Section 6-5

Evaporation Estimates for Conceptual Modeling

Introduction

In order to produce a proper water balance, conceptual models require realistic and consistent estimates of evaporation as well as precipitation. Although evaporation data will generally not affect the simulation accuracy of individual storm events nearly as much as precipitation data, good evaporation estimates are critical to producing a reasonable seasonal and annual water balance. Like the other input data used to drive the models, evaporation estimates should correspond as closely as possible to what actually occurs in nature. Biased estimates of evaporation will cause model parameters to take on unrealistic values and will deteriorate the quality of the simulations.

At this stage of the process it is assumed that all the data needed to determine evaporation estimates for use by the models are available in the proper form and that the data have been checked for consistency and adjusted if necessary. It is also assumed that the areas where evaporation estimates are to be generated have been determined based on the definition of the flow points needed for calibration and the possible subdivision of the drainage areas into elevation zones or subareas has been specified by other means. It is also assumed that it has been determined whether mountainous or non-mountainous area procedures should be used to compute the estimates. As with temperature, generally the mountainous area procedures only need to be used for evaporation when there are definite variations in elevation over the river basin.

Terminology

There are a number of terms that are used in conjunction with evaporation that sometimes take on different meanings to different people, thus, these terms need to be clearly defined as to how they are used in this manual.

- Potential Evaporation - Potential Evaporation (PE) is defined as the evaporation from a well wetted (i.e. the moisture supply is not limiting the evaporation), actively growing grass surface. The PE rate for grass under these conditions is calculated from the current meteorological conditions, i.e. temperature, humidity, wind, radiation, atmospheric stability, etc..

- Free Water Surface Evaporation - Free Water Surface (FWS) evaporation is the evaporation from a water surface with no heat storage. Evaporation from lakes and reservoirs involves some energy being used to warm the water body or being released as the water body cools and thus differs from FWS evaporation. Studies have shown that FWS evaporation is essentially the same as PE from a grass surface.
- Evapotranspiration (ET) Demand - ET Demand is the term used in the Sacramento Model to specify the evaporation that occurs when the moisture supply is not limiting given the type of vegetation that exists and the activity level of that vegetation. Thus while PE is defined f

or an actively growing grass surface, ET Demand is based on the actual vegetation in the are a and how active that vegetation is given the time of the year and other factors.

- Seasonal PE Adjustment Curve - The PE adjustment curve modifies PE values on a seasona l basis for both the type of vegetation and the activity level of the vegetation. Thus, it is the seasonally varying ratio of ET Demand to PE or expressed in another way, ET Demand is eq ual to PE times the seasonal PE adjustment curve.

- Actual ET - Actual ET is the amount of evaporation loss from a watershed or subarea given the ET Demand and the current moisture conditions and snow cover. The actual amount o f ET is limited by the amount of moisture in the soil and the evaporation rate is generally sup pressed when snow covers the vegetation. Actual ET is less than or equal to ET Demand.

- Pan Evaporation - Pan evaporation is the amount of evaporation as measured with an evapo ration pan. Pan evaporation differs from FWS evaporation in that there is some change in h eat storage due to changes in the temperature of the water in the pan and because energy tran sfer occurs through the sides and bottom of a pan. The evaporation pan used most commonl y in the United States is called a Class A pan.

- Pan Coefficient - The pan coefficient is the average ratio of FWS evaporation to the evapor ation measured by a pan. Pan coefficients are less than 1.0 since the evaporation measured by the pan is greater than FWS evaporation over the long-term. The pan coefficient for a Cl ass A pan is generally said to be about 0.7. The May-October pan coefficient actually varie s from 0.66 to 0.88 over the contiguous United States as shown on map 4 in NOAA Technica l Report NWS 33 [*Farnsworth and Peck*, 1982].

It is important to clearly understand these terms before reading the rest of this section and in orde r to properly prepare and use evaporation data with conceptual models. The Sacramento Model computes actual ET starting with an ET-Demand that is derived from PE and a seasonal PE adj ustment curve. The ET-Demand values input to the model can either be in the form of climatol ogical averages (defined at the mid-point of each month) or daily estimates (calculated by applyi ng an average seasonal PE adjustment curve to a daily PE time series).

Determination of PE

For use in deriving evaporation estimates for application with conceptual models, PE can be in th e form of daily time series or average monthly values.

- Daily PE is generally computed from meteorological factors using a Penman type equation. The most common equations use air temperature, dew-point, wind speed, and solar radiati on to compute a daily value of PE since atmospheric radiation and the data to derive stability are seldom available. If direct measurements of solar radiation are not available, the amou nt of solar energy can be estimated from percent sunshine using the method of Hamon, Weiss , and Wilson [1954] or sky cover using the method of Thompson [1976]. Values can be co

mputed only at synoptic stations or at other climate stations that include instrumentation to m easure these variables. Temperature, dew-point, and especially wind data must be adjusted to a specified instrument height. Lindsey and Farnsworth [1992] reported that using percent sunshine to estimate the amount of solar radiation produces a reasonably unbiased estimate of PE. This study also indicated that using sky cover to get solar radiation will result in a bi ased estimate of evaporation. The NWSRFS synoptic data program includes a correction fo r removing this bias. It should also be noted that with the introduction of ASOS the sky cov er data are no longer the same as the manual observations of sky cover that the Thompson me thod uses to compute solar radiation.

Daily values of PE could also be obtained from daily pan evaporation measurements using th e appropriate pan coefficient to adjust the measured values. To be more precise the measur ed pan values should be adjusted for changes in heat storage using daily measurements of the water temperature in the pan. Even then the pan coefficient is only the average relationshi p between pan evaporation and FWS evaporation and actually varies somewhat from day to d ay based on meteorological conditions.

