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A COMPARISON OF EVAPOTRANSPIRATION ESTIMATES USING ERDA HANFORD CLIMATOLOGICAL DATA

by

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NOTICE

The FORTRAN program referred to in this report is operable and stored at Water and Land Resources Department, Battelle, Pacific Northwest Laboratories, Richland WA; however, it was furnished by Dr. Morton and is held as proprietary in his name. Results from using the program will be furnished but the program will be held proprietary until either published or officially released by Dr. Morton.

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SUMMARY

Three methods of estimating monthly values of evapotranspiration on a year-round basis were compared by using the same set of long-term Hanford climatological data as input. Potential evapotranspiration calculated by all three methods yielded an annual value 5 to 9 times the mean annual precipitation. One method yields a value for actual evapotranspiration and one yields a value for areal evapotranspiration. These are compared on a monthly basis and show quite different distributions over the year. The third method examined is relatively new, was calibrated using data from arid stations and yields results that may be more truly representative of arid areas like Hanford.

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INTRODUCTION

A hydrologic budget is a quantitative statement of the balance between total water losses and gains of a basin or area, considering both surface and subsurface water. The most common factors included are precipitation, runoff and streamflow, evapotranspiration, underflow, and changes in soil moisture and groundwater storage. Of these factors evapotranspiration and soil moisture requirements have first priority on use of precipitation.(1) Soil moisture is not generally measured during basin studies and is usually small compared to precipitation and evapotranspiration, and in regional studies is generally regarded as insignificant.

Evapotranspiration depends on a supply of water, generally precipitation, and a supply of energy, primarily radiation. The radiation factors are well known and described whereas the processes determining the water supply and evapotranspiration are not as well known. Estimates of evapotranspiration are usually made from traditional and established methods. The evapotranspiration estimates become particularly important in groundwater modeling where supply available is determined by a budgeting method on a year-round basis, frequently over a grid of small areas with a water budget for each small area.

This report compares two conventional and widely-used methods of estimating evapotranspiration with a new method published in 1976. Because of the modeling need for estimates on a monthly basis over an entire year, methods developed for specific crops during only their growing season are not considered.

A large amount of climatological data is available for the ERDA Hanford Site. Precipitation and temperature measurements were taken daily beginning in 1912 and continuous hourly observations began in 1944.(2) Before the end of 1946 these observations were expanded to include the standard "surface observations" specified by the Weather Bureau (now the National Weather Service). These programs have resulted in a vast amount of historical observations that is available for a wide variety of use and application.

The purpose of this report is to use these long-term observations to compute and compare estimates of evapotranspiration for the ERDA Hanford area by three different methods. Two commonly used methods (Penman and Thornthwaite-Mather) are applied on a monthly basis and compared to a recently developed method by Dr. F. I. Morton, Hydrology Research Division, Water Resources Branch, Department of the Environment, Ottawa, Ontario, Canada. Each method is described briefly and the potential evapotranspiration by each method is shown on a common plot in Figure 1. The input data for each method used are from the same long-term monthly mean values taken from the historical data compiled from observations at the Hanford Meteorology Station.

DESCRIPTION OF AREA

The ERDA Hanford Site overlies the structural low point of the Pasco Basin, which in turn forms the physiographic low of the larger Columbia Basin of southeastern Washington and adjacent parts of Idaho and Oregon.(3) The Hanford Site is bounded on the southwest, west and north by large anticlinal ridges, on the east by the Columbia River and the White Bluffs, and on the south by the confluence of the Yakima and Columbia Rivers and by the city of Richland.

The Hanford Site surface consists of a low-lying, partly dissected and modified alluvial plain of the Columbia River. Altitudes vary from about 105 m above mean sea level (MSL) in the southeastern part to about 245 m MSL in the northwestern corners. The White Bluffs rise to an altitude of about 300 m MSL and the anticlinal ridges to the west rise to a maximum altitude of 1093 MSL at the crest of the Rattlesnake Hills.

