II.5-CALB-MAPE CALIBRATION SYSTEM MEAN AREAL POTENTIAL EVAPOTRANSPIRATION (MAPE) COMPUTATIONAL PROCEDURE

Introduction

This Chapter describes the procedures used to compute point potential evapotranspiration (PET) and mean areal potential evapotranspiration (MAPE) for use in model calibrations.

Evapotranspiration (ET) is the process through which water is lost to the atmosphere by evaporation from water, snow, plant and soil surfaces and from vegetation by transpiration of water through plants. If the amount of water extracted by ET from a basin into the atmosphere ET is large enough there may be a significant reduction in basin runoff.

The processes of evaporation and transpiration are difficult to separate so their effects are grouped together and called ET. However a consideration of the similarities and differences of the two processes is useful to understand how the process is modeled and better estimate parameters and values of PET for model calibrations and forecast applications.

Both evaporation and transpiration similarly depend on:

- o vapor pressure differences between the air and the surfaces from which the water is lost
- o a supply of moisture

In calm air vapor blankets form near air-surface interfaces which reduces vapor pressure differences between the air and the surface, suppressing water loss. Wind turbulence mixes the air, breaking up stratified moisture blankets and raising the vapor pressure differences to levels closer to those indicated by shelter or station measurements of air temperature and dew point depression. Simple estimates of evaporation are made from observations of pressure difference and wind travel:

$$E = (e_o - e_a)^n(a + bu_p) \qquad (1)$$

where e_o is the vapor pressure of the surface moisture
e_a is the vapor pressure of the air
u_p is the daily wind travel over the pan
n, a and b are empirical constants

Both evaporation and transpiration require a source of moisture. Evaporation from dry concrete or soil is negligible, even though a large vapor pressure difference exists. Similarly, transpiration from vegetation decreases as the soil in the root zone dries.

Evaporation differs from transpiration in some of the following ways. Evaporation continues only until surface moisture supplies are exhausted. Evaporative losses from soil surfaces continue only as long as moisture is available to the surface. Capillary effects bring some water from below the surface to extend the evaporation process but this action only affects a soil layer a few inches thick. The evaporating soil surface can become completely dry in a relatively short time, even while the relative humidity within the soil only a few inches below the surface can be 100 percent and plenty of soil moisture is available to plant roots.

Transpiration occurs as long as plant roots can extract water from the soil. The distribution of roots with depth in the soil makes the soil layer affected by transpiration much larger than that influenced by evaporation but this depth depends on the type of vegetative cover and the types of soils and their layering within the root zone. An additional factor controlling the rate of water loss is the stomatal process in the leaves. However since these stomatal processes vary with plant species and the life cycle of the plants, which usually have considerable variation over a watershed, they are included with other similar factors in a generalized seasonal transpiration demand in an annual curve.

The significance of noting the differences between evaporation and ET in river forecasting is as follows. In a hypothetical basin totally covered by water, evaporation would always occur at the potential rate. There would be little value in converting the potential rate of evaporation to ET. However in modeling water budgets for basins covered with significant vegetation, which is the general situation except in desert areas, transpiration plays the major role in governing water loss to the atmosphere. Thus, the development of some estimate of the seasonal variation in transpiration for each particular basin becomes very important. This curve is called the transpiration demand curve and the development is based on knowledge of the vegetation cover refined by calibration. PET estimates are developed by multiplying values in this curve by the daily potential evaporation (PE). In areas covered with deciduous vegetation, this curve nears zero in the winter after the leaves are dropped or the plants go dormant. But the curve values may be larger than one during the active growing season when the ratio of the total area of leaves on trees is significantly higher than the surface area of the ground. Thus knowing the make up of a basin, a modeler can consider how dependent the water loss will be on such things as transpiration demand curves and how dependent the curve will be on the winter formation of ice on open water, irrigation schedules or cultivation practices.

Conversion of PET to ET is generally estimated in the soil moisture accounting model though a series of calculations and approximations. As the available moisture in the root zone is depleted the ET is correspondingly reduced.