• Monthly average PE can be obtained from computations using meteorological factors or fro m average monthly pan evaporation adjusted by the appropriate pan coefficient. NOAA Te chnical Report NWS 34 [*Farnsworth and Thompson*, 1982] gives monthly average pan evap oration computed from meteorological stations for selected stations in each state. These val ues need to be adjusted by the appropriate pan coefficient to get average monthly PE. Tech nical Report 34 also contains tables of monthly average evaporation from pan data for the per iod 1956 to 1970. Averages of pan evaporation for other periods can be gotten directly fro m daily climatological stations that have pan measurements. Again the pan data need to be adjusted by the appropriate pan coefficient in order to get average monthly PE. In addition, in many parts of the country pan data are not available in the winter since the water in the pa ns will freeze. For these stations the ratio of annual FWS evaporation to May-October FWS values as determined from Technical Report NWS 33 can be used to determine the average amount of evaporation from November through April. Then a nearby meteorological statio n from report 34 can be used to prorate this total into monthly values.

Seasonal PE Adjustment Curves

The seasonal PE adjustment curve accounts for the type of vegetation in the area and the activity level of that vegetation. The curve is defined at the mid point of each month. When used with daily estimates of PE, linear interpolation is used between each point on the curve to determine the proper adjustment for each day. When monthly ET Demand is being input to the Sacrament o Model, then the average monthly PE is multiplied by the PE adjustment for that month to get th e ET Demand at the mid point of the month. Again linear interpolation is used to determine the ET Demand for a given day.

Studies have shown that the evaporation rates from most actively growing vegetation differs fro m the rate for grass on which PE computations are based. In addition, the evaporation rates can

vary considerably throughout the year as the vegetation goes through various stages from dormancy to active growth. A number of studies have shown that the total evaporation loss from a forest subjected to frequent rain, i.e. with leaves kept wet much of the time, can be 50% or more larger than the evaporation rate from grass (e.g. [*Calder, 1976]*. Under dry conditions the losses from a forest are much less due to stomatal control of water loss. For agricultural areas estimates of the seasonal PE adjustment curve can be computed for various crops using an FAO report [*Doorenbos and Pruitt*, 1977]. This report gives coefficients for various crops and climatic conditions that can be used to construct the seasonal adjustment curve based on the times of germination, attainment of full ground cover, start of maturing, and full maturity or harvest. For the crops listed, the PE adjustment during the active growing period varies from 0.8 to 1.25. There is also evidence that moss and lichen plants in tundra regions, such as Alaska and high elevations in the lower 48, use water at slower rates than does vegetation in warmer regions [*Patric and Black, 1968]*. Tundra plants function more like mulch than like transpiring vegetation. In such areas, evaporative demand, as specified by PE, can considerably exceed precipitation, but the soil almost always remains wet, even saturated, throughout the short summer season.

The PE adjustment curve used with the Sacramento Model is based solely on the time of the year and doesn't include any dynamics that account for differences in past and current climatic conditions from one year to another. For example, the activity level of vegetation in June could vary from a year with plenty of moisture and thus lush, green vegetation to a drought year when the vegetation has turned brown. The shape of the curve is also the same from year to year and thus any variations in the time when leaves come out in the spring or begin to turn colors in the fall are not taken into account. The PE adjustment curve used for hydrologic modeling is an integration of all the vegetation types and activity levels that exist over a watershed, elevation zone, or other area definition. Thus, some the information in the literature can serve as a guideline when coming up with a PE adjustment curve, but much of the process is subjectively based on a general knowledge of the type of vegetation in the area and the timing of changes in the activity levels.

Figures 6-5-1, 6-5-2, and 6-5-3 show seasonal PE adjustment curves that have been used for watershed calibrations at various locations around the country. Most of the curves in these figures exhibit a seasonal pattern of activity levels. This is because most of the watersheds contain considerable deciduous vegetation or crops that have a seasonal growth pattern. The curve for the watershed in western Washington shows essentially no seasonal variation. This watershed is covered predominantly with conifers, and the climatic conditions are such that the vegetation should be able to transpire throughout the year.

Figure 6-5-1. PE adjustment curves for watersheds in the east and south.

Figure 6-5-2. PE adjustment curves for watersheds in the mid-west and plains.

Figure 6-5-3. PE adjustments curves for watersheds in the western mountains.

Koren et al. [1998] compared NDVI green vegetation fraction values extracted from NCEP glob al data sets to PE adjustment curves from watersheds representing a northern mixed forest, south ern mixed forest, southern Appalachian highlands, and the southwest (these curves were include d in a 1970's prepared handout on deriving initial parameter values for the Sacramento Model).

A reasonable correlation was found between the green vegetation fraction and the PE adjustment factors. This resulted in an equation for estimating the PE adjustment factors from the NDVI green fractions. This method can be used to derive a seasonal PE adjustment curve, but the method may not be applicable to the whole country. This method is included in CAP.

Non-Mountainous Area ET Demand Estimates

Procedure

For non-mountainous areas of the United States the map of annual FWS evaporation (map 3) in NOAA Technical Report NWS 33 has been adopted as the standard for long-term average PE values. The annual FWS evaporation values from this map provide an estimate of annual PE which when properly prorated to monthly values and combined with a reasonable seasonal adjustment curve gives ET Demand estimates that generally produce a realistic water balance. Thus, all PE estimates used in non-mountainous areas should first be adjusted to conform to the annual FWS values given in Technical Report 33.

