unavailable at the other 18 sites. The differences ranged from −6 to +22 percent for the entire year and from −5 to +17 percent for the growing season. The median differences were +6 and −1 percent, respectively.

TABLE 6.—*Average potential evapotranspiration estimated by pan evaporation and by the six empirical methods for the entire year*

[Data are in inches except for the percentage difference (italicized) between the computed value and adjusted pan evaporation]

Site	Pan evaporation		Potential evapotranspiration computed by indicated method											
	Observed	Adjusted to equivalent lake evaporation	Thornthwaite		U.S. Weather Bureau		Lowry-Johnson		Hamon		Blaney-Criddle		Lane	
Group 1. Arid environment														
Backus Ranch, Calif.	113.0	81.4	36.6	*−55*			41.5	*−49*	37.2	*−54*	54.5	*−33*	71.1	*−12*
Davis Dam, Ariz.	161.6	97.0	41.6	*−57*			41.3	*−47*	52.6	*−46*	63.5	*−34*	88.6	*−8*
Death Valley, Calif.	172.7	104.0	44.8	*−57*			50.1	*−52*	62.8	*−40*	67.3	*−35*	93.6	*−10*
Fairmont, Calif.[1]	103.8	93.4	31.8	*−66*			37.6	*−60*	33.0	*−65*	52.0	*−44*	62.7	*−33*
Haiwee, Calif.[1]	68.0	61.2	32.8	*−46*			37.8	*−38*	34.0	*−44*	52.0	*−15*	67.8	*+11*
Hayfield, Calif.	145.5	88.8	49.0	*−45*					46.1	*−48*	60.5	*−32*		
Kettleman City, Calif.	106.4	77.6	37.0	*−52*			41.6	*−46*	40.3	*−48*	56.6	*−27*	70.8	*−9*
Las Vegas, Nev.	113.5	73.7	38.6	*−48*	73.2	*−1*	40.2	*−46*	44.3	*−40*	58.6	*−20*	79.7	*+8*
Page, Ariz.[2]			33.1				36.8		35.5		51.5		62.5	
Tinemaha, Calif.[1]	89.7	80.7	31.0	*−62*					32.4	*−60*	50.5	*−38*		
Group 2. Modified arid environment														
Indio, Calif.	100.4	62.3	43.0	*−31*			49.4	*−21*	51.6	*−17*	63.5	*+2*	83.7	*+34*
Phoenix, Ariz.	76.7	52.1	41.2	*−21*	63.5	*+22*	44.7	*−14*	47.4	*−9*	61.0	*+17*	82.4	*+58*
Tucson, Ariz.	92.5	63.8	39.7	*−38*	65.2	*+2*	43.8	*−31*	43.1	*−32*	59.0	*−7*	78.4	*+23*
Yuma, Ariz.	96.3	59.6	44.2	*−26*	70.0	*+17*	49.3	*−17*	52.9	*−11*	64.6	*+8*	88.9	*+49*
Group 3. Subhumid environment														
Beaumont, Calif.	70.8	48.8	30.0	*−39*			39.8	*−18*	32.3	*−34*	46.4	*−5*	63.9	*+31*
Caliente, Nev.			28.2				37.3		29.0		41.7		56.3	
Chula Vista, Calif.	66.0	49.5	30.0	*−39*			34.5	*−30*	29.9	*−40*	45.7	*−7*	57.6	*+16*
Escondido, Calif.[3]	57.9	53.3	31.3	*−41*			40.1	*−25*	31.7	*−41*	46.7	*−12*		
Fallon, Nev.	62.6	45.1	26.9	*−40*			35.5	*−21*	27.3	*−39*	45.0	*0*	50.2	*+11*
Los Angeles, Calif.	56.7	44.2	32.1	*−27*	46.7	*+6*	36.8	*−17*	32.4	*−27*	47.6	*+8*	59.4	*+34*
Riverside, Calif.	72.2	50.5	34.6	*−31*			42.5	*−16*	35.2	*−30*	48.6	*−4*	67.4	*+33*
Sacramento, Calif.	71.7	53.1	33.2	*−38*	49.7	*−6*	38.3	*−28*	34.0	*−36*	46.6	*−12*	59.6	*+12*
San Francisco, Calif.	53.8	42.0	38.0	*−9*	41.3	*−2*	32.9	*−21*	27.0	*−36*	43.0	*+2*	52.0	*+24*
San Jacinto, Calif.	72.8	52.4	32.5	*−38*			42.7	*−19*	33.2	*−36*	46.8	*−11*	59.9	*+14*
Stockton, Calif.	65.5	48.5	33.1	*−32*			38.9	*−20*	34.0	*−20*	46.8	*−4*	60.8	*+25*
Median differences				*−39*		*+6*		*−25*		*−39*		*−11*		*+15*

[1] Standard Colorado pan. [2] No winter data. [3] Colorado pan set in concrete.

