IV.1.2-MAP STEPS TO FOLLOW WHEN COMPUTING MEAN AREAL PRECIPITATION (MAP) FOR MODEL CALIBRATION

Bookmarks

Purpose . . . . [Bookmark]
Introduction . . . . [Bookmark]
Data Requirements and Preparations . . . . [Bookmark]
RECOMMENDED PROCEDURES FOR UTILIZING PROGRAM MAP . . . [Bookmark]
General Techniques for Mountainous Areas . . . . [Bookmark]
Developing Station Characteristics and Station Weights [Bookmark]
Gage Selection and Grid Orientation . . . . [Bookmark]
Station Characteristics . . . . [Bookmark]
Station Weights . . . . [Bookmark]
Importance of Synthetic Stations and Station Locations in the Calibration Process . . . . [Bookmark]
USE OF PRECIPITATION ADJUSTMENT FACTOR PXADJ AND SCF . [Bookmark]
Review of Previous Studies . . . . [Bookmark]
Current Gage Catch Studies . . . . [Bookmark]
Precipitation Adjustment Factors . . . . [Bookmark]
Initial Estimate of SCF . . . . [Bookmark]
Evaluation of the Parameter SCF . . . . [Bookmark]
References . . . . [Bookmark]
Tables . . . . [Bookmark]
Figures . . . . [Bookmark]
[Bottom]

Contents

Page

Purpose 1
Introduction 2
Data Requirements and Preparations 2
RECOMMENDED PROCEDURES FOR UTILIZING PROGRAM MAP 3
   General Techniques for Mountainous Areas 4
   Developing Station Characteristics and Station Weights . . . 7
      Gage Selection and Grid Orientation 7
      Station Characteristics 8
      Station Weights 9
      Importance of Synthetic Stations and Station Locations in the Calibration Process 10
USE OF PRECIPITATION ADJUSTMENT FACTOR PXADJ AND SCF 11
   Review of Previous Studies 11
   Current Gage Catch Studies 13
   Precipitation Adjustment Factors 14
   Initial Estimate of SCF 14
   Evaluation of the Parameter SCF 16
References 17

[Next] [Previous] [Bookmarks] [Top]

Purpose

This Section describes the steps follow when computing mean areal precipitation (MAP) values used for model calibration.

Included is information for making maximum use of all the various precipitation adjustment features and includes:

- o an outline of the preparation necessary in order to run the MAP program
- o a discussion of the various options and parameters within the MAP program with primary emphasis on developing mean areal precipitation estimates for mountainous areas
- o a discussion the use of precipitation adjustment factors available outside of the MAP program (PXADJ and SCF)

[Next] [Previous] [Bookmarks] [Top]

Introduction

Measurements of precipitation are a major input. Point precipitation data are converted to a mean areal precipitation estimate for use in the catchment model.

Many factors influence the estimate of mean areal precipitation, including but not limited to:

1. density and arrangement of the gage network
2. the particular site and gage characteristics at each location within the network
3. methods of areal analysis used
4. basin characteristics
5. storm characteristics
6. orographic effects
7. point precipitation measurement errors

Various procedures and options are available which should enable the user to obtain reliable mean areal precipitation estimates. Some of these options are contained within the Mean Areal Precipitation (MAP) program itself while others are part of the Manual Calibration Program or the snow accumulation and ablation model.

[Next] [Previous] [Bookmarks] [Top]

Data Requirements and Preparations

In order to use program MAP (Section III.7-MAP) some preliminary steps must be done. An inventory of the available hourly and daily precipitation which may be of use in the analysis should be obtained using program STAINV which is available at the Internet address http://dipper.nws.noaa.gov/hdsb/data/archived/index.html.

Using this inventory and the Annual Summaries of Climatological Data published by the National Climatological Data Center (NCDC) a selection can be made of all daily and hourly precipitation stations which may be of use in the analysis. Programs DLYTRAN and HLYTRAN can be used to get the time series data for the selected stations and are available at the Internet address http://dipper.nws.noaa.gov/hdsb/data/archived/index.html.

The Annual Summaries of Climatological Data and the monthly Climatological Bulletins (also published by NCDC) can be used to obtain other information about precipitation stations. Location (latitude, longitude), elevation, observation time, state and station number, location change, plus additional information about the precipitation stations (such as gage shielding information) are available from these publications.

The user may wish to consider generating 'synthetic' precipitation stations and/or using station characteristics during the MAP analysis. Additional information, such as isohyetal maps of the area in question, can be helpful in this situation. While no general reference can be given for this type of information, the National Weather Service has performed isohyetal studies in cooperation with other agencies. For example, the Portland RFC, in cooperation with the Soil Conservation Service, has performed isohyetal analysis for the states of Washington, Oregon and Idaho. The National Weather Service (Salt Lake City), in cooperation with various state agencies, has developed isohyetal maps for Utah, Oregon, New Mexico and Colorado. The National Weather Service, in cooperation with the U.S. Geological Survey (USGS), has performed an isohyetal analysis of New York and New England. This particular work was published as USGS Hydrologic Investigations Atlas HA7.

