COMPUTER PROGRAM FOR ESTIMATING EVAPOTRANSPIRATION USING THE THORNTHWAITE METHOD

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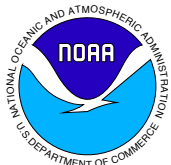
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1.0 INTRODUCTION

Understanding and estimating the earth's hydrologic cycle is important to water resource planners and managers. Evapotranspiration is one of the most difficult components of the hydrologic cycle to estimate. Thornthwaite and Mather (1955) developed a detailed method to estimate evapotranspiration. Although this method for computing potential and actual evapotranspiration is highly accepted and widely used, it is unfeasible to perform these calculations with large data sets. The computer program developed in this report allows the calculation of these parameters to be accomplished in a more efficient and timely manner.

2.0 EVAPOTRANSPIRATION

Potential evapotranspiration (PET), as described by Penman (1948), is "the amount of water transpired in a unit time by a short green crop completely shading the ground, of uniform height, and never short of water." This definition allows maximum evapotranspiration, which is only limited by the energy source (thermal energy) that is applied to the evaporative surface. Initially, evaporation from a wet soil is limited by the energy source, however, with time, this process is limited by the decreased rates of water flow to the active evaporative surface. Since the process of evaporation and transpiration in most watersheds is controlled by water flow through unsaturated soils (Brooks et al., 1990), potential evapotranspiration estimates may not represent true evapotranspiration values.

Thornthwaite and Mather's (1955) method of estimating PET is based solely on air temperature. PET estimates are based upon a 12-hour day (amount of daylight) and a 30-day month.

$$PET = 1.6 x \left(\frac{10 T_a}{I} \right)^a \qquad\qquad 1$$

where: T_a is the mean monthly air temperature, and I is the heat index;

$$I = \sum_{i=1}^{12} \left(\frac{T_{ai}}{5} \right)^{1.5}$$ 2

and a = .49 + .0179 * I - .0000771 * I² + .000000675 * I³,

where air temperature is summed over a 12-month period to a power.

Since evapotranspiration is limited over time by the flow of moisture from the soil zone to the evaporative surface, Thornthwaite included methods to compute actual evapotranspiration. First, moisture excess or deficiency is estimated by subtracting PET from precipitation; negative values represent the potential deficiency of water. Then actual evapotranspiration is found for months where a moisture deficiency is identified by estimating the change in storage of the soil moisture zone and subtracting that amount from precipitation.

Therefore, for months where the supply of thermal energy can evaporate all of the available precipitation, actual evaporation consists of a combination of the available precipitation and the amount of water taken from soil moisture storage.

3.0 METHOD

In order to apply Thornthwaite's method with the accompanying computer program, specific information is required:

(1) mean monthly or daily air temperatures;
(2) mean monthly or daily precipitation;
(3) necessary conversion and computational tables (**included in the computer program**);
(4) information on the water holding capacity of the depth of soil for which the balance is to be computed; and,
(5) the latitude and hemisphere of the watershed.

With the exception of the water holding capacity of the depth of soil, the other items are easily obtained. Tables 1-5 are excerpts from section IV of Thornthwaite and Mather (1957), the contents of which will aid in selecting the proper soil moisture retention table.

Table 1.--Shallow-Rooted Crops (Spinach, Peas, Beans, Beets, Carrots, etc.).

Soil Type	Available Water (mm/m)	Root Zone (m)	Applicable Soil Moisture Retention Table (mm)
Fine Sand	100	.5	50
Fine Sandy Loam	150	.5	75
Silt Loam	200	.62	125
Clay Loam	250	.40	100
Clay	300	.25	75

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Soil Type	Available Water (mm/m)	Root Zone (m)	Applicable Soil Moisture Retention Table (mm)
Fine Sand	100	.75`	75
Fine Sandy Loam	150	1.0	150
Silt Loam	200	1.0	200
Clay Loam	250	.80	200
Clay	300	.50	50

Table 2.--Moderately Deep-Rooted Crops (Corn, Cotton, Tobacco, Cereal Grains).

Soil Type	Available Water (mm/m)	Root Zone (m)	Applicable Soil Moisture Retention Table (mm)
Fine Sand	100	1.0	100
Fine Sandy Loam	150	1.0	150
Silt Loam	200	1.25	250
Clay Loam	250	1.0	250
Clay	300	.67	50

Table 3.--Deep-Rooted Crops (Alfalfa, Pastures, Shrubs).

