TECHNICAL NOTE

USDA NATURAL RESOURCES CONSERVATION SERVICE HAWAII

Engineering Technical Note - No. 2

ESTIMATING CONSUMPTIVE USE IN HAWAII

This coversheet transmits a copy of a technical note entitled "Estimating Consumptive Use in Hawaii." It is the re-release of a technical note originally written and sent out in May 1980.

The technical note covers procedures that may be used to estimate irrigation water requirements in Hawaii, which are still relevant today.

TECHNICAL NOTES

U.S. DEPARTMENT OF AGRICULTURE — HONOLULU, HAWAII — SOIL CONSERVATION SERVICE

ENGINEERING NO. 14

May 1980

ESTIMATING CONSUMPTIVE USE IN HAWAII

Introduction

This paper covers procedures that may be used to estimate irrigation water requirements on a farm or for a project in Hawaii. Because of the equations involved, it is intended that these procedures would be used by specialists in developing irrigation guides or project measures and not by field personnel.

Consumptive use of water, or evapotranspiration, is the amount of water used by the vegetative growth of a given area in transpiration and building of plant tissue, and that evaporated from adjacent soil or intercepted precipitation on the plant foliage in any specified time. Consumptive use is usually expressed as acre inches per acre or depth in inches.

Procedures for Estimation

In areas for which few or no measurements of consumptive use are available, it is usually necessary to estimate consumptive use of crops from climatological data. For this purpose, the Soil Conservation Service commonly uses the Blaney-Criddle method as it is described in TR-21.1/

The Blaney-Criddle method is based on an empirical relationship between evapotranspiration and mean air temperature and mean percentage of daytime hours. It does not take into account the effects of humidity, sunshine and wind. In Hawaii, mean air temperature and mean percentage of daytime hours do not vary very much throughout the year, as compared to the western states on the mainland. The variations in evapotranspiration that do occur in Hawaii are more related to variations in sunshine, wind and humidity than variations in air temperature and percentage of daytime hours. Since TR-21 does not consider solar radiation, wind, and humidity, it has not been used in Hawaii.

1/ "Irrigation Water Requirements," Technical Release No. 21, USDA-SCS Engineering Division (Revised September 1970).

Prepared by Dean M. Renner, Civil Engineer, Technical Support Staff

The Soil Conservation Service has been using pan evaporation for estimating consumptive use in Hawaii for several years.2/ Also, the sugar plantations use pan evaporation measurements as an index of the consumptive use of sugarcane. The sugar plantations have installed and maintained many pan evaporation stations in Hawaii.3/

There are problems in trying to use pan evaporation in estimating irrigation requirements. The pan evaporation data available is for stations located on sugarcane lands. There is very little data available for areas that are in diversified agriculture. For the pan evaporation data that is available, there is considerable variation due to pan environment at the micro level (pan height, vegetation around the pan, and wind). Because of these factors, it has not been possible to extrapolate estimated pan evaporation to areas where there are no pan stations.

A widely known method of estimating consumptive use of crops that considers temperature, humidity, wind, sunshine and elevation is the modified Penman equation.4/ The modified Penman equation will be the method used in this paper for estimating irrigation water requirements in Hawaii. This method should be more accurate for Hawaii than the Blaney-Criddle method since it considers more parameters, and it will not have the variability problems that occur using pan evaporation data.

The modified Penman equation estimates the evapotranspiration from well-watered alfalfa of uniform height and completely shading the ground. This well-watered short grass is considered a reference crop and its evapotranspiration will be referred to as ET_o.

To estimate the evapotranspiration of a crop, ET(crop), a crop coefficient, K_c, is applied to the reference crop evapotranspiration. The crop coefficients are based on the type of crop, its stage of development, and prevailing climatic conditions.5/ ET(crop) is found by $ET(crop) = K_c ET_o$.

ET(crop) estimated by this means refers to the evapotranspiration of a disease-free crop, growing in a large field under optimal soil conditions including sufficient water and fertility and achieving the full production potential of the crop under the given growing environment. Local conditions and agricultural practices may have an effect on ET(crop) which might require some correction.

2/ Blewitt, Ronald I, "Estimating Consumptive Use for Crops in Hawaii," Technical Note, Engineering No. 10, USDA-SCS, Honolulu, HI, March 1960.

3/ "Pan Evaporation in Hawaii 1894-1970," Report R51, State of Hawaii, Dept. of Land and Natural Resources, Honolulu, HI, January 1973.

4/ "Consumptive Use of Water and Irrigation Water Requirements," American Society of Civil Engineers, 1973.

5/ Doorenbos, J., and Pruitt, W.O., "Guidelines for Prediction of Crop Water Requirements," FAO Irrigation and Drainage Paper No. 25, FAO, Rome, 1974.

The Modified Penman Equation

The modified Penman equation for estimating the evapotranspiration from a well-watered short grass is:

$$ET_o = \frac{\Delta}{\Delta + \gamma} (R_n + G) + \frac{\gamma}{\Delta + \gamma} (15.36) (1.0 + 0.0062u_2) (e_z^o - e_z) \quad 4/$$

ET_o is in mm/day. To convert to inches/day, multiply by 0.00673.

Δ is the slope of saturation vapor pressure curve.

$$\Delta = 33.8639 [0.05904 (0.00738 \text{ Tmean} + 0.8072)^7 - 0.0000342]$$

where Tmean is mean temperature in degrees centigrade.

γ is the psychrometric constant.

$$\gamma = \frac{C_p P}{0.622 \lambda}$$

λ is the latent heat of vaporization.

$\lambda = 595 - 0.51$ Tmean, cal/gram

C_p is the specific heat of dry air at constant pressure

$C_p = 0.242$

P is the atmospheric pressure.

P = 1013 - 0.1055 E mb

E = elevation in meters.

Thus γ becomes:

$$\gamma = \frac{0.242 (1013 - 0.1055 E)}{0.622 (595 - 0.51 \text{ Tmean})}$$

4/ "Consumptive Use of Water and Irrigation Water Requirements," American Society of Civil Engineers, 1973.

R_n is the net solar radiation

$$R_n = 0.77R_s - \left[1.22 \frac{R_s}{R_{so}} - 0.18\right] \left[(0.325 - 0.44\sqrt{e_d}) \left(\frac{11.71}{10^8}\right) (Tmean+273)^4\right]$$

R_s is the mean observed solar radiation in cal/cm^2/day

R_{so} is the mean cloudless day solar radiation in, cal/cm^2/day, received at the earth's surface.

e_d is the mean vapor pressure at mean dewpoint temperature ($^\circ$C) in, mb, where:

$$e = 33.8639 \left[(0.00738\ Tmean + 0.8072)^8 - 0.000019\ (1.8\ Tmean + 48) + 0.001316\right]$$

G is the estimated mean soil heat flux in cal/cm^2/day

$$G = \frac{T_{i-1} - T_{i+1}}{\Delta t}\ (100),$$ where:

T_{i-1} is the mean air temperature, previous month, $^\circ$C.