The steps to follow for determining initial ET Demand values for each modeling area in a non-mountainous region are:

1. Obtain monthly estimates of PE as described earlier in this section based on meteorological variables or pan data and adjust the annual total to correspond to the value picked off map 3 of Technical Report 33. The PE may be in the form of daily values or monthly averages. The PE estimate can be based on a single station, a weighted average of several stations, or computed by using the MAPE program. The MAPE program can combine daily PE computed from meteorological variables and adjusted daily pan measurements to get a mean areal value. The MAPE program contains the option to make consistency checks and corrections.

2. Determine a seasonal PE adjustment curve as described earlier in this section. This curve is always defined at the mid point of each month.

3. Compute ET Demand. If climatological average values of ET Demand are to be used, the average PE for each month is multiplied by the PE adjustment for the month to get values of ET Demand that are assigned to the mid point of each month. If daily estimates of ET Demand are to be used by the model, the input is a daily time series of PE and the seasonal PE adjustment curve defined at the mid point of each month.

The only available guidance regarding the use of daily PE values as opposed to mean monthly estimates comes from a brief HRL study [*Anderson and Farnsworth*, 1981]. In this study simulations from three watersheds using both daily PE values with a seasonal PE adjustment curve and mean monthly ET Demand estimates were compared. The average monthly ET Demand values in both cases were kept exactly the same. The results are shown in Table 6-5-1. There was very little difference in simulation results in North Carolina, a little improvement when using daily PE values in Mississippi, and more improvement, especially in regard to monthly volume error

s, for the Oklahoma watershed. In general, two conclusions can be made from this study. First, PE data has more effect on volume computations than on daily flow calculations. Second, the use of daily PE data improves simulation results more in areas where there is a significant variation in PE amounts from one year to another. The greatest variability in annual PE values in the United States is in the southern plains.

During calibration the amount of ET Demand may need to be adjusted in order to obtain a good water balance. Estimates of long-term average precipitation should be quite reliable in a non-mountainous region, thus variations in ET Demand from one watershed to another should be related to differences in vegetation, as long as one doesn't neglect water balance terms such as diversions and deep aquifer recharge. When making adjustments in ET Demand, it is best to monitor how the seasonal PE adjustment curve is changing to make sure the transition from one month to another is realistic and that the differences in relationships from one watershed to another make sense.

	Daily RMS error (cms)		Monthly Vol. RMS error (mm)		
Watershed	Daily PE	Monthly Means	Daily PE	Monthly Means	Standard Deviation of Annual PE (mm)
Bird Ck. nr Sperry, OK	18.02	18.97	3.97	5.13	131.3
Leaf R. nr Collins, MS	15.76	16.02	7.54	7.91	89.3
Neuse R. nr Northside, NC	6.73	6.74	5.61	5.71	23.1

Table 6-5-1. Statistical comparison of streamflow simulations using computed daily PE values versus simulations using mean ET Demand estimates.

Mountainous Area ET Demand Estimates

Introduction

In mountainous regions the areal estimates of average precipitation are more likely to be in error than in non-mountainous areas. The isohyetal analysis used may reflect the general trend in how precipitation varies over the region, but at the watershed scale there can easily be random errors. Thus, if one treats the precipitation derived from the isohyetal maps as "true" and forces ET Demand adjustments to create a good water balance, it very likely that the resulting ET Demand

variation over the region will not make physical sense. There should be a reasonable variation in ET Demand with elevation since PE and vegetation are highly correlated with elevation. Thus the underlying assumption for the recommended procedure for determining evaporation in mountainous areas is:

> *ET Demand variations are more spatially predictable and contain less error than precipitation variations, thus it is more logical to determine a reasonable ET Demand versus elevation relationship and then adjust MAP if needed than to assume MAP is correct and adjust ET Demand to obtain the correct water balance.*

Two approaches are given in this manual for determining the relationship between ET Demand and elevation. Which approach is used depends on whether the precipitation amounts from the available isohyetal analysis can be used to generate a reasonable water balance over most watersheds in the region. If so, water balance computations can be used to determine how actual ET varies with elevation and can serve as a basis for determining an ET Demand versus elevation relationship. If areal precipitation estimates derived from the available isohyetal maps do not produce a reasonable water balance over most watersheds in the region, then it is best to derive the variation in ET Demand with elevation from information on the variation of evaporation and vegetation over the region and combine this with runoff data to determine the amount of precipitation needed to produce the proper water balance. One way to judge the quality of the precipitation estimates from an isohyetal map is to compare the resulting actual ET values to PE estimates for the region. Actual ET is generally less than PE in most regions, though the ratio will vary depending on climate. The ratio of actual ET to PE is lowest in an arid region. In a forested area with frequent rains, actual ET could be greater than PE as mentioned earlier in this section. A snow cover over substantial portions of the year will tend to suppress ET, thus reducing the ratio.

Before describing methods of obtaining an ET Demand versus elevation relationship, we should first look at how PE can vary with elevation as a guide. In mountainous areas the annual FWS map in Technical Report 33 is not drawn to a sufficiently small spatial scale to define PE at the watershed level. That map shows the general trend of PE variations in mountainous areas, but not at the detailed level needed for hydrologic modeling. The amount of PE at a given location is affected by the climate of that location. In the mountains there can be small scale variations in PE due to terrain effects on radiation and wind, however, at the watershed scale much of the variation in PE can be explained by elevation differences. PE decreases with elevation with the rate of decrease becoming less as elevation increases. Figure 6-5-4 shows the variation in PE with elevation for several regions of the United States. The two relationships from Technical Report 33 were produced by plotting pan measurements at various elevations over the regions and then using the average pan coefficient for the region to convert the values to FWS evaporation. The Alaska relationship was generated from values computed by the Thornthwaite method for stations in south central Alaska by Patric and Black [1968]. The Upper Missouri River basin relationship was determined from a few pan sites and values picked off map 3 of Technical Report 33. The other two relationships were determined by plotting PE derived from

Figure 6-5-4. PE versus elevation for various regions of the United States.

pan measurements and meteorological variables. The magnitude of PE varies from one region to another due to climatic differences, but the general shape of the curves are similar.