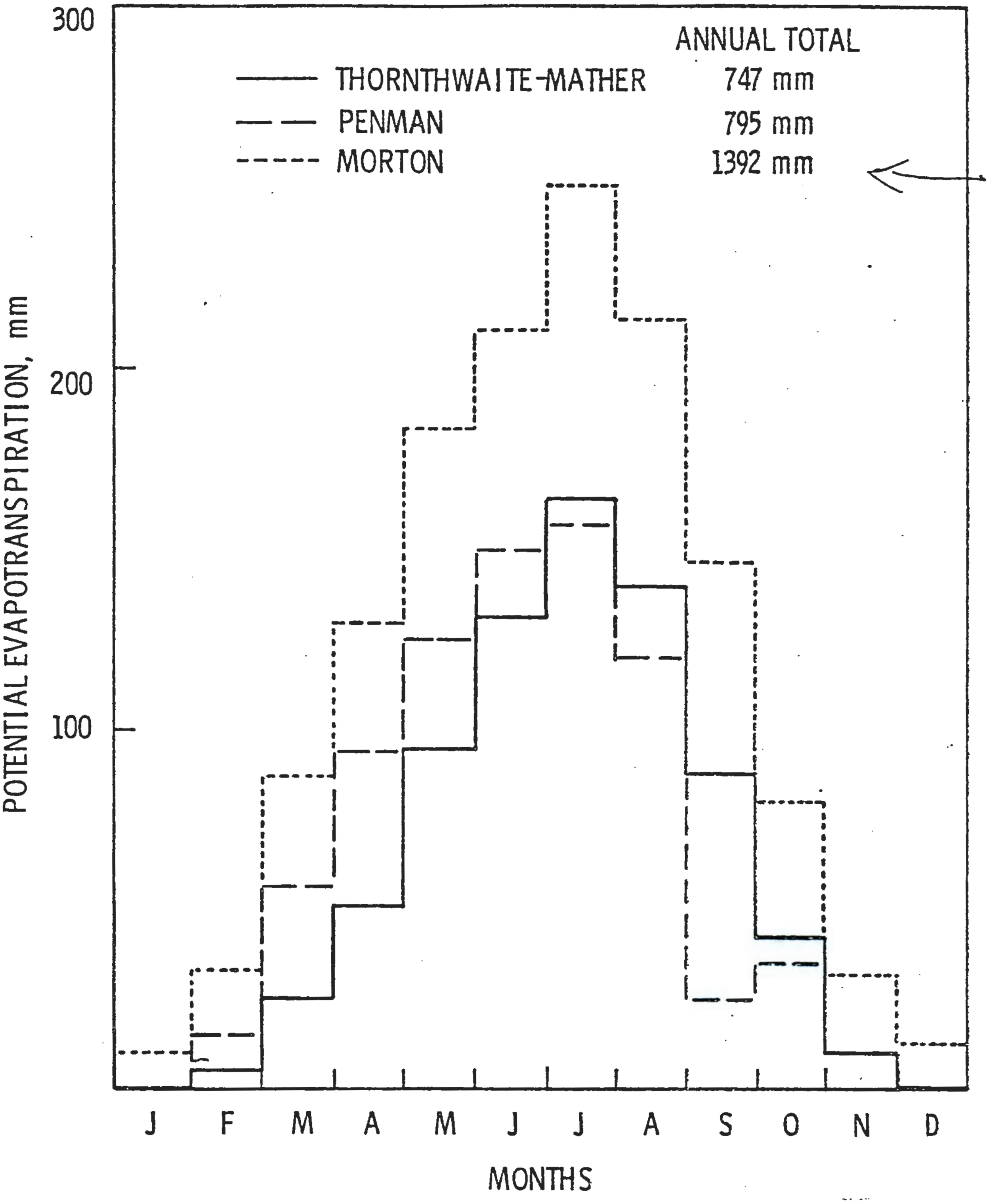


FIGURE 1. Comparison of Potential Evapotranspiration

INPUT DATA

The data recorded by the Hanford Meteorology Station and used in the three methods of estimating evapotranspiration are as follows:

- Average monthly temperature in degrees Fahrenheit at the 3-ft level
- Average monthly precipitation, including snow, ice pellets and sleet, in inches
- Average monthly wind speed at the 50-ft level in miles per hour (mph)
- Average monthly relative humidity in percent and dew point temperature in degrees Fahrenheit
- Average monthly station barometric pressure in inches of mercury
- Average monthly value of solar radiation on daily basis in langleys
- Average monthly sky cover from sunrise to sunset on a scale of 0 to 10.

The Hanford Meteorology Station is located approximately 40 km (25 miles) northwest of Richland, Washington, at latitude 46° 34'N and longitude 119° 36'W. Ground elevation is 223 m (733-ft) MSL.

The long term observations used for the different methods of estimating evapotranspiration came from records from the above location, with the exception of some of the early temperature and precipitation records. The history of the observing location is given in Reference 1. These long-term values are tabulated in Table 1.