T_{i+1} is the mean air temperature, following month, $^\circ$C.

Δ_t is the time in days between the midpoints of the two periods.

u_2 is the mean wind movement at a height of 2.0 meters in km/day. To convert from x meter height to 2.0 meter height, use the following relationship:

$$u_2 = u_x \left(\frac{2.0}{x}\right)^{0.2}$$

$(e_z^o - e_d)$ is the vapor saturation deficit, where:

e_z^o is the mean saturation vapor pressure in, mb.
This is the average of the e^o at mean maximum
air temperature and at mean minimum air temperature.

Thus:

$$(e_z^o - e_d) = \left(\frac{e^o \text{ at Tmax} + e^o \text{ at Tmin}}{z}\right) - e_d$$

The input data required to calculate ET_o by these equations is:

Mean maximum air temperature, ^oC

Mean minimum air temperature, ^oC

Mean air temperature, ^oC

Mean dewpoint temperature, ^oC

Mean wind movement, km/day

Height of wind measurement, meters

Mean cloudless day solar radiation, $cal/cm^2/day$

Mean observed solar radiation, $cal/cm^2/day$

Mean temperature, previous month, ^oC

Mean temperature, following month, ^oC

Time interval in days between midpoints

Elevation, meters.

A program has been developed for a programable calculator to calculate ET_o using the modified Penman equation. A copy of the listing of this program is in Appendix A.

This program was designed to calculate average monthly ET_o in inches per day. The program also converts the units on the input data. The data on a monthly basis needed to run this program is:

Mean maximum air temperature, ^oF

Mean minimum air temperature, ^oF

Mean dewpoint temperature, ^oF

Average wind speed, mph.

Mean cloudless day solar radiation, cal/cm^2/day

Mean observed solar radiation, cal/cm^2/day

Mean temperature, previous month, ^oF

Mean temperature, following month, ^oF

Elevation, ft.

Height of wind gage, ft.

Use of Modified Penman Equation in Hawaii

The problem with using the modified Penman equation in Hawaii is that there are no historical climatological stations in Hawaii that record all the data needed. For any climatological station that is used some of the data must be estimated.

The following procedures may be used for estimating the data required for the modified Penman equation. ET_o should be calculated by month. Existing temperature, rainfall, wind, and solar radiation data is available in monthly values.

The islands which make up the State of Hawaii are a series of mountains which rise from the ocean floor. This results in a rugged terrain which produces variations in climatic conditions from one location to another. Air that is brought in by trade winds has to move over and around the mountains. The resulting air flow becomes very complex and results in great differences from place to place in windspeed, cloudiness, and rainfall. Also, the air temperature varies with the elevation of the land. Because of these variations in climatic conditions, estimations of climatological data cannot be made on a statewide or islandwide basis, but must be made for local areas of consideration in an island or similar areas between islands.

To keep the local area of consideration for making estimates of climatological data as small as possible, these estimates can be developed using hydrographic areas and U.S. Geological Survey quad sheets.

Due to the variations in climatic conditions throughout the islands ET_o should be estimated at as many climatologic stations as possible. There is a considerable network of rainfall gages in Hawaii.6/ It is also possible to determine elevations throughout the state using USGS quad sheets. Temperature and solar radiation can be estimated by relating to elevation and rainfall.

Temperature Data

Mean air temperature varies with elevation, cloudiness, and wind. Within a quad sheet in a hydrographic area, a relationship between elevation and mean air temperature can be developed. Using this type of a relationship, the mean monthly temperature values can be estimated at rainfall stations that have no recorded temperature data.

To make a relationship between temperature and elevation, use climatologic stations with temperature data in the quad sheet and hydrographic area being

6/ "Climatologic Stations in Hawaii," Report R42, State of Hawaii, Dept. of Land and Natural Resources, Honolulu, HI, January 1973.

considered that are listed in Climatological Data.[7] Enough stations are needed to make a linear regression between temperature and elevation for each temperature parameter.

Solar Radiation

Insolation is the solar radiation received at the earth's surface. Yoshihara and Ekern[8] suggested that median annual rainfall and mean annual insolation can be correlated. They also suggested that a relationship may exist between mean monthly insolation and mean annual insolation.

To estimate observed solar radiation at a rainfall station that has no recorded solar radiation values, the mean annual insolation can be estimated first using an annual rainfall versus annual insolation relationship. The monthly insolation can be estimated from the annual insolation.

A relationship between mean annual insolation and rainfall has been developed for each hydrographic area in Hawaii. This relationship is expressed as a power function:

$$I_a = aP^b$$

where I_a = mean annual insolation, $cal/cm^2/day$

P = mean annual rainfall inches

Values for a and b are listed in Table 1 for each hydrographic area.

For the solar radiation stations in each hydrographic area and quad sheet, a relationship between monthly insolation and mean annual insolation can be made using the following equation:

$$\frac{I_m}{I_{cm}} = A + B\,\frac{I_a}{I_{ca}} \quad \text{8/}$$

where I_m = mean monthly insolation, $cal/cm^2/day$

I_{cm} = theoretical clear-sky mean monthly insolation, $cal/cm^2/day$

I_a = mean annual insolation, $cal/cm^2/day$

I_{ca} = theoretical clear-sky mean annual insolation, $cal/cm^2/day$

Table 2 contains the values of I_{cm} and I_{ca}.

7/ "Climatological Data Hawaii and Pacific," National Oceanic and Atmospheric Administration, National Climatic Center, Asheville, NC.

8/ Yoshihara, Takeshi, and Ekern, Paul C., "Solar Radiation Measurements in Hawaii," The Hawaii Natural Energy Institute, University of Hawaii, September 1977.

Dewpoint Temperature

The only locations where dewpoint temperatures are recorded in Hawaii are at the airport weather stations. The difference between annual mean air temperature and dewpoint temperature was related to median annual rainfall. The monthly differences between mean air temperature and dewpoint temperature were related to the annual differences between mean air temperature and dewpoint temperature. The relationship between annual mean air temperature minus dewpoint temperature and median annual rainfall is expressed by the equation:

$$T = 24.3P^{-.26}$$

where T = annual Tmean-Tdew °F

P = annual rainfall inches

For stations above 4000 ft. elevation use:

$$T = 25°F$$

The relationships between annual and monthly values of the difference between mean air temperature and dewpoint temperature are expressed by the equation:

$$M = mT+b$$

where M = monthly Tmean-Tdew °F

T = annual Tmean-Tdew °F

Values for the slope m and the intercept b are listed in Table 3 for each month.