TABLE [illegible].—*Average potential evapotranspiration estimated by pan evaporation and by the six empirical methods for the growing season*

[Data are in inches except for the percentage difference (italicized) between the computed value and adjusted pan evaporation]

Site	Pan evaporation		Potential evapotranspiration computed by indicated method											
	Observed	Adjusted to equivalent lake evaporation	Thornthwaite		U.S. Weather Bureau		Lowry-Johnson		Hamon		Blaney-Criddle		Lane	
Group 1. Arid environment														
Backus Ranch, Calif.	83.2	59.9	30.8	*−49*			30.5	*−49*	28.6	*−52*	41.4	*−31*	52.0	*−13*
Davis Dam, Ariz.	104.2	62.5	34.1	*−45*			34.0	*−46*	40.7	*−35*	47.7	*−24*	63.2	*+1*
Death Valley, Calif.	124.7	74.7	36.3	*−51*			35.5	*−52*	49.7	*−33*	51.4	*−31*	68.9	*−8*
Fairmont, Calif.[1]	77.9	70.1	26.0	*−63*			28.3	*−60*	25.0	*−64*	39.2	*−44*	46.7	*−33*
Haiwee, Calif.[1]	50.7	45.6	27.5	*−40*			28.6	*−37*	26.4	*−42*	40.0	*−12*	50.3	*+10*
Hayfield, Calif.	99.6	60.8	41.1	*−32*					34.9	*−43*	45.0	*−26*		
Kettleman City, Calif.	81.4	59.4	30.7	*−48*			30.9	*−48*	31.0	*−48*	43.0	*−27*	52.5	*−11*
Las Vegas, Nev.	79.4	51.6	32.4	*−37*	51.3	*−1*	30.6	*−41*	34.5	*−33*	43.5	*−16*	57.9	*+12*
Page, Ariz.	68.8	46.1	29.2	*−37*			29.4	*−36*	28.7	*−38*	41.2	*−11*	48.0	*+4*
Tinemaha, Calif.[1]	66.1	59.5	26.1	*−54*					25.3	*−57*	39.0	*−34*		
Group 2. Modified arid environment														
Indio, Calif.	70.1	43.5	34.3	*−21*			33.8	*−22*	38.8	*−11*	46.9	*+8*	58.5	*+34*
Phoenix, Ariz.	55.2	37.5	33.8	*−10*	43.9	*+17*	32.2	*−14*	36.1	*−4*	45.7	*+22*	57.7	*+54*
Tucson, Ariz.	63.4	43.6	32.1	*−26*	43.8	*0*	29.0	*−34*	32.4	*−26*	43.6	*0*	54.8	*+26*
Yuma, Ariz.	66.3	41.1	35.2	*−15*	47.5	*+15*	33.8	*−18*	39.6	*−4*	47.5	*+15*	61.4	*+49*
Group 3. Subhumid environment														
Beaumont, Calif.	47.3	32.6	25.0	*−23*			30.0	*−8*	23.3	*−28*	34.7	*+6*	45.2	*+28*
Caliente, Nev.	53.2	36.2	24.7	*−32*			28.9	*−20*	22.9	*−37*	33.7	*−7*	43.7	*+21*
Chula Vista, Calif.	41.1	30.8	20.2	*−34*			23.5	*−24*	19.9	*−35*	32.0	*+4*	37.8	*+23*
Escondido, Calif.[2]	40.8	37.5	22.2	*−41*			27.7	*−26*	21.8	*−42*	33.4	*−11*		
Fallon, Nev.	44.6	32.2	23.4	*−27*			28.0	*−13*	21.5	*−33*	32.8	*+2*	41.2	*+28*
Los Angeles, Calif.	38.7	30.2	21.5	*−29*	29.8	*−1*	24.8	*−18*	21.6	*−28*	33.4	*+10*	38.9	*+29*
Riverside, Calif.	46.7	32.7	26.0	*−20*			29.6	*−9*	25.0	*−24*	35.5	*+8*	46.0	*+41*
Sacramento, Calif.	53.0	39.2	26.3	*−33*	37.7	*−4*	28.6	*−27*	25.5	*−35*	35.5	*−9*	44.9	*+14*
San Francisco, Calif.	40.4	31.5	19.0	*−40*	30.0	*−5*	23.5	*−25*	18.3	*−42*	30.8	*−2*	36.2	*+15*
San Jacinto, Calif.	52.0	37.4	25.0	*−33*			30.5	*−18*	24.1	*−36*	34.7	*−7*	42.8	*+15*
Stockton, Calif.	51.8	38.3	26.7	*−30*			28.7	*−25*	25.3	*−34*	35.7	*−7*	45.9	*+20*
Median differences				*−33*		*−1*		*−25*		*−35*		*−7*		*+18*