In many regions the shape of the ET Demand versus elevation relationship should be somewhat similar to the shape of a plot of PE versus elevation. This will occur in regions where there is significant vegetation at all elevations and the transition from one type of vegetation to another is not dramatic. Such regions are those in the eastern part of the country and west of the Pacific crest. In other regions the variation in vegetation types and thus PE adjustments are so great that

the shape of a ET Demand versus elevation plot may not be similar to the PE versus elevation relationship. Watersheds in such regions may include various subsets of transitions from arid climate vegetation such as cactus and sagebrush to forested zones to alpine tundra to extremely high elevations with no vegetation at all. Such variations can occur in the intermountain west and Alaska. In the northern portions of the intermountain west, the ET Demand versus elevation relationship is likely similar to a PE versus elevation plot over the range in elevations where most of the runoff is generated. In addition to being difficult to determine, it probably is not that important to know the exact ET Demand versus elevation relationship over elevation ranges where little or no runoff is generated.

Determining ET Demand from a Water Balance Analysis

In order to use this approach to determine a ET Demand versus elevation relationship for a river basin, water balance computations for drainages within the basin should produce a plot of actual ET versus elevation that shows a clear relationship. There may be a few watersheds within the basin that deviate from the relationship defined by the others due to possible errors in the isohyetal analysis (as in Figure 6-3-5), but the results from most of the drainages should show a clear and realistic relationship. If there is no clear relationship or if the resulting actual ET values are not reasonable, then the second approach (i.e. using evaporation, vegetation, and runoff data) should be tried. The water balance approach works best for relatively wet regions where the ratio of actual ET to ET Demand is greater than about 0.75 or if the ratio is less, it is due to a long period of snow cover. In semi-arid regions where this ratio is lower, it is more likely that there will be considerable scatter in the actual ET values derived from water balance computations.

The steps to follow when trying to derive a ET Demand versus elevation relationship from the results of water balance computations are as follows:

1. Perform water balance computations for appropriate headwater and local drainages within the river basin to determine estimates of actual annual ET. Guidelines for water balance computations are in Section 6-3 under the section “Determination of Average Mean Areal Precipitation for Each MAP Area.”

2. Plot actual annual ET values derived from the water balance computations in step 1against the mean elevation of each drainage area (Figures 6-3-5 and 6-5-5 are examples of such plots). If most of the points define a clear relationship that is physically realistic, then draw a line that defines the actual annual ET versus elevation relationship for the basin. If the plot exhibits a lot of scatter or the values are physically unreasonable, then try the second approach to determining an ET Demand versus elevation relationship.

3. If possible, use pan data or estimates based on meteorological variables to determine annual PE values for sites at different elevations in the vicinity of the basin. Plot these points and draw a PE versus elevation line. This step is optional, but can be helpful as a guide for determining the shape of the ET Demand versus elevation relationship.

4. Obtain a point on the ET Demand versus elevation relationship by calibrating the initial he adwater basin (recommended strategy for calibrating the drainages in a river basin is discusse d in chapter 7) to determine the average annual ratio of actual ET to ET Demand. This is do ne through an iterative process.

a. Make an assumption as to the average annual ratio of actual ET to ET Demand to deter mine an initial estimate of the annual ET Demand for the watershed. If the headwater h as multiple elevation zones, the ratio generally increases with elevation when the typical l ength of snow on the ground is not substantially different between zones. When one zo ne has snow for a much longer period than others, its ratio will typically be smaller due to suppression of evaporation when a snow cover exists.

b. Using estimates of monthly PE and the seasonal PE adjustment curve generate monthl y ET Demand values (could use daily PE data, if available) for this drainage.

c. Adjust the seasonal PE adjustment curve until the resulting annual ET Demand is the s ame as the ET Demand which was based on the assumed ratio of actual ET to ET Deman d. Spreadsheets are an ideal tool for these calculations.

d. Calibrate the headwater area using these monthly ET Demand values. As the calibrat ion proceeds, check the resulting average annual ratio of actual ET to ET Demand and re vise the estimates of ET Demand based on the actual value of the ratio. This will typica lly have to be done once or twice.

e. Finally, take the resulting annual ET Demand value and plot it versus elevation on the graph produced in step 2.

5. Using the value of annual ET Demand from the initial headwater area, draw an initial esti mate of the curve showing how ET Demand should vary with elevation over the river basin. The actual annual ET and PE versus elevation plots can be helpful in drawing this curve. Also how the ratio of actual ET to ET Demand likely varies with elevation should be taken in to account.

6. Verify the ET Demand versus elevation curve by using annual ET Demand from this relati onship to calibrate other headwater areas at different elevations. Adjust annual ET Demand and thus the curve if the resulting ratio of actual ET to ET Demand is unrealistic.

7. Use the resulting annual ET Demand versus elevation relationship when calibrating all of t he other drainages within the river basin. Seasonal PE adjustment curves used to prorate th e annual ET Demand into monthly values should reflect changes in the vegetation types and activity patterns with elevation. Some scatter about the defined relationship is allowed base d on the location of the drainage within the basin (e.g. areas in the northern part of a river bas in might be assigned a slightly lower annual ET Demand for a given elevation than an area in the southern part of the basin). During the calibrations, corrections to the long-term water balance should be made by adjusting the amount of precipitation rather than changing the ET Demand curve.