TABLE 1. Hanford Long-Term Averages

Month	Temp[a]		Precip[a]		Rel. Hum.[b]	Dew Point[c]		Sky Cover[b]		Bar. Press[c]		Wind[d]	Solar[e] Rad.
	°F	°C	in.	mm	%	°F	°C	0-10	Sun %*	in.	mb	mph	ly
Jan	29.4	-1.4	0.93	23.6	75.7	23.2	-4.9	7.8	36	29.28	992.6	6.3	118
Feb	36.2	2.3	0.62	15.7	69.9	27.4	-2.6	7.4	42	29.28	992.6	7.0	200
Mar	45.2	7.3	0.36	9.1	55.8	27.3	-2.6	6.7	52	29.21	990.2	8.4	340
Apr	53.2	11.8	0.40	10.2	46.7	30.4	-0.9	6.4	55	29.19	989.5	9.0	470
May	61.8	16.6	0.45	11.4	42.2	36.0	2.2	5.8	62	29.17	988.9	8.8	571
June	69.4	20.8	0.57	14.5	39.6	41.2	5.1	5.2	69	29.13	987.5	9.2	626
July	76.4	24.7	0.14	3.6	31.8	42.3	5.7	2.7	90	29.14	987.8	8.6	659
Aug	74.2	23.4	0.19	4.8	34.8	42.8	6.0	3.3	86	29.14	987.8	8.0	551
Sep	65.2	18.4	0.30	7.6	40.6	39.5	4.2	4.1	79	29.17	988.9	7.5	418
Oct	53.1	11.7	0.58	14.7	57.8	36.9	2.7	5.9	61	29.24	991.2	6.7	262
Nov	40.0	4.4	0.85	21.6	72.9	31.1	-0.5	7.5	41	29.29	992.9	6.2	135
Dec	32.6	0.3	0.86	21.8	80.4	27.5	-2.5	8.1	32	29.29	992.9	6.0	91

(a) 1912-1970
(b) 1946-1970
(c) 1950-1970
(d) 1945-1970
(e) 1953-1970

* Sunshine Percentages calculated from $s = 1.0 - 0.016\ sc - 0.0084\ sc^2$
where sc = Sky Cover
s = Sunshine Percentage as a decimal (see Reference 4, p. 257)

PENMAN METHOD

The Penman equation, an energy balance method,(5) connects evapotranspiration or consumptive use to the amount of radiative energy gained by a surface. The experimental work was performed in a humid part of England, not far from the ocean and in an area essentially covered with growing vegetation. Experience in the use of the Penman equation has shown that it works well under these climatic conditions but may not be as applicable in arid, low humidity regions (such as Hanford) where temperature and radiant energy may not be as well balanced as in England.

The method has been widely used in England, parts of Australia and in the eastern United States. One limitation in its use has been a lack of sufficient climatological measurements by weather stations in many localities. The equation and method of use are well established in the literature and the equation is shown here only to illustrate its form and data required. The usual form is:(6)

$$U = \frac{AH + 0.27E}{A + 0.27}$$

where

$E = 0.35(e_a - e_d)(1 + 0.0098\ w_2)$

$H = R(1-r)(0.18 + 0.55S) - B(0.56-0.092\ e_d^{0.5})(0.10 + 0.90S)$

U = potential evapotranspiration or consumptive use in mm/day

A = slope of saturated vapor pressure curve of air at absolute temperature T_a in °F (mmHg/°F)

H = daily heat budget at surface in mm H_2O/day

R = mean monthly extraterrestrial radiation in mm H_2O/day

r = reflection coefficient of surface

S = estimated ratio of duration of bright sunshine to maximum possible duration of bright sunshine

e_a = saturation vapor pressure at mean air temperature in mm Hg

e_d = saturation vapor pressure at mean dew point in mm Hg

$B = \sigma Ta^4$ σ = Boltzmann constant = 2.01×10^{-9} mm/day

Ta = absolute temperature

w_2 = mean wind velocity at 2 m above ground in miles/day, from

$$w_2 = w_1\left(\frac{\log 6.6}{\log h}\right)$$, where w_1 = measured wind velocity at height h(ft)

The evapotranspiration calculated from the Hanford long term climatic observations by the Penman equation is shown on a monthly basis in Figure 1.

THORNTHWAITE-MATHER METHOD

The Thornthwaite equation was developed in an effort to establish a relatively simple expression for evaportranspiration or consumptive use that would utilize readily available climatic data.(7) The empirical equation is based on an exponential relationship between mean monthly temperature and mean monthly consumptive use. The formula was developed on the postulate that temperature was a good index to energy in a zone of essential equilibrium, and was based largely on experience in central and eastern United States.

Thornthwaite's equation uses a heat index of monthly values based on the mean temperature for each month. The monthly values are summed for the annual temperature efficiency index which is used to calculate potential evapotranspiration. The equation is applicable to humid, well-vegetated areas but is less reliable in arid, low-humidity regions.

Thornthwaite and Mathers(8) extended this method to calculate average potential evapotranspiration, water deficits and water surpluses using tables of soil moisture retention. This method has been widely used and applied to large portions of the earth.

The Thornthwaite equation is:(5)

$$U = 1.6\left(\frac{10t}{TE}\right)^a$$

where

$a = 0.000000675(TE)^3 - 0.0000771(TE)^2 + 0.01792TE + 0.49239$

U = potential evapotranspiration in cm/mo

t = mean monthly temperature in °C

TE = temperature efficiency index, equal to the sum of 12 monthly values of the heat index $i = \left(\frac{t}{5}\right)^{1.514}$

The potential and actual evapotranspiration was calculated by the Thornthwaite-Mather method using the same Hanford long-term data as for the Penman method. The results are shown in Figure 1.