The ET Estimation Process

Generally the first step for estimating ET is to estimate PE from a water surface. To have a standard meaning for PE, we define it as evaporation from a very shallow water layer in which the evaporation is negligibly affected by heat storage in the water. It is also called free water surface. The requirement for a shallow layer is used to avoid the problems connected with energy that goes into heat storage in deeper ponds or lakes. The energy used in heating water is subtracted from the incoming energy otherwise used for evaporation. At the same time, water that is warmer than the air has extra energy to enhance the evaporation process. Over an annual cycle, the change in heat storage in most lakes is considered to be negligible, but on a daily basis can influence PE considerably. PE is useful because it is also considered to be generally the maximum rate at which water is expected to be lost from natural surfaces such as wet soils or from most adequately watered vegetation. Some studies have suggested that when the leaf area index (the ratio of the surface area of leaves to the horizontal soil surface) exceeds three, the evapotranspiration can also rise above the PE estimated using pan methods (Kristensen, 1974). These increases in ET can be accounted for in the transpiration demand curves.

Potential Evaporation Data Sources

Potential evaporation (PE) estimates used for input to the rainfall-runoff model are derived from observations obtained from the National Weather Service Class A pan or when pan data are not available from estimates derived from measurements of air temperature, humidity, wind and radiation, combined in an equation to give values similar to the pan measurements. These observations should conform to specifications described in National Weather Service Observing Handbook Number 2 'Substation Observations'. The primary source of PE estimates from pans for calibrations are:

1. (a) Data available from the National Climatic Data Center (NCDC): These pan values are modified to PE by a method described by Kohler et al. (1955). This method requires a mean of daily air and pan water temperatures. The maximum and minimum temperatures required to compute these means are also available from NCDC although the water temperature may not always be there. It also requires the mean station pressure and the wind travel over the pan.

   The correction technique is based on the idea that there are three energy exchange processes between the water in the pan and the environment. This energy exchange occurs through either evaporation, back radiation or sensible heat transfer. Sensible heat transfer is the heating of the environment in contact with the pan. Both the pan and a natural water surface such as a lake interact similarly with the atmosphere in terms of evaporation and back radiation. However the pan sits above the ground and exchanges energy through its sides and bottom.

   When a pan is warmer or colder than its environment, sensible heat transfer takes place. In this pan, evaporation and radiative transfer also occur at a higher (lower) rate than occurs when the pan is at the ambient temperature. The fraction of the energy resulting from the higher (lower) temperatures that would go into evaporation is given by taking the ratio of the incremental energy going into evaporation to the total of the incremental energy exchanges as given by:

$$\alpha = \frac{E_L^{*}-E_L}{(E_L^{*}-E_L) + (Q^{*}-Q_{bs}) + (Q_h^{*}-Q^{h})} \qquad (2)$$

where E_L^* is daily lake evaporation at the higher water surface temperature that differs from than the surrounding air temperature
E_L is the observed daily lake evaporation
Q_{bs} is the energy lost to back radiation
Q_h^* is the sensible heat transfer

Experience has shown that on the average, evaporation from free water surfaces is only 0.7 the amount from pans. When the temperature of the water is higher (lower) than the air, sensible heat exchange brings energy out of (into) the pan, the magnitude of this sensible heat transfer Q_h being related to the difference between the air and water temperatures. E_L which is the same as PE is then:

$$E_L = (E_p + \alpha_p Q_h) \qquad (3)$$

where αp is the value given by Equation 2 for the pan

Each of these terms can be computed except for the evaporation. By following the basic equations listed in the reference, the following relationship for lake evaporation in units of inches is arrived at:

$$E_l = 0.70[E_p+0.00051P\alpha_p(0.37+0.0041u_p)(T_o-T_a)^{0.88} \qquad (4)$$

where E_p is the observed pan evaporation in inches
P is the pressure in inches of mercury
u_p is the daily wind travel past the pan in miles per day
T_o is the observed water surface temperature in degrees Fahrenheit
T_a is the observed air temperature in degrees Fahrenheit

(b) If pan water temperature is not available PE can be generated from pan evaporation by a coefficient taken from NOAA Technical Report 'Evaporation Atlas of the Contiguous 48 States'. These coefficients are generally near to 0.7.

(c) If no other data are available rough estimates of PE values can be obtained by multiplying the pan data by the constant coefficient of 0.7.