[1] Standard Colorado pan.

[2] Colorado pan set in concrete.

Lowry-Johnson method.—Potential evapotranspiration was computed by the Lowry-Johnson method for 23 of the 25 sites. Maximum daily temperatures were not available for the period of record at two sites. The differences ranged from −16 to −60 percent for the entire year and from −8 to −60 percent for the growing season. The median difference was −25 percent for both periods. The values estimated by the Lowry-Johnson method were lower than the adjusted pan evaporation at all sites.

Hamon method.—Potential evapotranspiration was computed for all sites by the Hamon method. These differences ranged from −9 to −65 percent for the entire year and from −4 to −65 percent for the growing season. The median differences were −39 and −35 percent, respectively. The Hamon method, like the Lowry-Johnson and Thornthwaite methods, gave estimates of potential evapotranspiration that were lower than the adjusted pan evaporation at all sites.

Blaney-Criddle method.—Data from all sites were used for computing potential evapotranspiration by the Blaney-Criddle method. The differences ranged from −44 to +17 percent for the entire year and from −44 to +22 percent for the growing season. The median differences were −11 and −7 percent, respectively.

Christiansen and Mehta (1965, p. 21) estimated actual pan evaporation by use of a modified Blaney-Criddle method in which K (consumptive-use coefficient) is based on mean temperature and windspeed rather than dependent on type and location of crop. By this modified method, data from several sites in this study gave results which were generally within ±30 percent of actual pan evaporation. Because this study was restricted to the estimation of potential evapotranspiration and because this modified Blaney-Criddle method did not significantly improve estimates of actual pan evaporation, a comparison of the results is not presented in this report. Also, it is somewhat difficult to find a common ground for basing the value of K on the type of crop as Blaney and Criddle did or on temperature and windspeed as Christiansen and Mehta did.

Lane method.—Data from 22 of the 25 sites were used to compute potential evapotranspiration by the Lane method. The differences ranged from −33 to +58 percent for the entire year and from −33 to +54 percent for the growing season. The median differences were +15 percent and +8 percent, respectively.

RESULTS OF THE ANALYSIS

Tables 6 and 7 present a summary of the measured and adjusted pan evaporation and the average values of potential evapotranspiration estimated by the six methods at the selected sites for the entire year and for the growing season. The differences, in percent, between the values estimated by each of the six methods and the adjusted pan evaporation are also shown in tables 6 and 7.

Table 8 summarizes the differences, in percent, between potential evapotranspiration estimated by each of the six methods and adjusted pan evaporation for the sites in an arid environment. Tables 9 and 10 are similar to table 8, except that table 9 refers to a modified arid environment and table 10 to a subhumid environment.

Table 8 shows that the Lane method gave satisfactory results in an arid environment. At eight of the nine group 1 sites, values estimated by the Lane method agreed within ±13 percent with the adjusted pan evaporation values. The Weather Bureau method was used at only one group 1 site, and the evapotranspiration estimated by that method differed from the adjusted pan evaporation by −1 percent. The four other methods gave much lower values of potential evapotranspiration than the values of adjusted pan evaporation.

Table 9 shows that the Blaney-Criddle and Weather Bureau methods gave satisfactory results at the sites in a modified arid environment. For both methods, the estimated potential evapotranspiration agreed within ±22 percent of the adjusted pan evaporation. More or less satisfactory results were obtained in this environment with the Hamon and Lowry-Johnson methods. The Lane method, however, gave estimates of potential evapotranspiration that were much higher than the adjusted pan evaporation, and the Thornthwaite method gave estimates that were much lower, particularly those for the entire year.