Soil Type	Available Water (mm/m)	Root Zone (m)	Applicable Soil Moisture Retention Table (mm)
Fine Sand	100	1.5	150
Fine Sandy Loam	150	1.67	250
Silt Loam	200	1.5	300
Clay Loam	250	1.00	250
Clay	300	.67	200

Table 4.--Orchards.

Table 5.--Closed Mature Forest.

Soil Type	Available Water (mm/m)	Root Zone (m)	Applicable Soil Moisture Retention Table (mm)
Fine Sand	100	2.50	250
Fine Sandy Loam	150	2.00	300
Silt Loam	200	2.00	400
Clay Loam	250	1.60	400
Clay	300	1.17	350

4.0 FORTRAN PROGRAM "*EVAP*"

This FORTRAN program was developed following Thornthwaite and Mather's methods as outlined in their 1957 publication. It includes all the necessary tables to complete the required computations. These tables and the input data files should reside in the same directory as the executable program. In order to successfully run the FORTRAN program **EVAP,** monthly precipitation, air temperature, latitude of the watershed, and moisture holding capacity of the soil is needed. Provided below are two examples in which Thornthwaite and Mather's method was applied. The first is an example used in Thornthwaite and Mather (1957; pg. 18) from Bismarck, North Dakota, and the second is a data set that is provided with the computer program. **Example 1:**

Precip m	Temp °C	PET mm	Actual ET mm
11.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00
23.00	0.00	0.00	0.00
39.00	5.60	30.78	30.78
59.00	12.50	78.00	70.00
85.00	17.60	114.84	100.00
57.00	21.00	139.65	89.00
46.00	19.60	120.78	66.00
31.00	14.50	75.60	39.00
24.00	7.20	30.69	26.00
14.00	0.00	0.00	0.00
14.00	0.00	0.00	0.00

Columns 1-4 are precipitation, temperature, potential evapotranspiration (PET), and actual evapotranspiration, respectively. Temperature and precipitation from this example were input into the program, which resulted in a PET and Actual ET output. The PET and Actual ET values mimic Thornthwaite's values, differing only by a tenth of a millimeter (mm) due to computer precision.

Example 2:
The user should follow this example format when inputting their own data. Monthly temperature and precipitation data must be entered in the form of an ASCII text file. Below is an example of the input file *Climate.dat* that is provided with the program

1970	01	-9.76	34.16
1970	02	-4.84	9.03
1970	03	0.63	58.80
1970	04	7.97	93.43
1970	05	14.19	152.00
1970	06	18.74	166.77
1970	07	22.78	59.61
1970	08	22.07	13.82
1970	09	16.74	230.49
1970	10	11.70	70.95
1970	11	3.07	63.62
1970	01	-2.10	36.64
1971	01	-9.06	41.70
1971	02	-5.26	65.63
1971	03	-1.39	37.74

Columns 1 and 2 of this file are the year and month, respectively. Columns 3 and 4 are the monthly air temperature in degrees Celsius and precipitation totals in millimeters. **Note:** this file should not contain values for missing data, if data is missing, simply leave that month out of the data file. The output file is listed below:

Year	Month	Precip	Temp	PET	Actual ET
1970	01	34.16	0.00	0.00	0.00
1970	02	9.03	0.00	0.00	0.00
1970	03	58.80	0.00	0.00	0.00
1970	04	93.43	7.97	36.96	36.96
1970	05	152.00	14.19	83.16	83.16
1970	06	166.77	18.74	115.20	115.20
1970	07	59.61	22.78	147.06	137.61
1970	08	13.82	22.07	129.60	90.82
1970	09	230.49	16.74	81.12	81.12
1970	10	70.95	11.70	48.45	48.45
1970	11	63.62	3.07	9.72	9.72
1970	12	36.64	0.00	0.00	0.00
1971	01	41.70	0.00	0.00	0.00
1971	02	65.63	0.00	0.00	0.00
1971	03	37.74	0.00	0.00	0.00

Again, columns 1-2 are year and month, and columns 3-6 are precipitation, temperature, potential evapotranspiration (PET), and actual evapotranspiration in units of millimeters. **Note:** Thornthwaite makes the assumption that evapotranspiration ceases for temperatures at or below 0 degrees C, therefore, negative temperatures are changed to zero, and, consequently, evapotranspiration does not occur.

Figure 1 has been created for the watershed outputs from the input file (*Climate.dat*). This watershed is located on Lake Michigan's eastern shore at a latitude of 43 degrees and an approximate soil moisture retention of 350 mm. As expected, actual evapotranspiration is consistently lower than PET and averages about 66% of the total precipitation, which fits the range of 50-90% for the state of Michigan.