2. Estimated Class A pan data and PE can be derived from observations of air temperature, dew point, wind speed and solar radiation (or an estimate of solar radiation based on percent sunshine or percent cloud cover). The estimate comes from using the equation derived by Penman (1948):

$$E_L = 0.7 \left(\frac{Q_n + E_a \gamma}{\Delta + \gamma} \right) \qquad (5)$$

where Q_n is net radiation exchange
Δ is the slope of the saturation vapor pressure curve at air temperature Ta
γ is a factor defined by the Bowen Ratio equation:

$$R = \gamma \frac{(T_o - T_a)}{(e_o - e_a)} \qquad (6)$$

E_a is the pan evaporation assuming that the air and water surface temperatures are very nearly the same

These equations have been fit to a mathematical equation by Lamoreux (1962):

$$E_L = \frac{[\epsilon^{T_a - 212)(0.104 - .01066 \ln R)} - 0.0001 + 0.0105 (e_s - e_a)^{0.88} (0.37 + .0041 u_p)]}{[0.04686 (0.0041 T_a + 0.676)^7 + 0.01497]} \qquad (7)$$

where R is solar radiation measured in langleys
e_s is the saturation vapor pressure
e_a is the vapor pressure of water at the observed temperature

Values for solar radiation that were as an index for net radiation are not routinely available. Two other measurements have been used to index radiation. They are hours of sunshine and percent sky cover. A method of deriving values of solar radiation from percent sunshine was developed by Hamon et al. (1954). However real-time daily reports for hours of sunshine are supplied in a separate report and not included with other surface observations. So although this measurement was used extensively in developing the evaporation maps in NOAA Technical Report 33, the primary observation used operationally has been percent sky cover. The method of estimating solar radiation from percent sunshine was developed by Thompson (1976).

The sky cover estimate of solar radiation is used by program SYNTRAN (http://dipper.nws.noaa.gov/hdsb/data/archived/index.html) to compute solar radiation R as:

$$R = [B+(1 - N^{0.61} * (1 - B)] * Y_{100} \qquad (8)$$

where B is a parameter that depends on the location of the station
N is the fraction of the sky covered by clouds (decimal fraction)
Y_{100} is the clear sky radiation for the given day of the year

Experience with this estimate has shown that some estimates are about 10 percent low on the average, resulting in similarly low values of PE. Therefore an additional procedure has been developed which includes the following steps:

1. The long term average value for PE must be determined for the first order station of interest using program SYNTRAN.

2. Divide this value into the value for the same point on Map 3 of NTR 33. This ratio serves as the correction factor in MAPE. Figure 1 shows selected stations. Table 1 lists the station data used to develop Figure 1.

3. Stations for which correction factors are not available should no longer be used to computed daily PE estimates in the Operational Forecast Program Function MAPE. Such stations should be redefined without PE parameters and the NETWORK command run using the PPINIT program. If predetermined weights are used for operational MAPE computations the MAPE areas using the stations to be deleted must be redefined before deleting the stations. Any stations that continue to be used operationally to compute PE which have no available correction factor will be assigned a default correction factor.

4. For watersheds calibrated previously a PEADJ value needs to be determined and applied through the rainfall/runoff model. The proper adjustment to be applied is:

$$PEADJ = \frac{PE_{calib}}{PE_{33}} \qquad (9)$$

where PEADJ is the rainfall/runoff model PE adjustment factor
PE_{calib} is the long-term mean annual value of the PE time series used during calibration
PE_{33} is the weighted standard PE from Map 3 of NTR 33 for the stations used to by the Operational Forecast Program Function MAPE times

For watersheds that were calibrated using PE computed using percent sunshine or measured solar radiation (both of which produce PE estimates close to the standard) a PEADJ of 1.0 is appropriate.