This procedure may be somewhat difficult to follow, thus it will be illustrated step by step using the Merrimack River Basin in New Hampshire and Massachusetts.

Step 1 – Water balance values were computed for all appropriate headwater areas and a coupl e of local areas within the Merrimack Basin. The WATERBAL operation was used to calcu late the water balance components (requires the inclusion of the SNOW-17 and SAC-SMA o perations -- nominal parameter values were specified). The MAP time series were based on the PRISM estimates of annual precipitation. The PXADJ and SCF model parameters wer e set to 1.0 so that there would be no changes made to the MAP values. The water balance values are shown in Table 6-5-2.

Step 2 – The actual ET values generated by the water balance analysis were plotted against th e mean elevation of each watershed as shown in Figure 6-5-5. There is a reasonable relatio nship between actual ET and elevation. Some of the scatter is undoubtedly caused by clima te differences resulting from variations in latitude and distance from the coast and some is du e to sight variations in vegetation from one area to the next, however, a major portion of the s catter could be caused by inaccuracies in the PRISM isohyetal analysis.

Step 3 – There were two pan evaporation sites and two locations with evaporation computed from meteorological factors within the basin. All the sites were at similar elevations, thus it was not possible to construct a PE versus elevation relationship. The available data were u sed to derive an estimate of mean monthly PE that was thought to be realistic for a 500-1000 foot elevation in the central part of the basin. This seasonal variation in PE is shown in Fig ure 6-5-6. This PE corresponds to an annual total of 27.3 inches.

Step 4 – The Smith River near Bristol, NH (BRSN3 - mean elevation of 1117 feet) was chose n as the initial headwater area to be calibrated for the Merrimack Basin. This watershed has a single elevation zone. As far as arriving at a final ET Demand estimate for BRSN3, the s teps were as follows:

4.a – A value of 0.75 was used as the initial estimate of the ratio of actual ET to ET Dem and for BRSN3. This was just a guess.

4.b& c – An initial guess of the shape for the seasonal PE adjustment curve was made for BRSN3. This curve was then adjusted so that when the values were multiplied by the monthly PE shown in Figure 6-5-6 to get ET Demand, the resulting annual ratio of actual ET to ET Demand was about 0.75. This initial PE adjustment curve is shown in Figure 6-5-7. The resulting monthly ET Demand values are shown in Figure 6-5-6 and represe nt an annual total of about 25.2 inches.

Watershed	Period(WY)	Pcpn	Runoff	ET
BRSN3	49-77 49-93	41.6 41.9	23.1 23.2	18.5 18.7
PTRN3	49-77	43.8	23.4	20.8

DVSN3	49-78	42.9	22.6	20.3
SOUN3	52-77 52-87	39.7 40.4	19.5 20.0	20.2 20.4
SOHN3	49-76	44.0	23.0	21.0
WGTM3	49-77 49-92	43.8 44.8	22.4 23.4	21.4 21.4
GFFN3	49-78	42.3	21.0	21.3
NCIN3	49-70	42.5	20.6	21.9
FBGM3	73-93	48.4	26.3	22.1
SAXM3	81-93	47.1	25.0	22.1
MAYM3	49-77 49-93	45.0 45.7	22.1 22.5	22.9 23.2
WLMM3	65-93	44.7	21.8	22.9
RUMN3	49-77	39.0	24.2	14.8
WOON3	49-77	49.7	36.5	13.2
HENN3(local)	49-77	42.0	23.8	18.2
PLMN3(local)	49-77	45.2	28.1	17.1

Table 6-5-2. Water Balance Analysis for the Merrimack Basin (values are in inches).

4.d – The BRSN3 watershed was calibrated following the guidelines given in chapter 7. Early on in the calibration it became clear that the ratio of actual ET to ET Demand for this watershed had been underestimated. It was evident that the ratio was more in the range of 0.85-0.9 rather than the initial guess of 0.75. Thus, the PE adjustment curve was altered and new ET Demand values computed. When the calibration was completed, the ratio of actual ET to ET Demand was 0.87. The final PE adjustment curve is shown in Figure 6-5-6. The final monthly ET Demand values, which resulted in an annual total of 21.7 inches, are shown in Figure 6-5-7.

4.e – The annual ET Demand for BRSN3 was plotted versus elevation on the plot produced in step 2 as shown in Figure 6-5-5.