5.0 CONCLUSION

Although evapotranspiration is an elusive quantity of the water balance, Thornthwaite's method has been widely used as a source of quantification. Using this laborious method is now more efficiently accomplished with the aid of this computer program that allows automatic "look up" capabilities to Thornthwaite's tables and computes minor calculations.

6.0 REFERENCES

Brooks, K.N., P.F. Ffolliott, H.M. Gregersen, and J.L. Themes. *Hydrology and the Management of Watersheds*. Iowa State University Press, Ames, IA, 50010 (1991).

Penman, H.L. Natural evaporation from open water, bare soil, and grass. Proc. R. Soc London, Ser. A 193:120-145 (1948).

Thornthwaite, C.W., and J.R. Mather. The Water Balance. Laboratory of Climatology Publ. 8. Centerton, NJ (1955).

Thornthwaite, C.W., and J.R. Mather. *Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance*. Drexel Institute of Technology, Laboratory of Climatology, Publications in Climatology 10(3), 311 pp. (1957).
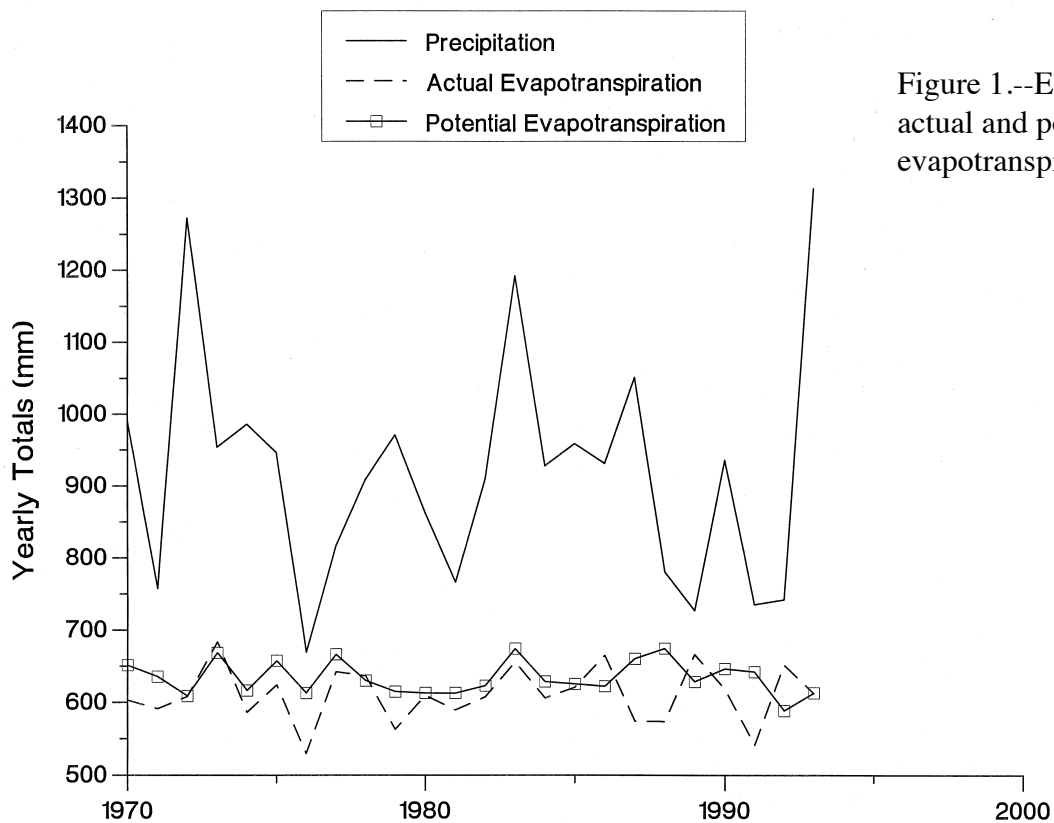
Figure 1.--Estimated actual and potential evapotranspiration.

INSTRUCTIONS

Obtain the program from GLERL's anonymous FTP area:
   ftp://ftp.glerl.noaa.gov/publications/tech_reports/glerl-101

FORTRAN Program Execution File: Evap.exe
FORTRAN Program: Evap.for
Data Files:

Climate.dat	Table26.dat
Table2.dat	Table27.dat
Table4.dat	Table28.dat
Table5.dat	Table29.dat
Table6.dat	Table30.dat
Table7.dat	Table31.dat
Table23.dat	Table32.dat
Table24.dat	Table33.dat
Table25.dat	