Wind

There is little published wind information for the state of Hawaii. Airport and harbor weather stations traditionally maintain continuous wind records and provide much of the long-term wind data. A summary of wind data at airport stations in Hawaii is shown on Table 4.

General estimates of wind velocity[5/] are shown on Table 5. For truck crops the wind level will probably be light or moderate, due to the installation of

5/ Doorenbos, J., and Pruitt, W.O., "Guidelines for Prediction of Crop Water Requirements," FAO Irrigation and Drainage Paper No. 25, FAO, Rome, 1974.

windbreaks or the crops being grown in sheltered locations. For field crops the wind level will probably be moderate, strong, or very strong.

For estimating ET_o an average annual wind velocity of 11 mph can be used with a gage height of 22 ft. Also, the ratio of ET_o calculated at annual wind velocities of 4.5 and 18 mph to that of ET_o calculated at an annual velocity of 11 mph can be made. The monthly distribution of these average annual velocities that are shown on Table 6 should be used for calculating ET_o.

Crop Coefficients

Crop coefficients applicable to the method for estimating ET_o described in this paper for Hawaii are listed in Table 7.

These crop coefficients were determined by comparing ET_o estimated by the modified Penman equation with published reports of consumptive use of lettuce[11/], [12/] and sugarcane[13/]. For crops other than lettuce and sugarcane the crop coefficients are based on the crop coefficients by Doorenbos and Pruitt[5/], modified using the crop coefficients for lettuce and sugarcane.

5/ Doorenbos, J., and Pruitt, W.O., "Guidelines for Prediction of Crop Water Requirements," FAO Irrigation and Drainage Paper No. 25, FAO, Rome, 1974.

11/ Wu, I-pai, and Gitlin, Harris M., "Irrigation Schedule for Lettuce," Sketches and Doodles from the Engineer's Notebook, Number 101, Sept. 1977, Cooperative Extension Service, University of Hawaii.

12/ Wu, I-Pai, and Gitlin, Harris M., "Optimal Irrigation Application for Lettuce," Sketches and Doodles from the Engineer's Notebook, Number 102, October 1977, Cooperative Extension Service, University of Hawaii.

13/ Ekern, Paul C., "Consumptive Use of Water by Sugarcane," Technical Report No. 37, Water Resources Research Center, University of Hawaii, Honolulu, HI, July 1970.

TABLE 1

Annual Insolation vs. Annual Rainfall

$I_a = aP^b$

where I_a = annual insolation

P = annual rainfall

Island	Hydrographic Area	a	b	r
Kauai	21	712	-.14	-.53
	22	1305	-.28	-.66
	23	693	-.11	-.43
	24			
	25	600	-.09	-.25
Oahu	31	636	-.10	-.85
	32	1348	-.35	-.93
	33	1577	-.33	-.98
	34	880	-.20	-.57
	35			
	36	1259	-.29	-.65
Molokai	41			
	42			
	43			
	44			
Lanai	51			
	52			
Maui	61	616	-.08	-.57
	62	1083	-.29	-.88
	63	598	-.06	-.72
	64			
	65			
Hawaii	81	1321	-.27	-.74
	82	1357	-.25	-.52
	83	1653	-.39	-.88
	84	649	-.10	-.98
	85	1888	-.38	-.91

TABLE 2

Mean Cloudless Day Solar Radiation
($cal/cm^2/day$)

Latitude	Monthly (Icm)												Annual
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	(Ica)
18° 52' 30"	510	643	656	718	722	754	724	694	684	603	547	484	644
19° 00' 00"	509	642	656	719	722	755	724	694	683	602	546	483	644
19° 07' 30"	508	641	655	719	723	755	725	695	683	602	545	482	644
19° 15' 00"	507	640	655	719	723	756	726	695	682	601	543	481	643
19° 22' 30"	506	639	654	719	724	757	726	695	682	600	542	480	643
19° 30' 00"	505	638	654	719	724	757	727	696	682	600	541	478	643
19° 37' 30"	503	637	653	719	725	758	727	696	681	599	540	477	642
19° 45' 00"	502	636	653	720	725	759	728	696	681	598	539	476	642
19° 52' 30"	501	635	652	720	726	759	728	697	680	598	538	475	642
20° 00' 00"	500	634	652	720	726	760	729	697	680	597	537	474	642
20° 07' 30"	499	633	651	720	726	760	729	697	679	596	536	473	642
20° 16' 30"	498	632	651	720	727	761	730	697	679	595	534	471	641
20° 34' 30"	495	630	649	720	728	762	731	698	678	593	531	468	640
20° 42' 30"	494	628	649	720	728	763	731	698	677	592	530	467	640
20° 50' 00"	493	628	648	720	729	763	732	698	677	591	529	465	639
20° 57' 30"	491	627	648	720	729	764	732	698	676	590	527	464	639
21° 05' 00"	490	626	647	720	729	764	732	698	676	589	526	463	638
21° 11' 15"	489	625	647	720	729	765	733	698	675	588	525	462	637
21° 13' 15"	489	624	646	720	729	765	733	698	675	588	524	462	637
21° 15' 00"	489	624	646	720	729	765	733	699	675	588	524	461	637
21° 22' 30"	488	623	646	720	730	766	734	699	674	588	523	460	637
21° 30' 00"	487	622	645	720	731	766	734	699	674	586	522	459	636
21° 37' 30"	485	621	645	720	731	767	734	699	673	585	520	457	636
21° 45' 00"	484	620	644	720	732	767	735	699	673	584	519	456	636
21° 52' 00"	483	619	643	720	732	767	735	699	673	584	518	455	636
21° 59' 00"	482	619	643	720	732	768	735	699	672	582	517	454	635
22° 07' 00"	481	617	642	720	733	768	736	700	672	582	515	452	635
22° 14' 30"	480	617	642	720	733	769	736	700	671	581	514	451	634

Data from Table 3.1, p. 22 of Reference 4/

TABLE 3

Tmean-Tdew of annual vs. monthly

M = mT+b

M = monthly Tmean-Tdew °F

T = annual Tmean-Tdew °F

Mo.	m	b
Jan.	0.27	5.6
Feb.	0.39	5.2
Mar.	0.63	2.7
Apr.	0.95	-0.1
May	0.92	1.1
June	0.98	1.4
July	1.14	-0.5
Aug.	1.30	-1.7
Sep.	0.86	2.2
Oct.	0.94	0.5
Nov.	0.75	1.9
Dec.	0.67	2.2