Table 10 shows that the Blaney-Criddle method also gave satisfactory results in a subhumid environment. Results of the computations by the Blaney-Criddle method at all 11 group 3 sites were within ±12 percent of the adjusted pan evaporation. Fair results, though consistently low, were obtained with the Lowry-Johnson method, and poor results were obtained with the Hamon, Lane, and Thornthwaite methods. The Hamon and Thornthwaite methods gave estimates of potential evapotranspiration that were much lower than the adjusted pan evaporation; the Lane method gave estimates that were much higher than the adjusted pan evaporation. The Weather Bureau method was used at only three group 3 sites, and, while the results obtained at these sites were good, they constitute too small a sample on which to make conclusions.

In an arid environment, an evaporation pan provides an index to potential evapotranspiration only for the microclimate existing at the pan site. Pruitt and Angus (1961) showed that evaporation from a Weather Bureau class A pan in a dry fallow field was about 30 percent greater than that from a similar pan in a grass field, 750 feet away.

TABLE 8.—*Summary of differences between potential evapotranspiration estimated by the six empirical methods and adjusted pan evaporation in an arid environment*

Range of differences (percent)	Number of sites with differences in indicated range											
	Entire year						Growing season					
	Thornthwaite	Weather Bureau	Lowry-Johnson	Hamon	Blaney-Criddle	Lane	Thornthwaite	Weather Bureau	Lowry-Johnson	Hamon	Blaney-Criddle	Lane
+11 to +20						1						1
+1 to +10						1						3
0						0						0
−1 to −10		1				3		1				1
−11 to −20					2	1					3	2
−21 to −30					1	0					3	0
−31 to −40			1	2	5	1	4		2	4	3	1
−41 to −50	3		3	4	1		3		4	3	1	
−51 to −60	4		3	2			2		2	2		
−61 to −70	2			1			1			1		
Total	9	1	7	9	9	7	10	1	8	10	10	8

TABLE 9.—*Summary of differences between potential evapotranspiration estimated by the six empirical methods and adjusted pan evaporation in a modified arid environment*

Range of differences (percent)	Number of sites with differences in indicated range											
	Entire year						Growing season					
	Thornthwaite	Weather Bureau	Lowry-Johnson	Hamon	Blaney-Criddle	Lane	Thornthwaite	Weather Bureau	Lowry-Johnson	Hamon	Blaney-Criddle	Lane
+61 to +70						1						1
+51 to +60						1						1
+41 to +50						1						1
+31 to +40		1				1					1	1
+21 to +30								2				
+11 to +20		1			1			0			1	
+1 to +10		1			2			1			1	
0					0						1	
−1 to −10				1	1		1		2	2		
−11 to −20			2	2			1		1	1		
−21 to −30	2		1	0			2		1	1		
−31 to −40	2		1	1								
Total	4	3	4	4	4	4	4	3	4	4	4	4

TABLE 10.—*Summary of differences between potential evapotranspiration estimated by the six empirical methods and adjusted pan evaporation in a subhumid environment*

Range of differences (percent)	Number of sites with differences in indicated range											
	Entire year						Growing season					
	Thornthwaite	Weather Bureau	Lowry-Johnson	Hamon	Blaney-Criddle	Lane	Thornthwaite	Weather Bureau	Lowry-Johnson	Hamon	Blaney-Criddle	Lane
+41 to +50												1
+31 to +40						3						0
+21 to +30						2						5
+11 to +20						4						4
+1 to +10		1			2						5	
0		0			1						0	
−1 to −10	1	2			4			3	2		5	
−11 to −20	0		5		3		1		4		1	
−21 to −30	1		5	3			4		5	3		
−31 to −40	7			6			5			6		
−41 to −50	1			1			1			2		
Total	10	3	10	10	10	9	11	3	11	11	11	10

To attain water use equivalent to potential evapotranspiration in an arid environment, as at the group 1 sites, irrigation is required to provide an ample water supply (a condition defined as necessary for potential evapotranspiration). Irrigation will modify the microclimate by increasing the humidity of the air; therefore, to obtain a reliable index of the potential evapotranspiration with an evaporation pan, the pan must be exposed to the modified microclimate. In other words, a pan cannot be used at an unirrigated desert site to obtain a measure of the potential evapotranspiration at that site. Evaporation data so obtained provide a spurious standard for judging the reliability of other methods of computing potential evapotranspiration in an arid environment.