MORTON METHOD

The Morton method is a revision of a formulation using a conceptual model for estimating evaporation and transpiration. This method was originally published by Morton in 1975(9) and revised in 1976.(9) The model is based on the interactions between the evaporating surfaces and the temperature and humidity of the overpassing air. The original equation was the Penman equation in the form:(9)

$$E_p = \frac{\Delta}{\Delta+\gamma}R_A + \frac{\gamma}{\Delta+\gamma}f_A(v-v_D)$$

where

E_p = potential evaporation

R_A = areal net radiation

f_A = areal vapor transfer coefficient

v, v_D = saturation vapor pressures at air and dew point temperatures, respectively

Δ = rate of change of saturation vapor pressure with respect to air temperature

γ = the psychrometric constant.

The revised form is:(10)

$$E_p = \frac{\Delta}{\Delta+\lambda}R_a + \frac{\lambda}{\Delta+\lambda}f_A(v-v_D)$$

where

$$\lambda = \gamma + \frac{4\sigma(T+273)^3}{f_A}$$

σ = the Stefan-Boltzman constant

T = temperature, °C

and the other variables are defined as above.

From the relationship between potential evaporation and areal evaporation by Bouchet(11) and Morton,(12) a complementary relationship has been proposed that is expressed as:(9)

$$\delta E_P + \delta E_A = 0$$

where

E_A = areal evaporation
δE_A = the change in E_A caused by a change in the availability of water
δE_P = the resultant change in potential evaporation.

From the above relationships, the Morton formulas are expressed as:(10)

$$E_P = DR_A + (1-D)E$$

where

$D = (1 - \frac{\lambda}{\Delta})^{-1}$ = Penman weighting factor
$E = f_A(v-v_D)$

and

$$E_A = 2\psi(R_A + M) - E_P$$

E_A = areal evaporation = the evaportranspiration from an area so large that the effects of the evapotranspiration on the temperature and humidity of the overpassing air are fully developed.
ψ = an improvement to the Priestly-Taylor weighting factor
M = advection energy term.

The Morton method requires as input: latitude, average atmospheric pressure and average annual precipitation for each station, and air temperature, dew point temperature and the ratio of observed to maximum possible sunshine duration for each time period. A FORTRAN program (presently unpublished) by Morton and modified slightly at Battelle, PNL, will accept either solar radiation measurements or sunshine percentage values as input. For sunshine percentage input the program computes extra-atmospheric insolation, various albedo values, precipitable water vapor, a dust extinction coefficient, partial transmissivity due to absorption and finally incident insolation at the station.

The results of using Morton's FORTRAN program with the Hanford long-term data is input are shown in Figure 1.

DISCUSSION

The quality and volume of historical climatological observations at the ERDA Hanford Site provides an excellent set of input data for comparing methods used to estimate evapotranspiration on a year-round basis. The three methods considered here are different enough in approach to be meaningfully compared when the same input is used.

The Penman method has been the most complete theoretical approach and has been widely used since its publication where the necessary input data are available. Various modifications have been made to the method and a variety of tables and nomographs have been assembled for its use (see Reference 13 for example). Penman's equation shows that consumptive use as represented by evapotranspiration is inseparably connected to incoming solar energy. Penman found, however, that coefficients were necessary to reduce the potential consumptive use rate to the actual water use of what was essentially a growing pasture in England. Good correlation was obtained between measured and computed consumptive use with the derived coefficients.

The Penman equation is best applied to a moist area so large that the effects of evaporation on the temperature and humidity of the overpassing air are fully developed or to a moist area so small that the effects of evaporation are insignificant.(9,10)

The Thornthwaite-Mather method is based on temperature with a correction applied for latitude. To use the soil moisture retention tables for computing actual evapotranspiration, water surplus, water deficit and soil moisture, some information or estimates are needed about the nature of the soil and the amount of available water in the root zone. The soil information should include the depth, type and structure of the soil, which determine its moisture holding capacity. The original Thornthwaite equation, based on moderate to deeply rooting crops in humid areas, assumed a 10-cm water storage capacity in the plant root zone. Later modification led to tables of soil moisture retention which are used to estimate the rate of evapotranspiration at selected moisture content from soils with different values of total moisture holding capacity.(8)

The Thornthwaite-Mather method can be used as a bookkeeping procedure beginning with station temperature, precipitation data and a specified root zone water capacity for the particular soil type, and then computing the heat index, temperature efficiency index and potential evapotranspiration corrected for latitide. The soil moisture retention tables for this root zone water capacity can be used to obtain the amount of soil moisture retained after a given amount of evapotranspiration has occurred. Using these tables leads to the change in storage from field capacity or a potential water deficiency and to the actual evapotranspiration. The results of this procedure using the Hanford long-term data and a root zone water capacity of 150 mm are shown in Table 2.