TABLE 4

Airport Wind Data

Month	Airport Stations				
	Lihue Ave. Vel. mph	Honolulu Ave. Vel. mph	Kahului Ave. Vel. mph	Hilo Ave. Vel. mph	Average Velocity mph
Jan.	10.3	9.9	11.0	7.4	9.65
Feb.	11.3	10.7	11.2	7.8	10.25
March	11.8	11.6	12.4	7.6	10.85
April	12.4	12.2	13.3	7.4	11.3
May	12.0	12.2	13.3	7.2	11.2
June	12.4	12.9	14.8	7.1	11.8
July	13.0	13.7	16.0	6.9	12.4
Aug.	12.7	13.5	15.0	6.8	12.0
Sept.	11.3	11.7	12.9	6.7	10.65
Oct.	10.9	10.9	12.0	6.7	10.1
Nov.	11.6	11.0	11.7	6.7	10.25
Dec.	11.4	11.1	11.6	7.2	10.3
Average	11.7	11.8	13.0	7.1	10.9
Gage ht. ft.	20	25	21	21	22

TABLE 5

General Wind Levels 5/

General Wind Level	Velocity Range (mph)
light	less than 4.5
moderate	4.5 to 11
strong	11 to 18
very strong	greater than 18

With 4.5 mph - wind is felt on face and leaves start to rustle.

With 11 mph - twigs move; paper blows away; flags fly.

With 18 mph - dust rises; small branches move.

With greater than 18 mph - small trees start to move; waves form on inland waters.

TABLE 6

Average Wind Velocities By Month

Month	Annual 11.0 mph	Annual 4.5 mph	Annual 18.0 mph
January	9.8 mph	4.0 mph	16.0 mph
February	10.3 mph	4.2 mph	16.9 mph
March	11.0 mph	4.5 mph	18.0 mph
April	11.4 mph	4.7 mph	18.7 mph
May	11.3 mph	4.6 mph	18.5 mph
June	11.9 mph	4.9 mph	19.4 mph
July	12.5 mph	5.1 mph	20.5 mph
August	12.1 mph	4.95 mph	19.8 mph
September	10.8 mph	4.4 mph	17.6 mph
October	10.2 mph	4.2 mph	16.7 mph
November	10.3 mph	4.2 mph	16.9 mph
December	10.3 mph	4.2 mph	16.9 mph

TABLE 7

Crop Coefficients

Crop	Crop Stage	K_c
All truck crops	Initial	0.50
	Development	0.50
Lettuce	Mid Season	0.80
	Late Season	0.50
Cabbage	Mid Season	0.89
Broccoli	Late Season	0.75
Onion	Mid Season	0.89
	Late Season	0.70
Carrots	Mid Season	0.94
	Late Season	0.66
Potato (Irish)	Mid Season	0.99
	Late Season	0.66
Sweet Potato	Mid Season	0.94
	Late Season	0.63
Sugarcane (drip)	0-2.0 month	0.40
	2.0-6 month	0.72
	6-12 month	0.75
	12-24 month	0.86

REFERENCES

1/"Irrigation Water Requirements," Technical Release No. 21, USDA-SCS Engineering Division (Revised September 1970).

2/Blewitt, Ronald I, "Estimating Consumptive Use for Crops in Hawaii," Technical Note, Engineering No. 10, USDA-SCS, Honolulu, HI, March 1960.

3/"Pan Evaporation in Hawaii 1894-1970," Report R51, State of Hawaii, Dept. of Land and Natural Resources, Honolulu, HI, January 1973.

4/"Consumptive Use of Water and Irrigation Water Requirements," American Society of Civil Engineers, 1973.

5/Doorenbos, J., and Pruitt, W.O., "Guidelines for Prediction of Crop Water Requirements," FAO Irrigation and Drainage Paper No. 25, FAO, Rome, 1974.

6/"Climatologic Stations in Hawaii," Report R42, State of Hawaii, Dept. of Land and Natural Resources, Honolulu, HI, January 1973.

7/"Climatological Data Hawaii and Pacific," National Oceanic and Atmospheric Administration, National Climatic Center, Asheville, NC.

8/Yoshihara, Takeshi, and Ekern, Paul C., "Solar Radiation Measurements in Hawaii," The Hawaii Natural Energy Institute, University of Hawaii, September 1977.

9/How, Karl T. S., "Solar Radiation in Hawaii 1932-1975," Report R57, State of Hawaii, Dept. of Land and Natural Resources, Div. of Water and Land Development, Honolulu, HI, January 1978.

10/"Rainfall of the Hawaii Islands," State of Hawaii, Hawaii Water Authority, September 1959.

11/Wu, I-pai, and Gitlin, Harris M., "Irrigation Schedule for Lettuce," Sketches and Doodles from the Engineer's Notebook, Number 101, Sep. 1977, Cooperative Extension Service, University of Hawaii.

12/Wu, I-pai, and Gitlin, Harris M., "Optimal Irrigation Application for Lettuce," Sketches and Doodles from the Engineer's Notebook, Number 102, October 1977, Cooperative Extension Service, University of Hawaii.

13/Ekern, Paul C., "Consumptive Use of Water by Sugarcane," Technical Report No. 37, Water Resources Research Center, University of Hawaii, Honolulu, HI, July 1970.

APPENDIX A

ETo by Modified Penman Method Program

Hewlett-Packard 9825A Calculator 9871A Printer Program

Title: ET_o by Modified Penman Method 0-27

Development Date: 10-2-78

Revision Date: 6-5-79

Program Number:

Programmed by: SCS Honolulu Dean Renner

Program Status: Operational

Reviewed by:

Approved:

Equipment: Program developed for the Hewlett-Packard 9825A Calculator and 9871A Printer.