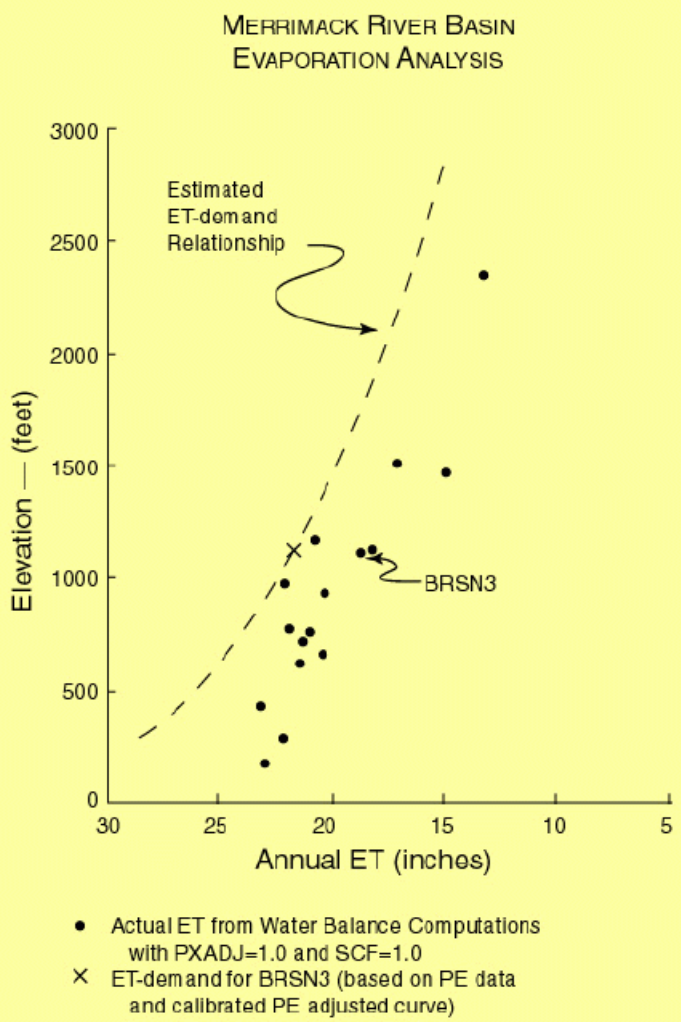
MERRIMACK RIVER BASIN
EVAPORATION ANALYSIS
Estimated
ET-demand
Relationship
BRSN3
Elevation — (feet)
3000
2500
2000
1500
1000
500
0
30
25
20
15
10
5
Annual ET (inches)
Actual ET from Water Balance Computations
with PXADJ=1.0 and SCF=1.0
ET-demand for BRSN3 (based on PE data
and calibrated PE adjusted curve)

Figure 6-5-5. Evaporation versus elevation relationships for the Merrimack River bas in.

Figure 6-5-6. Evaporation Values for the Smith River near Bristol, NH (BRSN3).

Figure 6-5-7. Season PE Adjustment Curves for BRSN3.

Step 5 – An estimate of the relationship between ET Demand and elevation was drawn for th e Merrimack Basin using the trend in the actual ET versus elevation plot as a guide. This re lationship is shown in Figure 6-5-5.

Step 6 – To test the validity of the estimated relationship between ET Demand and elevation

derived in step 5, model simulation runs were made for two other headwater areas at differen t elevations. These were the Pemigewasset River near Woodstock, NH (two subareas with mean elevations of 1465 and 2846 feet) and the Assabet River near Maynard, MA (mean ele vation of 448 feet). Annual ET Demand values for these watersheds were picked off the cur ve shown in Figure 6-5-5 and prorated to monthly values. The proration was based on modi fying the shape of the seasonal PE adjustment curve for BRSN3 for perceived variations in v egetation activity and type from one area to another and adjusting the values so that when mu ltiplied by the monthly PE shown in Figure 6-5-6, the resulting ET Demand had the correct a nnual total (variations of PE with elevation are implicitly absorbed into the seasonal adjustm ents). In deciding whether the estimated relationship between ET Demand and elevation wa s realistic, the higher and lower elevation watersheds were not calibrated, but instead the para meters determine for BRSN3 were used for the simulations. This seemed reasonable at this point in the calibration process since an assessment of hydrologic variability had suggested t hat model parameters should be quite similar over the entire Merrimack Basin (see Figure 4. 2). These simulations resulted in variations in the ratio of actual ET to ET Demand to vary from around 0.85 at the lowest elevation to slightly over 0.9 at the highest elevation. This s eemed quite realistic.

Step 7 – The annual ET Demand versus elevation relationship shown in Figure 6-5-5 was use d to calibrate the other watersheds within the Merrimack Basin. Some slight deviations off this relationship were made to account for the location of each watershed within the basin (e. g. slightly different ET Demand values were used when watersheds at similar elevations wer e located at different latitudes). Figure 6-5-8 shows the actual annual ET Demand values u sed in the final calibration of each watershed. The figure also indicates those watersheds fo r which precipitation values needed to be adjusted in order to obtain the proper water balance (this was done by using PXADJ in the SNOW-17 operation). As mention previously it is more reasonable to establish a realistic relationship between ET Demand and elevation and t hen adjust precipitation if needed than to treat the isohyetal map as the truth and alter the ET Demand to get the proper water balance. The isohyetal analysis was quite good for this rive r basin such that none of the MAP time series had to be adjusted by more than 5%.

Determining Precipitation and Actual ET from Runoff, Evaporation, and Vegetation Information

This approach uses estimates of how ET Demand varies with elevation to determine the average amount of precipitation and actual ET over a river basin. This approach is primarily for use in areas where the isohyetal estimates of annual precipitation are not considered realistic. This is f requently the case in regions with very sparse precipitation networks such as Alaska (see section "Determination of the Average Mean Areal Precipitation in Data Sparse Regions" in Section 6-3). This approach could also be tried in regions where there is a lot of scatter in the actual ET ve rsus elevation plot determined from water balance computations. This approach relies on using runoff data and an estimate of actual ET to determine the amount of average annual