TABLE 2. Thornthwaite-Mather Water Balance for Hanford, Washington 150 mm Root Zone Water Capacity, All Values in mm

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Potential Evapotr.	0	4.8	24.5	51.3	93.6	130.7	163.6	139.1	88.2	41.9	9.4	0	747.
Precip.	23.4	15.2	9.4	9.7	11.9	14.2	3.8	5.1	7.6	14.7	21.8	22.6	159.
Difference	23.4	10.4	-15.1	-41.6	-81.7	-116.5	-159.8	-134.0	-80.6	-27.2	12.4	22.6	-588
Storage Change	23.4	10.4	2.2	-18.0	-23.0	-17.0	-9.0	-3.0	-1.0	0	12.4	22.6	
Moisture Storage	59.4	69.8	72.0	54.0	31.0	14.0	5.0	2.0	1.0	1.0	13.4	36.0	
Actual Evapotr.	0	4.8	11.6	27.7	34.9	31.2	12.8	8.1	8.6	14.7	9.4	0	164.
Moisture Deficit	0	0	12.9	23.6	58.7	99.5	150.8	131.0	79.6	27.2	0	0	583
Moisture Surplus	0	0	0	0	0	0	0	0	0	0	0	0	0
Runoff	0	0	0	0	0	0	0	0	0	0	0	0	0

The Morton method challenges the assumption that in the relationship between potential evaporation and areal evaporation, the former is the independent variable and the latter is the dependent variable. Furthermore that the use of potential evapotranspiration as a causative or forcing function is limited to the two specific situations where the Penman method is best applied and that potential evaporation may be a value that responds in a complementary way to changes in the availability of water for areal evaporation. A result of this approach is that the potential evaporation in a completely humid area should be half the potential evaporation in a contiguous completely arid area. For a complete discussion of these concepts see Reference 10.

The Morton method assumes that potential evaporation is governed by the supply of radiation and water to the surface of the surrounding area. Experience has shown that the assumption is reasonable with the two following exceptions:(10)

1. Near consistent or continuous surface changes or sharp environmental discontinuities such as a coastline where temperature and humidity observations may not be representative of the surrounding area.
2. During periods of negative net radiation, potential temperature and specific humidity inversions can persist down to the surface; and the vapor pressure deficit may be directly influenced by advections of heat and water vapor associated with large-scale air mass movements.

A constraint on the model is that areal evaporation is always less than or equal to potential evaporation. Limitations on the model's application are:

1. Accurate humidity data are required
2. It cannot be used for short time intervals
3. It cannot be applied to deep lakes with large seasonal temperature changes
4. It cannot be used to predict the effects of natural or man-made changes, since it neither uses nor requires knowledge about the soil-vegetation system.

The model is complete and does not require local optimization of coefficients. The calibration included 180 station-months of data from arid regions (El Paso, Texas; Phoenix and Yuma, Arizona) and can be applied directly to Hanford conditions and data.

RESULTS

The results of the three methods discussed are presented graphically in Figure 1 and can be compared on a monthly basis by observation. It should be noted that the Penman and Thornthwaite-Mather methods, which were developed for regions more humid than Hanford, yield considerably lower annual values for potential evapotranspiration than the Morton method, which included arid regions in its calibration.

The Penman equation is dependent on the coefficients used and is quite sensitive to changes in these coefficients. For example, following the line of reasoning used by Penman(5) and using Hanford long-term climatologic data suggests that the term (0.18 + 0.55S) in the Penman equation may be more like (0.21 + 0.57S) for Hanford. This change leads to an annual potential evapotranspiration of 899.8 mm compared to 795.4 mm for the given coefficients. Penman reported that for the state of Virginia, a humid area, the expression used was (0.22 + 0.54S) and also noted a suggested seasonal variation in the values he found for Rothamsted, England. This variation in coefficients, even in humid areas for which the method was developed, suggests that the method may not be as valid or directly applicable to arid areas.

The Thornthwaite-Mather method assumes that the root zone is at field capacity--that is, no surplus of gravitational water and no deficit of capillary water when evapotranspiration begins. However, in arid areas such as Hanford, as the difference between potential evapotranspiration and precipitation-storage is accumulated, the difference soon becomes negative, indicating a deficit in available water at the beginning of the evapotranspiration season. Thus, the soil moisture is not at the assumed field capacity. Through the year as the amount of water use exceeds the precipitation, field capacity is never attained. This is reflected in Table 2 in the 583 mm water deficit and 0.0 mm water surplus. In practical terms, this means that essentially all the precipitation is used during the year with none available for runoff or to percolate down to the groundwater system.

The Morton method yields a larger annual potential evapotranspiration value than the other two and requires no local calibration or assumptions about the soil-vegetation system. It was also calibrated with data from arid stations. The calculated value of areal evaporation is slightly less than the actual evapotranspiration from the Thornthwaite-Mather method and also slightly less (11.6 mm) than the average annual precipitation.