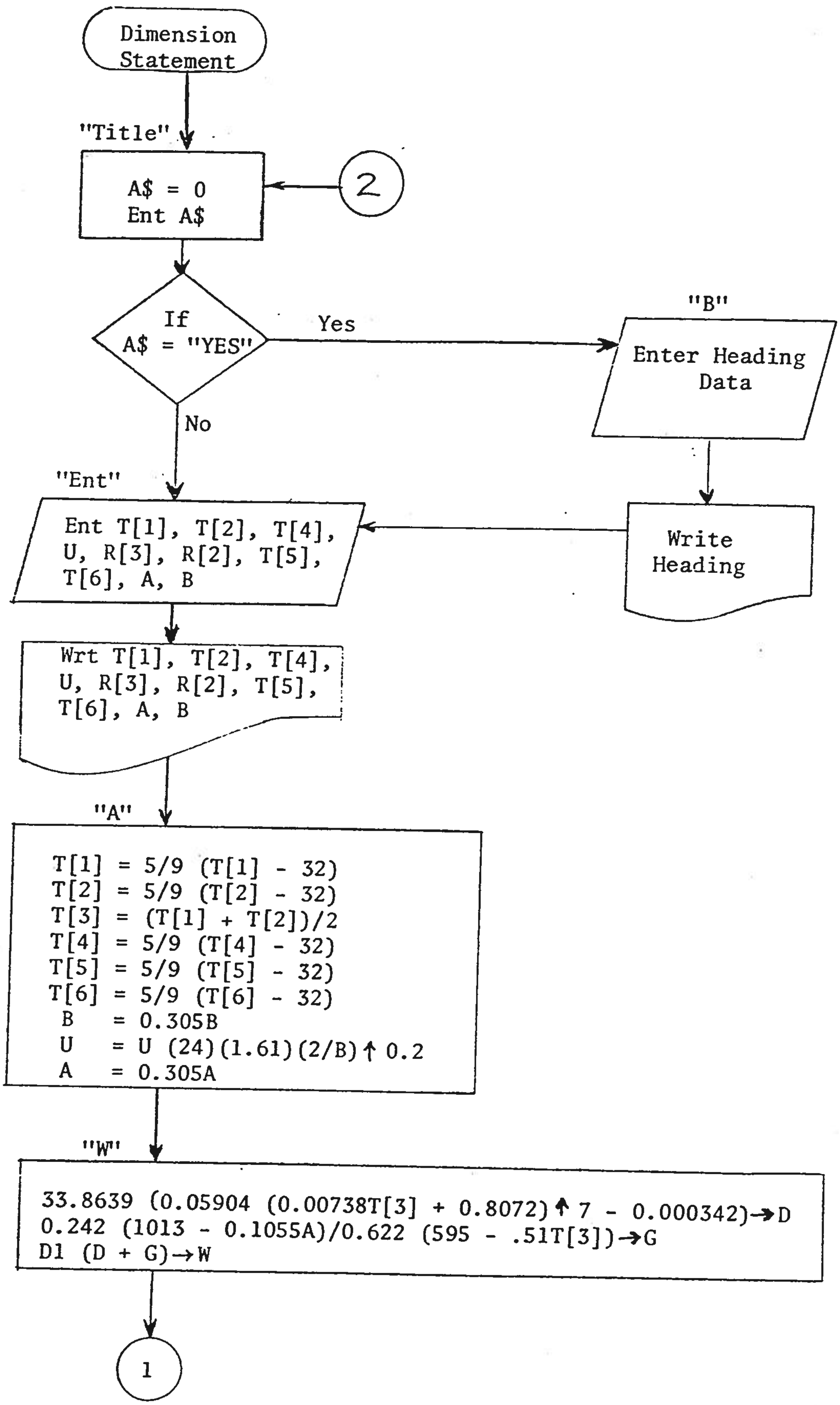
VARIABLES

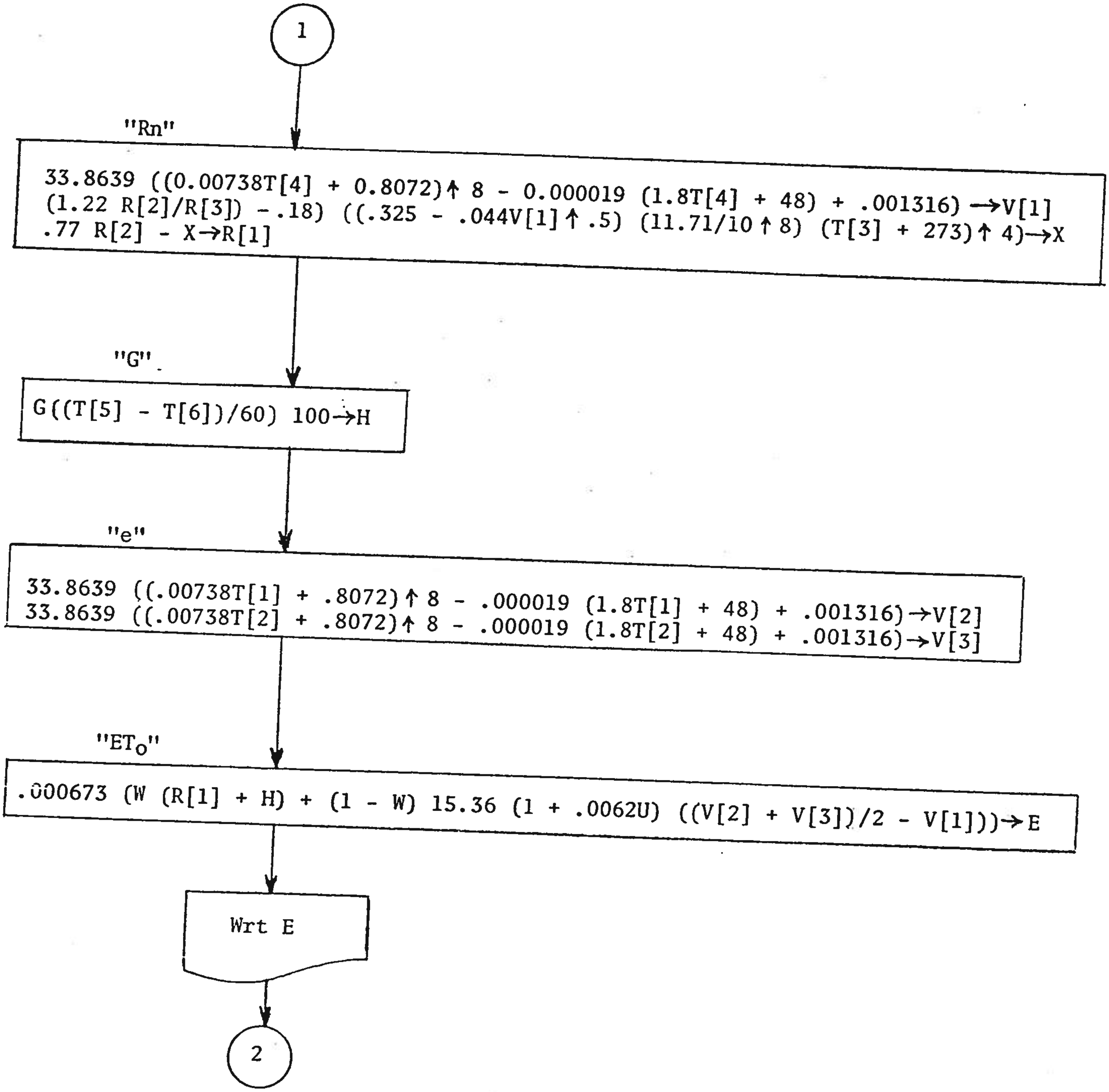
ET_o by Modified Penman Method Program

Variable	Description
T[1]	Tmax °F
T[2]	Tmin °F
T[3]	Tmean °F
T[4]	Mean Dewpoint Temperature °F
U	U_2, Average Wind Speed mph.
R[1]	Net Solar Radiation R_n
R[2]	Mean Observed Solar Radiations R_s
R[3]	Cloudless Day Solar Radiation R_{so}
T[5]	Tmean °F, Previous Month
T[6]	Tmean °F, Following Month
A	Elevation ft.
B	Wind Gage Height ft.
D	Δ
G	γ
W	W
V[1]	e_d, Mean Vapor Pressure at Dew Point Temperature
V[2]	e_{tmax}, Mean Vapor Pressure at Tmax
V[3]	e_{tmin}, Mean Vapor Pressure at Tmin
H	G, Estimated Mean Soil Heat Flax
E	ET_o, in./day