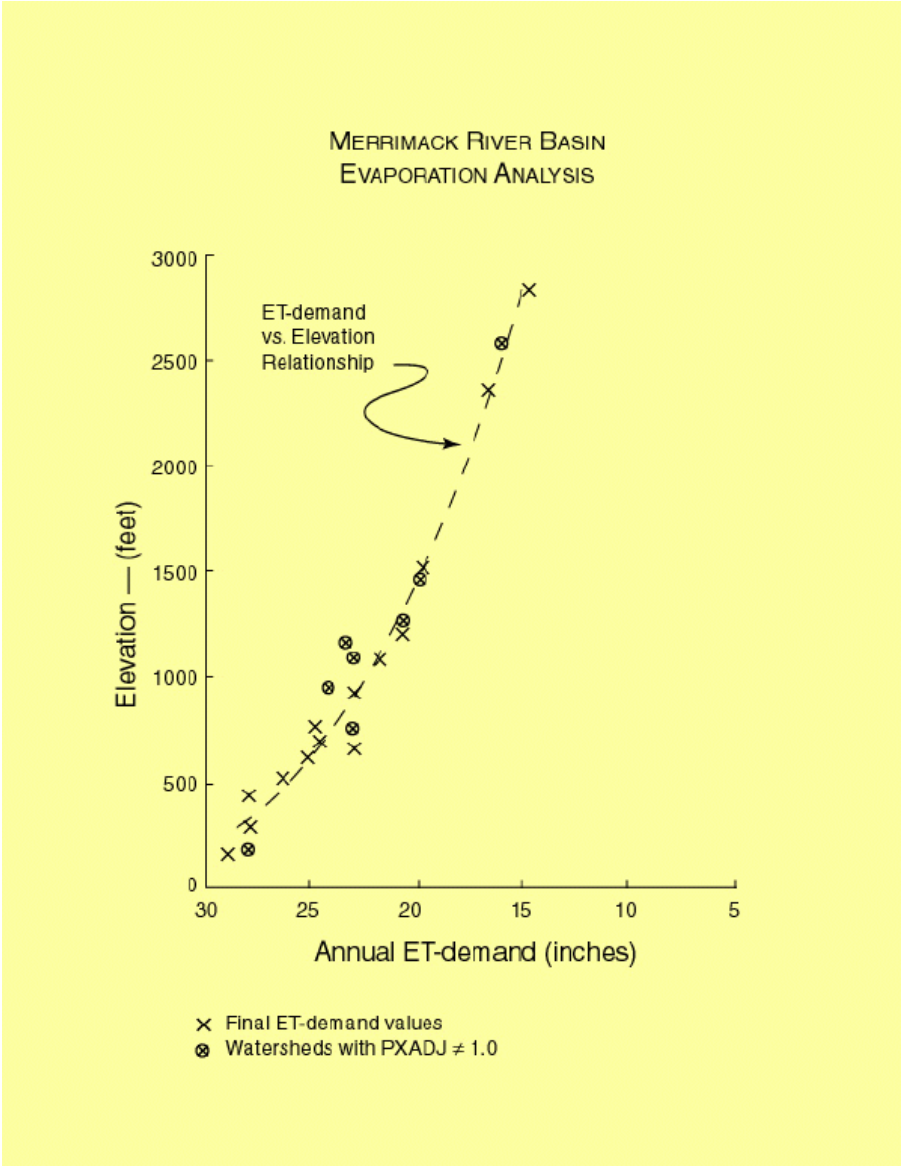
MERRIMACK RIVER BASIN
EVAPORATION ANALYSIS
ET-demand
vs. Elevation
Relationship
Elevation — (feet)
3000
2500
2000
1500
1000
500
0
30
25
20
15
10
5
Annual ET-demand (inches)
Final ET-demand values
Watersheds with PXADJ ≠ 1.0

Figure 6-5-8. Final ET Demand values used for the Merrimack River basin.

precipitation. In Alaska this method can give more reliable estimates of average annual precipitation than estimates based on precipitation gage data because the precipitation network is sparse and the amount of actual annual ET is relatively small as compared to annual runoff. If this approach was used in an area where evaporation is much greater than runoff, such as the central Arizona mountains, it would probably not produce precipitation estimates that were as good as those determined by an isohyetal analysis using only precipitation gage data even though the water balance estimates of actual ET using the isohyetal map information might show considerable scatter. In such an area it might be possible to use a blend between the two approaches to estimate how ET Demand should vary with elevation and to refine the precipitation pattern over the region. The steps to follow when deriving precipitation and ET Demand versus elevation estimates from evaporation and runoff data are as follows (again a spreadsheet is ideal for doing these computations):

1. Determine a relationship between annual PE and elevation.

2. Select watersheds within the river basin with good runoff data and adjust for any diversions or other gains or losses.

3. For the initial headwater area to be calibrated determine the annual PE at the mean elevation of the drainage. If multiple elevation zones are being used, determine the annual PE value at the mean elevation of each zone.

4. Prorate the annual PE amounts into average monthly values.

5. Subjectively determine values for the seasonal PE adjustment curves based on the vegetation types and activity patterns within the watershed or each elevation zone. These curves may vary considerably with elevation if the vegetation cover and climate changes substantially with elevation.

6. Multiply the average monthly PE times the seasonal PE adjustments to get monthly ET Demand estimates at each elevation. From these monthly values compute the annual ET Demand.

7. Make an assumption as to the ratio of actual ET to ET Demand for the watershed or each zone.

8. Estimate the actual ET by multiplying the ratio from step 7 times the annual ET Demand values from step 6. If there are multiple elevation zones, weight each actual ET value by the portion of the watershed that it represents to get the annual actual ET for the entire watershed.

9. Add the annual actual ET to the average annual runoff to get an estimate of the average annual precipitation. If there are elevation zones, this precipitation can be prorated to each zone by using the precipitation pattern shown in the isohyetal analysis. MAP time series can then be generated that contain these average annual precipitation amounts by using the mountainous area precipitation procedure described in Section 6-3.