No accounting of this 11.6 mm of water is made here. It may or may not be a significant percentage (about 7%) of the annual precipitation for an area meeting Morton's definition of areal evaporation.

The Morton areal evapotranspiration and the Thornthwaite-Mather actual evapotranspiration are shown for comparison in Figure 2. The Morton areal evapotranspiration shows a different distribution over the year than the Thorthwaite-Mather actual evapotranspiration. For example, the Morton values show evapotranspiration occurring when the mean monthly temperature is near or less than 0°C and that evapotranspiration falls to zero in August when the soil moisture has been exhausted and precipitation is very low.

To check the operation of Morton's FORTRAN program and for information on the variability of the Hanford climate, two consecutive 5-year periods (1966-70 and 1971-75) in addition to the long-term data were also used as input. The potential evapotranspiration varied only slightly from the long-term figures, but the areal evapotranspiration varied from 111.0 mm to 173.4 mm compared to the long-term mean of 147.4 mm. This deviation from the long term is due to the variation in precipitation and net radiation for these time periods. These comparisons are summarized in Figure 3.

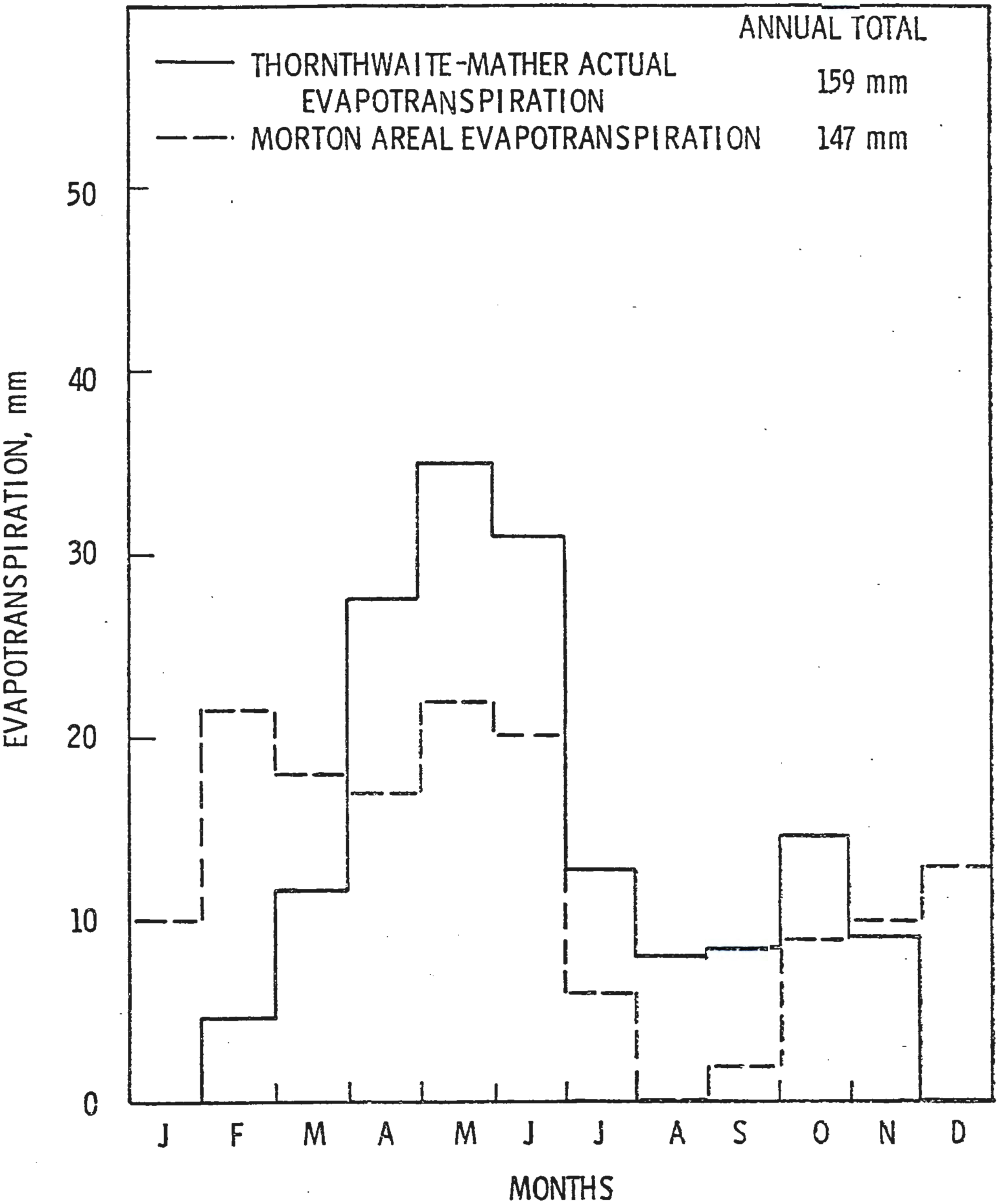