FLOW CHART

ET_o by Modified Penman Method Program




1
"Rn"
33.8639 ((0.00738T[4] + 0.8072)↑8 - 0.000019 (1.8T[4] + 48) + .001316) →V[1]
(1.22 R[2]/R[3]) -.18) ((.325 - .044V[1]↑.5) (11.71/10↑8) (T[3] + 273)↑4)→X
.77 R[2] - X→R[1]
"G"
G((T[5] - T[6])/60) 100→H
"e"
33.8639 ((.00738T[1] + .8072)↑8 - .000019 (1.8T[1] + 48) + .001316)→V[2]
33.8639 ((.00738T[2] + .8072)↑8 - .000019 (1.8T[2] + 48) + .001316)→V[3]
"ETo"
.000673 (W (R[1] + H) + (1 - W) 15.36 (1 + .0062U) ((V[2] + V[3])/2 - V[1]))→E
Wrt E
2

Hewlett-Packard 9825A Calculator 9871A Printer Program

Title: ETo by Modified Penman Method 0-27

```
0: prt "ETo by Modified Penman Method";spc 2
1: dim T[6],R[3],V[3],A$[10],B$[6,40],C$[6]
2: "Title":"0"+A$
3: ent "If you wish a Heading enter Yes",A$
4: if cap(A$)="YES";gto "B"
5: gto "Ent"
6: "B":
7: ent "enter Your Initials",B$[5],"enter Date",B$[6]
8: fmt 1,2b,33x,"ETo by Modified Penman Method",15x,"By: ",c3
9: fmt 2,77x,"Date: ",c8,3b
10: wrt 6.1,10,10,B$[5]
11: wrt 6.2,B$[6],13,10,10
12: ent "Station Name and Key No ?",B$[1],"Month :",B$[2]
13: ent "Quad Sheet ?",B$[3],"Enter Vegetation Zone",B$[4]
14: fmt 3,25x,"Station:",c40,"  Month:",c10
15: fmt 4,25x,"Quad Sheet:",c6,6x,"Vegetation Zone:",c4,b
16: wrt 6.3,B$[1],B$[2]
17: wrt 6.4,B$[3],B$[4],10
18: fmt 5," Month",4x,"Tmax",4x,"Tmin",2x,"Dewpoint",2x,"Ave",5x,"I cm"
19: fmt 6,49x,2b," Im   ",3x,"Previous",1x,"Next",4x,"Elev",4x,"Wind     ETo"
20: fmt 7,3x,"or      oF      oF    Tmean    Wind   Solar   Solar    Month"
21: fmt 8,66x,2b,"Month     ft    :gage   in/day"
22: fmt 9,"  Sta ",21x,"oF      mph      Rad      Rad     Tmean oF Tmean oF"
23: fmt 1,82x,2b,"ht ft"
24: wrt 6.5;wrt 6.6,27,10;wrt 6.7;wrt 6.8,27,10;wrt 6.9;wrt 6.1,27,10
```

```
25: "Ent":
26: ent "Tmax deg F",T[1],"Tmin deg F",T[2],"Mean Dewpoint T deg F",T[4]
27: ent "Ave Wind mph",U,"Theoretic Clear Sky Sol Rad Icm",R[3]
28: ent "Actual Solar Rad Im",R[2],"Tmean deg F previous month",T[5]
29: ent "Tmean deg F following month",T[6],"Elevation ft",A
30: ent "Wind gage ht ft",B
31: ent "enter Month or Station Number",C$
32: fmt 2,c6,10f8.1
33: wrt 6.2,C$,T[1],T[2],T[4],U,R[3],R[2],T[5],T[6],A,B
34: "A":(5/9)(T[1]-32)→T[1];(5/9)(T[2]-32)→T[2];(T[1]+T[2])/2→T[3]
35: (5/9)(T[4]-32)→T[4];(5/9)(T[5]-32)→T[5];(5/9)(T[6]-32)→T[6];.305B→B
36: U(24)1.61(2/B)^.2→U;.305A→A
37: "W":33.8639(.05904(.00738T[3]+.8072)^7-.0000342)→D
38: .242(1013-.1055A)/.622(595-.51T[3])→G;D/(D+G)→W
39: "Rn":33.8639((.00738T[4]+.8072)^8-.000019(1.8T[4]+48)+.001316)→V[1]
40: (1.22(R[2]/R[3])-.18)((.325-.044V[1]^.5)(11.71/10^8)(T[3]+273)^4)→X
41: .77R[2]-X→R[1]
42: "G":((T[5]-T[6])/60)100→H
43: "e":33.8639((.00738T[1]+.8072)^8-.000019(1.8T[1]+48)+.001316)→V[2]
44: 33.8639((.00738T[2]+.8072)^8-.000019(1.8T[2]+48)+.001316)→V[3]
45: "ETo":.000673(W(R[1]+H)+(1-W)15.36(1+.0062U)((V[2]+V[3])/2-V[1]))→E
46: fmt 3,8x,2b,f8.2
47: wrt 6.3,27,10,E
48: gto "Title"
*12972
```

APPENDIX B

Example Calculations for ET_o

Procedure for ET_o Estimation

General

ET_o will be calculated by quad sheet. Hydrographic areas will also be considered, so if a quad sheet is subdivided by hydrographic areas, ET_o will be calculated for each hydrographic area on the quad sheet.

Solar Radiation (Insolation) is the most difficult parameter to determine for the Modified Penman Method. ET_o will be calculated at stations where Solar Radiation can be estimated. Since solar radiation may be correlated to rainfall, ET_o will be calculated at those stations that have rainfall records.

One station in each quad sheet in a hydrographic area will be used as a reference station.

For the reference station, ET_o will be calculated for each month of the year. For the other stations on the quad sheet, ET_o will only be calculated for the peak month and will be estimated for the other months from the ratios of peak month ET_o.

Prepare worksheets 1 through 7 as shown on the attached example.