The values for air temperature come from observed station values. The values for the vapor pressures require humidity data and are normally generated from observations of air and dew point temperature. The difference between the vapor pressures of air and free water surfaces for temperatures above -16 degrees Fahrenheit is approximated by:

$$e_s - e_a = (0.0041T_a + 0.676)^8 - (0.0041T_d + 0.676)^8 - 0.000019(T_a - T_d)) \quad (10)$$

where T_d is the dew point temperature in degrees Fahrenheit

The values of u_p are developed from hourly or other frequent periodic observations during the day and averaging over the day to get the total miles traveled during the day. The wind observations are normally observed at elevations above the ground, much higher than the recommended 2 feet and are generally adjusted, assuming a logarithmic distribution from the observed height to 2 feet. In NWSRFS computations, a curve was developed using wind observations from several stations having both anemometers on pans and at a broad range above the ground. Points were plotted and a curve drawn. A general equation for wind distributions is given as:

$$\frac{u_p}{u_z} = \left(\frac{2}{z}\right)^k \quad (11)$$

where u_p is the wind measured just above the pan (2 feet above the surface)
u_z is the wind measured at the anemometer level

The pan wind is then given as:

$$u_p = 24u_z(2/Z)^k \quad (12)$$

where u_z is the hourly observed wind speed at height Z
k is the coefficient determined from curve fitting

The equation for k was empirically fit to give the following equation:

$$k = 0.474 - 0.00246z + (z^2)8.44*10^{-6} \quad (13)$$

where z is the height of the anemometer above the ground

3. Long-term monthly means are tabulated in Climatological Data or the NOAA Technical Report 'Mean Monthly, Seasonal and Annual Pan Evaporation in the United States' (Farnsworth and

Thompson, 1982).

4. A middle-of-the-month long-term mean value can be generated from time series of pan data. The network of evaporation stations is adequate for determining mean basin PE in most non-mountainous areas. Reference to Maps 2 and 3 in the previously mentioned NOAA Technical Report show the spatial variability of PE on a May-to-October and an annual basis. Reference to these maps should assist a user in relating the degree to which available data represent the area of a given basin. Peculiarities of mountainous areas such as canyons with northeastern aspects or drainage winds must be considered in choosing adjustment factors for PE values.

Note that PE is a daily estimate and techniques have not been developed in NWSRFS to develop PE on any shorter time scales.

The advantages and disadvantages on the benefits of using daily PE data as opposed to a mean ET-demand curve are:

Advantages:

1. Differences in PE from day-to-day are considered. For example, evaporation rates differs significantly from clear days to rainy days.

2. Deviations from normal PE lasting for weeks or months are properly accounted for.

Disadvantages:

1. Meteorological variables used to compute PE may be inaccurate because:

    a. daily means of dewpoint and wind are based on only a few observations per day

    b. the relationship between sky cover or percent sunshine and radiation is quite variable

    c. sensors can deteriorate or be moved thus affecting the values reported

2. The data used to compute PE and the PE estimate itself need to be check frequently for consistency. This is generally not done operationally, thus PE estimates could easily become biased.

3. Sky cover estimates may not be available as ASOS is fully implemented.

To get some quantitative measure of the effect of using estimated PE or mean ET-demand on simulated discharge, we made comparative runs on three basins. All of the basins were in areas that receive little or no snow and were originally calibrated using PE time series computed from meteorological factors. Mean ET-demand values were obtained from the PE time series and the PE adjustment curve by solving for mean ET-demand values that would be equal to the long-term ET-demand for each month as computed from the PE data. These values were then adjusted slightly by using PEADJ so that the streamflow bias was about the same for the runs using estimated PE and mean ET-demand.

Table 2 shows the overall results of this comparison. As can be seen, there was no difference between the two runs in North Carolina, a slight difference in Mississippi and a more pronounced difference in Oklahoma. The magnitude of the change as might be expected is greatest in the basin which has the largest variation in annual PE. Also, as would be expected, the difference in PE between the two runs had more effect on the monthly volume RMS error than on the daily statistics. A close examination of the results indicates that 2/3 or more of the significant differences between the two runs occurred during sizable runoff events when the soil moisture deficits were zero or near zero. This indicates that the differences in PE during periods of precipitation were more of a factor than PE over the weeks or months preceding a runoff event. This suggests that simulations using mean values for PE could be improved by reducing PE during period of precipitation. This practice would reduce the difference between model runs using estimated PE and mean values of PE.

Once PE for a basin has been determined, the application of a transpiration demand curve must be determined. These two quantities multiplied together provide an estimate of the PET. As the soil layers begin to dry, the actual ET decreases until the soil moisture is depleted to the level that plant roots can no longer pull water molecules away from the soil. At that point vegetation wilts and ET essentially stops. The process of ET between the maximum value of PET and zero is controlled by the water available in the soil and is approximated in an essentially linear fashion within the soil moisture accounting models.