We used this standard at our group 1 sites, and it is therefore not surprising that the methods gave values of potential evapotranspiration that were generally lower than the adjusted pan evaporation. The methods that used arid-land data in their derivation were based on water use by irrigated crops, and these methods therefore should not be tested against evaporation from a pan set in an unirrigated desert environment. Group 1 data were therefore eliminated from consideration in determining which of the six methods was best.

Consequently, the results of this study clearly indicated that of the six, the Blaney-Criddle and Weather Bureau methods are the most effective for estimating potential evapotranspiration. At all 15 sites in the subhumid and modified arid environments, potential evapotranspiration computed by the Blaney-Criddle method checked the adjusted pan evaporation within ±22 percent. Potential evapotranspiration computed by the Weather Bureau method also checked the adjusted pan evaporation within ±22 percent at the six group 2 and group 3 sites where it was used. This percentage range is generally accepted as the range of reliability of the regional pan-evaporation coefficients used to determine lake evaporation.

Potential evapotranspiration computed by the Weather Bureau method agreed with adjusted pan evaporation equally well in all three environments tested. This was expected as this is all the method attempts to do. The Blaney-Criddle method however attempts to predict the potential evapotranspiration that would occur under a condition that can only exist in the presence of an ample water supply. Thus, under conditions required for potential evapotranspiration to be achieved, both the Blaney-Criddle and the Weather Bureau methods give satisfactory results. Because of the general unavailability of the climatological data required for the Weather Bureau method, the Blaney-Criddle method was concluded to be the most practical for use.

SUMMARY AND CONCLUSIONS

This study compared potential evapotranspiration, computed from climatological data by each of six empirical methods, with pan evaporation adjusted to equivalent lake evaporation by coefficients. The comparison is based on the assumption that evaporation from a shallow lake approximates the potential evapotranspiration in the local area. The time periods used for the comparisons were the calendar year and the growing season, May through October. In general, the values compared were 10-year averages for these two periods. The six methods compared were the Thornthwaite, Weather Bureau (a modification of the Penman method), Lowry-Johnson, Hamon, Blaney-Criddle, and Lane. The region selected for the study was the arid and subhumid areas of Arizona, California, and Nevada.

Twenty-five sites, where pan-evaporation and concurrent climatological data were available, were used in the study. Of these sites, 5 were in Arizona, 17 were in California, and 3 were in Nevada. The lack of some types of climatological data at various sites made it impossible to use all six methods at all sites. The 25 sites included a wide range of climatic conditions. Ten of the sites (group 1) were in a highly arid environment and four of them (group 2) were in an arid environment that was modified by extensive irrigation. The remaining 11 sites (group 3) were in a subhumid environment. The term "subhumid," as used here, refers to an environment marked by summers that are dry and cool relative to the arid environment and winters that have relatively high precipitation.

For the wide range of climatic conditions in this study, only the Weather Bureau method gave estimates of potential evapotranspiration that closely agreed with the adjusted pan evaporation at all sites where the method was used. However, lack of the required climatological data restricted the use of the Weather Bureau method to seven sites. Results obtained by use of the Thornthwaite, Lowry-Johnson, and Hamon methods were consistently low. Results obtained by use of the Lane method agreed with adjusted pan evaporation at the group 1 sites, but were consistently high at the group 2 and 3 sites.

During the analysis it became apparent that adjusted pan evaporation in an arid environment (group 1 sites) is a spurious standard for judging the reliability of the methods that were tested. To attain water use equivalent to potential evapotranspiration in an arid environment, as at the group 1 sites, it is necessary to irrigate to provide an ample water supply. Irrigation will modify the microclimate by increasing the humidity of the air. Therefore, to obtain a reliable index of the potential evapotranspiration with an evaporation pan, it is necessary that the pan be exposed to the modified microclimate. The evaporation pans at the group 1 sites do not meet this criterion; those at the group 2 sites do. Group 1 data were accordingly eliminated from consideration as to which of the six methods was the best.

The results of this study indicated the Blaney-Criddle method, which uses climatological data that can be readily obtained or deduced, to be the most practical of the six methods for estimating potential evapotranspiration. At all 15 sites in the two environments, potential evapotranspiration computed by the Blaney-Criddle method checked the adjusted pan evaporation within ±22 percent. This percentage range is generally considered to be the range of reliability of pan-evaporation coefficients.

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