Stations

1. ET_o Stations - Determine the climatologic stations for each quad sheet within a hydrographic area that have rainfall data. Report R42, "Climatologic Stations in Hawaii", lists all of the climatologic stations in Hawaii and which quad sheet they are located in.

   On worksheet 1 list these rainfall stations and the mean annual rainfall for each station.

   Rainfall data can be obtained from the State of Hawaii, Department of Land and Natural Resources.

2. The reference station will be a rainfall station in each quad sheet of a hydrographic area which also has temperature and/or solar radiation data. If more than one station in a quad sheet has temperature and/or solar radiation data, use the station with longest combined period of record rainfall, solar radiation, and temperature data.

   If there is no station in a quad sheet of a hydrographic area with temperature or solar radiation data, use a station from an adjoining quad in the hydrographic area.

   List the length of record for each possible reference station on the Reference Station Worksheet.

Indicate on worksheet 1 which station is the reference station.

3. On worksheet 2 list the reference station name and number, quad sheet, and elevation.

Temperature Data

4. On worksheet 2 for the reference station enter the following temperature data for each month:

   a. Mean Maximum Temperature ^oF
   b. Mean Minimum Temperature ^oF
   c. Mean Temperature previous month ^oF
   d. Mean Temperature following month ^oF

Dewpoint Temperature

5. For the reference station determine the Annual Tmean-Tdew using the equation:

$$T = 24.3P^{-.26}$$

where T = annual Tmean-Tdew ^oF

P = annual rainfall inches

For stations above 4000 ft. elevation use:

$$T = 25^oF$$

For each month for the reference station determine the monthly Tmean-Tdew from the annual Tmean-Tdew using the relationships:

$$M = mT+b$$

where M = monthly Tmean-Tdew ^oF

T = annual Tmean-Tdew ^oF

Values for the slope m and the intercept b are listed in Table 3 for each month.

For the reference station for each month determine the Dewpoint Temperature by:

$$Tdew = \frac{Tmax + Tmin}{2} - M$$

Round off the Tdew to the nearest degree, enter on worksheet 2 for each month.

Wind

6. Average annual wind velocities of 4.5, 11, and 18 mph can be used at a gage height of 22 feet. For most cases an average annual velocity of 11 mph will be used.

On worksheet 2 enter the monthly wind velocity from Table 6 for the average annual velocity used.

Solar Radiation

7. On worksheet 1 list the mean annual insolation for any climatological stations listed that have solar radiation data. Solar radiation data can be obtained from report R57, "Solar Radiation in Hawaii 1932-1975." For the stations listed on worksheet 1 which have no solar radiation data determine the actual mean annual insolation using the relationship and values shown on Table 1.

8. For the reference station list the monthly theoretical clear-sky mean monthly insolation from Table 2 on worksheet 2.

9. If the reference station has recorded solar radiation data, list the actual mean monthly insolation on worksheet 2, and go to step 17.

10. If the reference station does not have recorded solar radiation data, list on worksheet 3 the solar radiation stations in the quad sheet in the hydrographic area being considered. If no solar radiation stations are in the quad, go to adjoining quad sheets in the same hydrographic area.

11. For each station listed on worksheet 3 enter:

    a. Latitude

    b. $\frac{I_a}{I_{ca}}$

    c. The average monthly insolation I_m

    d. For each month and station the theoretical clear-sky insolation from Table 2.

    e. For each month and station calculate: $\frac{I_m}{I_{cm}}$

12. By linear regression on worksheet 3 develop the relationship for each month between $\frac{I_m}{I_{cm}}$ and $\frac{I_a}{I_{ca}}$.

$$\frac{I_m}{I_{cm}} = A + B \frac{I_a}{I_{ca}}$$

13. On worksheet 4 enter for each month, A and B determined in step 12.

14. On worksheet 4 enter the annual mean insolation for the reference station from worksheet 1.

15. On worksheet 4 enter the annual mean clear-sky insolation (I_{ca}) from Table 2 for the reference station.

16. On worksheet 4 for the reference station enter for each month the mean clear-sky insolation from Table 2 (I_{cm}).

    Calculate for each month the actual insolation (I_m):

$$I_m = I_{cm} \left(B \frac{I_a}{I_{ca}} + A\right)$$

    Enter I_{cm} and I_m for each month on worksheet 2.

Monthly ET_o Calculation

17. Calculate average monthly ET_o in./day using HP 9825A calculator and the program listed in Appendix A. Determine which month has the peak ET_o.

Other Stations Peak Month ET_o

18. On worksheet 5 enter all the station numbers from worksheet 1 except the reference station.

Temperature Data

19. If any of the stations listed on worksheet 5 have recorded temperature data, enter the following temperature data for the peak month:

    a. Mean maximum temperature ^oF

    b. Mean minimum temperature ^oF

    c. Mean temperature for previous month ^oF

    d. Mean temperature for following month ^oF

Temperature data can be found in "Climatological Data Hawaii and Pacific" by the National Oceanic and Atmospheric Administration.

If all the stations listed on worksheet 5 have recorded temperature data, go to step 22.

20. For stations listed on worksheet 5 that do not have recorded temperature data the temperatures will have to be estimated for the peak month.

On worksheet 6 enter:

a. Elevation and temperature values for temperature stations in the quad sheet and hydrographic area.

If no temperature stations are in the quad sheet, go to adjoining quads in the same hydrographic area.

The temperature values are for peak month: mean maximum temperature ^{o}F, mean minimum temperature ^{o}F, mean temperature for previous month ^{o}F, and mean temperature for following month.

b. By linear regression determine the relationship between elevation and each temperature value:

$T = m(Elev)+b$

Enough stations are needed so that m is negative.

21. Using the relationship developed in step 20b., calculate the following values for the stations without recorded temperature data on worksheet 5.

a. Mean maximum temperature ^{o}F

b. Mean minimum temperature ^{o}F

c. Mean temperature for previous month ^{o}F

d. Mean temperature for following month ^{o}F

Dewpoint Temperature

22. For each station listed on worksheet 5 determine the annual Tmean-Tdew using the equation:

$T = 24.3P^{-.26}$

where T = annual Tmean-Tdew ^{o}F

P = annual rainfall inches

For stations above 4000 ft. elevation use:

$T = 25^{o}F$

For the stations listed on worksheet 5 determine for the peak month the monthly Tmean-Tdew from the annual Tmean-Tdew using the relationship:

$M = mT+b$

where M = monthly Tmean-Tdew ^{o}F

T = annual Tmean-Tdew ^{o}F

Values for the slope m and the intercept b are listed in Table 3 for each month.