10. Calibrate the watershed using the MAP time series and the ET Demand values from step 6. The MAP time series will typically have to be regenerated a couple of times during the calibration process as the model values of the ratio of actual ET to ET Demand are more precisely determined. Also the distribution of precipitation with elevation may need to be altered if there is evidence that the initial pattern is unrealistic. The pattern of how precipitation is distributed with elevation can often be verified by comparing the amount of snow generated in various zones with available snow observations or by comparing modeled glacial changes with reported trends.

11. Calibrate other watersheds in the river basin using steps 3 through 10. Utilize the values used and determined during previous calibrations when working on new drainages. A single ET Demand versus elevation relationship for the entire river basin should emerge, as well as estimates of average annual precipitation for various watersheds and elevation zones. The ratio of these precipitation estimates to those obtained from the isohyetal analysis should be able to be used to adjust the isohyetal maps for portions of the basin where calibration is not possible.

To illustrate this approach we will use the Chisana River near Northway, Alaska. This 3280 mi^2 watershed is located on the north side of the Wrangell Mountains and varies in elevation from about 1700 to over 10000 feet with an average elevation of about 3500 feet. About 6% of the wa

tershed is covered by glaciers. There is one precipitation station with a long record at the outl et and 2 others with short records at lower elevations in the watershed and about a dozen other su ch stations, all below 3200 feet and many with short records, scattered over a large area surround ing the watershed. A comparison of the PRISM estimate of precipitation for the watershed of 21 inches as compared to measured runoff of 9.7 inches results in an actual ET of 11.3 inches. Thi s actual ET value was considered to be somewhat high given the length of the snow cover period over much of the watershed, thus it was decided to derive an estimate of average annual precipi tation from runoff data and evaporation estimates. This was done in the following manner:

1. Monthly PE values were derived for low elevations in south central Alaska from pan data and an estimate of PE during the winter months. This seasonal PE curve and the pan sites u sed to create the curve are shown in Figure 6-5-9. The annual PE represented by this curve is 19 inches.

2. Using the shape from this low elevation seasonal PE curve and the relationship between P E and elevation shown for south central Alaska in Figure 6-5-4, monthly PE curves were con structed for the mean elevation of the lower and upper zones in the Chisana watershed (glaci er zone is considered to have no evaporation). These curves are shown in Figure 6-5-10. The annual PE for the lower zone with a mean elevation of 2400 feet is 14.3 inches and the annual PE for the upper zone with a mean elevation of 6000 feet is 6.7 inches.

3. Seasonal PE adjustment curves were subjectively estimated for each elevation zone as sho wn in Figure 6-5-11. The lower zone is primarily muskeg, willows, and black spruce. The upper zone is above the tree line with a mixture of tundra and barren areas.

4. Seasonal ET Demand curves were then calculated by multiplying the average daily PE for each month times the PE adjustment for that month. The resulting ET Demand curves are s hown in Figure 6-5-12. The total annual ET Demand based on these curves is 8.5 inches for the lower zone and 2.0 inches for the upper zone.

Figure 6-5-9. Low elevation seasonal PE curve for south central Alaska.

Figure 6-5-10. Seasonal PE curves for Chisana watershed elevation zones.

Figure 6-5-11. Seasonal PE adjustment curves for the Chisana River.

Figure 6-5-12. ET Demand curves for the Chisana River.

5. The next series of steps were to estimate the ratio of actual ET to ET Demand for each zone, use those values to calculate annual actual ET for the watershed, add annual actual ET to the average annual runoff to estimate the annual average precipitation, generate MAP time series based on this precipitation amount, and calibrate the watershed using this time series and ET Demand curves from step 4. Based on the calibration, the estimates of the ratio of actual ET to ET Demand were revised and new precipitation time series generated. The initial guess as to the ratio of actual ET to ET Demand was 0.75 for each zone. Based on the initial calibration, the ratio was adjusted to 0.8 for the lower zone and 0.6 for the upper zone. These values of the ratio gave annual actual ET values of 6.8 and 1.2 inches for the lower and upper zones, respectively, and a watershed average actual ET of 5.2 inches (lower zone comprises 72% of the area, the upper zone 22%, and the glaciers 6%). The average annual runoff was 9.7 inches which when added to the annual actual ET gave a watershed average precipitation of 14.8 inches (PRISM estimate was 21 inches). Elevation zone values of annual precipitation were determined by multiplying the watershed average by the ratio of zone precipitation to watershed precipitation from the PRISM analysis. These ratios were 0.73, 1.53, and 2.29 for the lower, upper, and glacial zones, respectively, which resulted in average annual precipitation values for the zones of 10.8, 22.7, and 34.0 inches. These values produced a reasonable simulation of streamflow and seasonal snow cover for the watershed and changes over time to the glaciers seemed realistic.

This approach was also used in the Upper Kenai River basin in Alaska to get annual precipitation estimates that would produce a reasonable water balance and actual ET values. For the Trail River near Lawing this approach resulted in an actual annual ET of 4.2 inches and an annual precipitation of 69.5 inches. The PRISM annual precipitation for the watershed was 96.7 inches.

Mountainous Area Evaporation Summary

No matter which of the two approaches in this manual are used to get evaporation estimates in a mountainous region or whether some other approach is followed, it is essential to end up with evaporation estimates that are physically realistic in both magnitude and spatial variability over the river basin. With the real potential for errors in precipitation amounts derived from any isohyetal analysis at the watershed scale, one cannot assume that the precipitation amounts are correct and then adjust evaporation to whatever values are needed to produce a near zero water balance. This approach is guaranteed to produce unrealistic estimates of evaporation. Therefore an app

roach must be followed that uses evaporation values that are realistic and vary logically with ele vation. Any adjustments that may be needed to produce a near zero water balance should be mad e to the precipitation estimates.