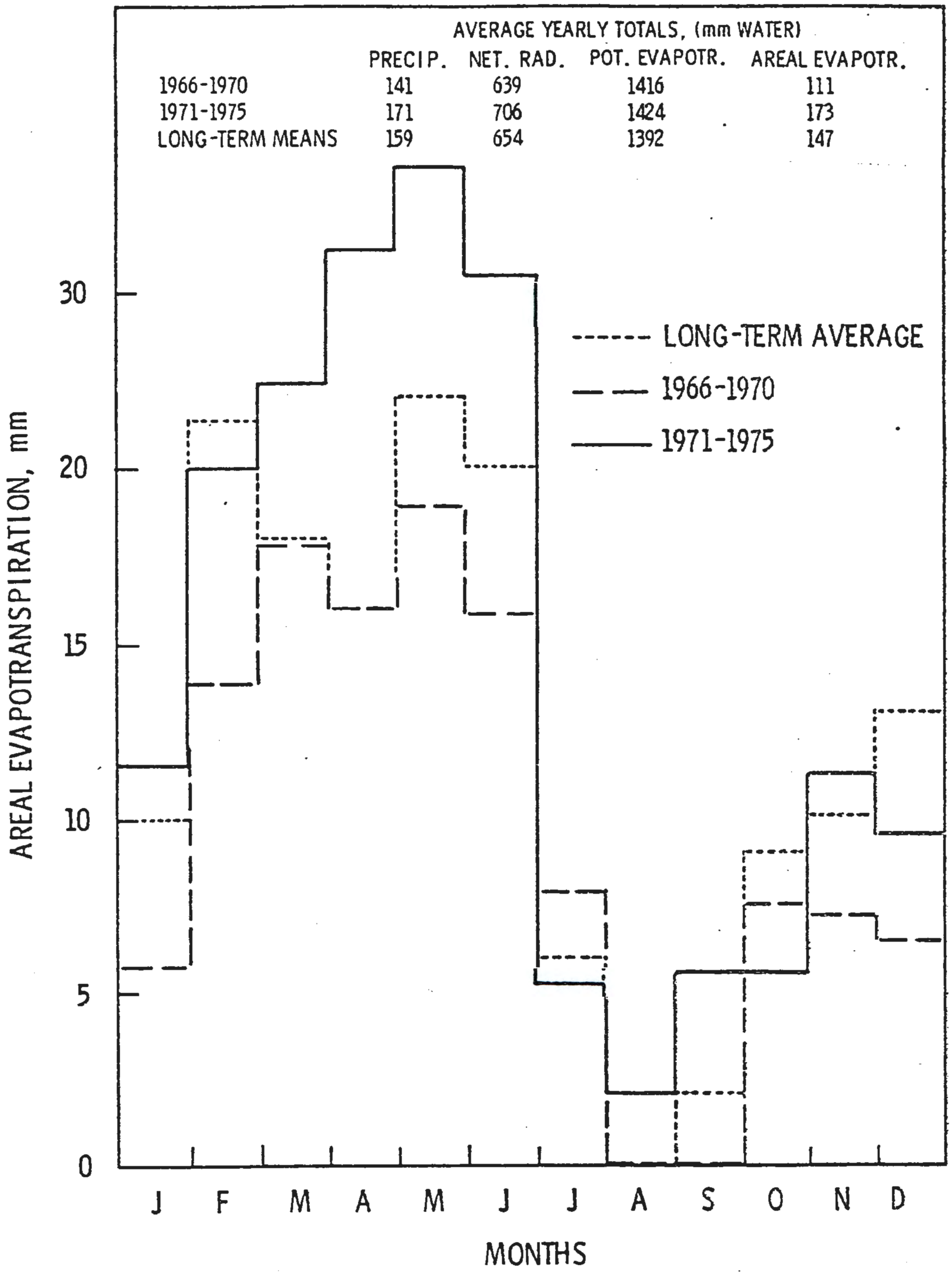


FIGURE 2. "Actual" and "Areal" Evapotranspiration



AVERAGE YEARLY TOTALS, (mm WATER)

	PRECIP.	NET. RAD.	POT. EVAPOTR.	AREAL EVAPOTR.
1966-1970	141	639	1416	111
1971-1975	171	706	1424	173
LONG-TERM MEANS	159	654	1392	147

FIGURE 3. Areal Evapotranspiration by Morton's Method for Periods 1966-1970, 1971-1975 and Long-Term Average

The concept presented by Morton that there is a complementary relationship between potential and areal evaporation may account for some of these differences. This concept indicates that potential evaporation responds negatively to changes in the availability of water for areal evaporation and is more an effect than a cause of areal evaporation. This is also true for evaporation pans or any other small moist area. The concept predicts that the potential evaporation in a waterless desert would be decreased by 50% if the surrounding area were abundantly irrigated, or that, as mentioned before, the potential evaporation in a completely humid area should be half the potential evaporation in a contiguous completely arid area. The potential evapotranspiration for Hanford by the Penman method is 57% of that computed by the Morton method; the Thornthwaite-Mather value is 54% of the Morton value. No conclusion can be drawn from these relationships as yet.