For each station on worksheet 5 determine the Dewpoint Temperature for the peak month by:

$$Tdew = \frac{Tmax + Tmin}{2} - M$$

Round off the Tdew to the nearest degree and enter on worksheet 5.

Wind

23. Use the wind velocity for the peak month from worksheet 2. Enter this value on worksheet 5.

Solar Radiation

24. For each station on worksheet 5 list peak month theoretical clear-sky mean monthly insolation from Table 2 on worksheets 1 and 5.

25. If any of the stations on worksheet 5 have recorded solar radiation data, list the actual mean monthly insolation on worksheets 1 and 5.

If all of the stations on worksheet 5 have recorded solar radiation data, go to step 31.

26. On worksheet 3 list the solar radiation stations in the quad sheets in the hydrographic area being considered. If no solar radiation stations are in the quad, go to adjoining quad sheets in the same hydrographic area.

If worksheet 3 was used for the reference station, go to step 29.

27. For each station listed on worksheet 3 enter:

a. Latitude

b. $\frac{I_a}{I_{ca}}$

c. The average peak month insolation I_m

d. For the peak month and station the theoretical clear-sky insolation from Table 2.

e. For the peak month and station calculate: $\frac{I_m}{I_{cm}}$

28. By linear regression on worksheet 3 develop the relationship for the peak month between $\frac{I_m}{I_{cm}}$ and $\frac{I_a}{I_{ca}}$.

$$\frac{I_m}{I_{cm}} = A + B \frac{I_a}{I_{ca}}$$

29. a. On worksheet 1 enter the theoretical clear-sky mean annual insolation for each station from Table 2.

b. Calculate the actual mean monthly insolation using the values of A and B for the peak month developed in step 28.

$$I_m = I_{cm} \left(A + B \frac{I_a}{I_{ca}}\right)$$

List the values of I_m on worksheet 1.

30. List the values of theoretical clear-sky mean monthly insolation (I_{cm}) and actual mean monthly insolation (I_m) for the peak month from worksheet 1 for each station on worksheet 5.

Calculate ET_o

31. For each station on worksheet 5 list the station elevation and the wind gage height. The wind gage height will be the same as on worksheet 2.

32. Calculate the peak month ET_o for each station on worksheet 5 using the HP 2825A calculator and the program listed in Appendix A.

Summarize Monthly ET_o

33. On worksheet 7 enter:

    a. Each station from worksheet 1

    b. Reference station monthly ET_o

    c. For the other stations peak month ET_o

    d. Calculate the monthly ET_o for each station and month from the reference ET_o and the ratios of the peak month ET_o of the reference station to the other stations.

ET_o CALCULATIONS
Worksheet 1

Sheet_____ of_____

By______________ Date________________ Project________________________

Quad__________ Hydrographic Area________ Reference Station______________

Peak Month____________________

Station	Mean Annual Rainfall Inches	Ia Actual Mean Annual Insolation cal/cm2/day	Latitude	Ica Theoretical Mean Annual Clear Sky cal/cm2/day	Icm Theoretical Mean Monthly Clear Sky cal/cm2/day	Im Actual Mean Monthly Insolation cal/cm2/day

ETo CALCULATIONS

REFERENCE STATION WORKSHEET

Sheet______ of______

By________________ Date__________________ Project______________________________

Hydrographic Area__________________________

		Length of Record - Years			
Quad	Station	Rainfall	Temperature	Solar Radiation	Total

ET_o CALCULATIONS
Worksheet 2 - Determination of Peak Month

Sheet_____ of_____

By__________ Date__________ Project____________________ Quad__________

Hydrographic Area__________ Reference Station Name and No._______________ Elevation (ft.)__________

Month	Mean T_{max} °F	Mean T_{min} °F	Dewpoint T_{dew} °F	Average Wind Velocity miles/hour	I_{cm} Theoretical Mean Monthly Clear Sky cal/cm2/day	I_m Actual Mean Monthly Insolation cal/cm2/day	Previous Month T_{mean} °F	Following Month T_{mean} °F	Elevation Feet	Wind Gage Height Feet	ET_o Inches/Day
January											
February											
March											
April											
May											
June											
July											
August											
September											
October											
November											
December											

ET_o CALCULATIONS
Worksheet 3

Sheet_____of_____

______________________ Quad__________ Hydrographic Area______________

Month												
	March			April			May			June		
$\frac{I_m}{I_{cm}}$	I_m	I_{cm}	$\frac{I_m}{I_{cm}}$	I_m	I_{cm}	$\frac{I_m}{I_{cm}}$	I_m	I_{cm}	$\frac{I_m}{I_{cm}}$	I_m	I_{cm}	$\frac{I_m}{I_{cm}}$
	September			October			November			December		

ET_o CALCULATIONS
Worksheet 4 - Monthly Isolation

Sheet_____ of_____

By__________ Date__________ Project____________________

Quad_______ Hydrographic Area________ Reference Station No.________

Month	A	B	I_a	I_{ca}	I_{cm}	$\frac{I_a}{I_{ca}}$	I_m
January							
February							
March							
April							
May							
June							
July							
August							
September							
October							
November							
December							

ET_o CALCULATIONS
Worksheet 5 - Peak Month ET_o

Sheet_____ of _____

By____________ Date____________ Project________________________ Quad____________

Hydrographic Area______________ Peak Month______________

Station	Mean T_{max} °F	Mean T_{min} °F	Dewpoint T_{dew} °F	Average Wind Velocity miles/hour	I_{cm} Theoretical Mean Monthly Clear Sky cal/cm²/day	I_m Actual Mean Monthly Insolation cal/cm²/day	Previous Month T_{mean} °F	Following Month T_{mean} °F	Elevation Feet	Wind Gage Height Feet

ET_o CALCULATIONS
Worksheet 6 - Temperature Stations

By________ Date________ Project________

Hydrographic Area________ Peak Month________

Quad	Station	Elevation ft.	Mean Tmax °F	Mean Tmin °F	Previous Month Tmean °F	Following Month Tmean °F
		m				
		b				

$$T = m(Elev.) + b$$

ET_o CALCULATIONS
Worksheet 7 - ET_o Summary

Sheet_____ of_____

By__________ Date_______________ Project________________________ Quad__________

Hydrographic Area_______ Reference Station No._______ Peak Month_______________

Month	Wind Vel. mi./hr.	Reference Station Ave. ET_o in./mo.	Ratio to Peak Month	Average ET_o in./day Station No.	Station No.	Station No.	Station No.	Station No.
Jan.								
Feb.								
Mar.								
Apr.								
May								
June								
July								
Aug.								
Sept.								
Oct.								
Nov.								
Dec.								
Jan.								
Feb.								
Mar.								
Apr.								
May								
June								
July								
Aug.								
Sept.								
Oct.								
Nov.								
Dec.								