Practical Computation of Evapotranspiration Losses

The primary input to water loss computations is PE which has been described in the preceding section. PE is largely independent of the influences of soils and vegetation. It is usually obtained using program DLYTRAN (http://dipper.nws.noaa.gov/hdsb/data/archived/index.html) which accesses pan data and where air and water temperatures data is available converts pan evaporation to potential evaporation (PE). This conversion is required because evaporation from a pan follows a somewhat different energy exchange process than does evaporation from lakes and vegetation. The Class A pan, which sits above the ground, exchanges energy through its sides and bottom as well as at the pan water surface.

Normal warm season evaporation can dry out soil surfaces very quickly, causing evaporation from bare soil to drop to a low value. The principal loss process then becomes the transpiration from plants which continues at a fairly high level so long as soil moisture is available in the root zone. To include this effect in our hydrologic model, a vegetative demand or transpirational demand curve is used. This curve is used to approximate mathematically the annual cycles of the dominant species of trees and plants on a basin where they actively transpire during the growing season and enter into a dormant cycle during the winter. In the dormant cycle plants transpire very little, even though weather and soil moisture conditions dictate a significant amount. During the period of dormancy, values on the demand curve may be as low as 0.1. During the spring, as trees leaf out and crops grow and develop, values increase to 1.0 or more. The vegetative demand values are multiplied by the daily PE values to get a quantity, which is referred to as evapotranspiration demand (ED). The effect of soil moisture is taken into account in the soil moisture accounting model where actual evapotranspiration is computed.

References

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Kohler, M. Nordenson, T. and Fox, W.: 'Evaporation from Pans and Lakes', Weather Bureau Research Paper No. 38, May 1955.

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Figure 1. Map of SYNTRAN stations

Multipliers shown which remove bias from SYNTRAN point PE estimates. These corrections can be used in MAPE and will correct the long-term mean values from SYNTRAN to the evaporation atlas values.

Table 1. PE correction factors

Name	State	Ratio
ALEXANDRIA	LA	1.21
ALLENTOWN	PA	1.16
ASHEVILLE	NC	1.07
BATON ROUGE	LA	1.12
BINGHAMTON	NY	1.23
BRADFORD	PA	1.39
BRISTOL	TN	0.99
CHARLOTTESVILLE	VA	1.11
CHATTANOOGA	TN	1.15
DALLAS	TX	1.18
ELMIRA	NY	1.24
FORT SMITH	AR	1.12
HARRISBURG	PA	1.21
HUNTSVILLE	AL	1.14
JACKSON	MS	1.15
KNOXVILLE	TN	0.98
LAKE CHARLES	LA	1.21
LITTLE ROCK	AR	1.05
MARTINSBURG	WV	1.21
MEMPHIS	TN	1.11
MERIDIAN	MS	1.18
MOBILE	AL	1.09
NASHVILLE	TN	1.03
NEW ORLEANS	LA	1.10
NEWARK	NJ	1.11
PADUCAH	KY	1.17
PHILADELPHIA	PA	1.18
RICHMOND	VA	1.15
ROANOKE	VA	0.97
SHREVEPORT	LA	1.12
SPRINGFIELD	MO	1.12
WASHINGTON	DC	1.10
WILLIAMSPORT	PA	1.25
WILMINGTON	DE	1.27
W-BARRE/SCRANTON	PA	1.23

Table 2. Overall statistical comparison of streamflow simulations using estimated daily PE and/or mean PE values

	Daily Statistics					Monthly Volume RMS Error (MM)			Standard Deviation Estimates of Annual PE (MM)
	RMS Error (CMS)			Correlation Coefficient					
Basin	Est.	Mean	Change	Est.	Mean	Est.	Mean	Change	
Bird Creek near Sperry, Oklahoma	18.02	18.97	5.3%	.968	.965	3.97	5.13	29.0%	131.3
Leaf River near Collins, Mississippi	15.75	16.02	1.7%	.962	.754	7.54	7.91	5.0%	89.3
Neuse River near Northside, North Carolina	6.73	6.74	0.3%	.936	.936	5.61	5.71	1.8%	23.1