It may be that the complementary relationship proposed by Morton is actually being demonstrated between Hanford and the surrounding irrigated areas. The Penman and Thornthwaite-Mather methods, because of their development in humid areas, may more truly reflect conditions of the irrigated part of an arid area, while the Morton method may reflect conditions in the non-irrigated arid area. Further work is needed in the Hanford area to investigate this relationship.

The Penman equation was developed in areas of extensive short vegetation and moist surfaces (Reference 5, p. 128) and does not consider precipitation, either natural or "man-made", directly. The Thornthwaite-Mather water balance is based on the difference between potential evapotranspiration and precipitation--if precipitation is abundant, whether natural or in the form of irrigation, the actual evapotranspiration approaches the potential, but the potential evapotranspiration is not affected directly.

The Morton method thus seems to be the most appropriate for the arid ERDA Hanford Site and to the Columbia Basin area in general because of its development and calibration using data from arid stations. The differences in potential evapotranspiration estimates among the three methods are considered to be due to the differences in climatic conditions under which they were developed, calibrated and generally applied.

The Pasco Basin area should provide a suitable situation for checking Morton's concept of a complementary relationship between potential and areal evaporation, and examining its implications. The ERDA Hanford Site includes about 1550 km^2 of arid desert land with the Hanford Meteorology Station inside its boundaries. Adjoining the area are large tracts of irrigated land with alfalfa, grapes, sugar beets and other crops. Furthermore, irrigation is over-abundantly applied (probably 600 to 1200 mm during the growing season) judging from the irrigation-return water problems in the area.

CONCLUSIONS

The following conclusions are drawn from the results of applying the three methods to the same set of input data:

1. Potential evapotranspiration at Hanford using long-term climatological data exceeds precipitation by a factor of 5 to almost 9 in all three methods used.
2. No precipitation is available in general after evapotranspiration for runoff or recharge or to even bring soil moisture up to field capacity. The Morton method does show that precipitation exceeds areal evaporation by 11.6 mm on a yearly average of long-term data. No conclusion is drawn from this.
3. The Morton method is preferred here because of its development and calibration to include arid regions and because of the correspondence it shows between areal evapotranspiration and moisture availability.
4. The concept of a complementary relationship between potential and areal evaporation has implications that should be investigated. Morton has provided support for this concept and the Pasco Basin-Hanford area with large irrigated areas and adjoining large arid regions could provide further tests of the concept.

REFERENCES

1. W. C. Walton, Groundwater Resources Evaluation. McGraw-Hill Book Co., New York, 1970.

2. W. A. Stone and others; Climatography of the Hanford Area. BNWL-1605, Battelle Pacific Northwest Laboratories, Richland, WA, June 1972.

3. Environmental Statement, Waste Management Operations, Hanford Reservation. Richland, WA, ERDA, WASH-1538, Vol. 2, Appendixes, July 23, 1975.

4. J. E. Christiansen, "Pan Evaporation and Evapotranspiration from Climatic Data", Proc. ASCE, Jour. Irr. and Dr. Div. IR2, Proc. Paper 5988, June 1968.

5. H. L. Penman, "Natural Evaporation from Open Water, Bare Soil and Grass," Proc. Royal Soc. London. Series A, Vol. 193, pp. 120-145, 1948.

6. V. T. Chow, ed., Handbook of Applied Hydrology. McGraw-Hill, New York, 1964.

7. O. W. Israelsen and V. E. Hansen, Irrigation Principles and Practices. John Wiley and Sons, New York, 3rd Edition, 1962.

8. C. W. Thornthwaite and J. R. Mather, "The Water Balance," Climatol. Vol 8, No. 1, Laboratory of Climatol., Drexel Institute, 1955, 104 pp.

9. F. I. Morton, "Estimating Evaporation and Transpiration from Climatological Observations," Jour. Appl. Meteorology. Vol. 14, No. 4, pp. 488-497, June 1975.

10. F. I. Morton, "Climatological Estimates of Evapotranspiration," Proc. ASCE, Jour. of Hydraulics Div. Paper 11974, Vol. 102, No. HY3, pp. 275-290, March 1976.

11. R. J. Bouchet, "Evapotranspiration reelle et potentielle, signification climatique," Proc. General Assembly Berkeley, IASH. No. 62, pp. 134-143, 1963.

12. F. I. Morton, "Catchment Evaporation and Potential Evaporation--Further Development of a Climatologic Relationship," Jour. Hydrol. Vol. 12, No. 2, pp. 81-99, 1971.

13. W. D. Criddle, "Methods of Computing Consumptive Use of Water," Am. Soc. Civil Eng. Proc. Paper 1507, Jan 1958.