Good maps are essential for the MAP analysis. National topographic maps are available from the USGS with the 1=250,000 (1°x 2°) series generally being adequate. If more detail is required in a particular basin, 15-minute (1=62,500) or even 7 1/2-minute (1=24,000) maps are also available from the USGS.

[Next] [Previous] [Bookmarks] [Top]

RECOMMENDED PROCEDURES FOR UTILIZING PROGRAM MAP

The Mean Areal Precipitation (MAP) program provides an efficient means of processing the large amounts of precipitation data required to provide estimates of mean areal precipitation for continuous hydrologic modeling.

Precipitation is measured as a point value. Areal analysis of this point data requires some procedure to estimate precipitation at ungaged locations and at gaged locations during periods of missing data. Program MAP estimates precipitation data at desired locations by a grid system utilizing a one over distance square weighting scheme (1/d**2).

The computation of mean areal precipitation is accomplished within MAP by estimating all missing hourly and daily precipitation values for all stations being used. Daily precipitation is distributed as an hourly time series on the basis of hourly precipitation. Mean areal precipitation estimates are computed by multiplying hourly precipitation by station weights for all stations within the area of interest and summing these results in 1 hour, 3 hour or 6 hour increments. Station weights can be predetermined subjective judgments developed by the user, grid point weights (1/d**2) or Thiessen weights. For a more complete description of this procedure see Chapter II.6-CALB-MAP [Hyperlink].

Most techniques for estimating areal precipitation values are acceptable for relatively flat areas. In this situation a reasonable level of accuracy can be achieved assuming adequate precipitation gages exist and that they are uniformly distributed. However a major problem arises in situations where the basin is mountainous and where most of the precipitation gages are located in the lower elevations of the basin. In this situation, areal estimates of precipitation are generally low because there is no precipitation input from the major runoff-producing portion of the basin (i.e., the higher elevations).

One possible solution to this problem is the generation of synthetic precipitation stations. The one over distance square (1/d**2) procedure, which is used for estimating missing point data from surrounding stations, can be used to generate a precipitation record for a synthetic station. Station characteristics, which are monthly values used to modify generated precipitation data primarily for elevation effects, can be developed so that the generated synthetic station will have a generated record which reflects the user's needs.

An additional option is available in program MAP to help the user evaluate and modify the total precipitation analysis. A consistency analysis can be used to develop precipitation double mass plots for each station against a specified group of stations. If the double mass plot shows an inconsistency in the record of any particular precipitation station, the user can modify this precipitation record can be modified by a selected factor for any period of time within the record.

[Next] [Previous] [Bookmarks] [Top]

General Techniques for Mountainous Areas

The following general techniques have been used when applying MAP to mountainous areas.

All daily and hourly precipitation stations which are in or near the basin should be located and examined in terms of areal and elevation representativeness. If there is good gage representation throughout the basin, then a normal processing of precipitation data could continue without using any of the special features of MAP.

If problems exist in the precipitation gage representation, the first option in MAP to be considered would be station characteristics. Examine monthly normal precipitation values for all stations. A station should be selected as a 'base station'. A base station should be a station which:

- o has a long-term reliable climatological record

- is representative of a large portion of the basin

This base station can then serve as a guide for determining station characteristics at all other stations. Monthly characteristics for each station can be determined by a process as simple as a ratio of normal monthly precipitation:

$$\text{Characteristic } i,j = \frac{\text{mean monthly precipitation } i,j}{\text{mean monthly precipitation base station},j}$$

where I is the given station
j is the month

If monthly station characteristics are determined in this manner, it is helpful to smooth the results by some technique such as plotting a smoothed curve of station monthly characteristics versus time. Also monthly characteristics could be arbitrarily chosen by the user to reflect a particular basin characteristic such as seasonal storm patterns.

It is recommended that all gage locations be plotted on an area elevation curve of the basin. This will point out elevation bands that are not being represented adequately by the observing network. Consideration should be given to locating additional 'synthetic' stations in unrepresented elevation bands.

The number of synthetic stations and their locations are subjective choices. The synthetic station will be estimated by the nearest gage in each of the four quadrants surrounding it. This will influence the choice of locations. The synthetic station elevation can be selected by the user and does not have to match the actual elevation for its chosen location in the basin. The synthetic gage should ideally be located so that if it is a high elevation station it will be estimated by other high elevation stations. If it is a low elevation station, it should be located so that it will be estimated by low elevation stations.

Gages outside the basin of interest can be used to estimate precipitation of gages within the basin. In fact, it is wise to include all gages that could have an effect on the precipitation estimating processes within a basin.

The station characteristics from existing gages can be used to help determine the synthetic station characteristics. For example, if a high elevation synthetic station is being developed, an average of all the station characteristics from existing gages at or near the desired elevation either in or near the basin could be used for the station characteristics or the synthetic station. One possible method is to plot the average monthly characteristics versus time, smooth the curve and use values read from the curve for the synthetic station characteristics.

Isohyetal analysis can be used to refine the synthetic station's precipitation characteristics. If a high elevation synthetic station is desired, an estimate of monthly or annual precipitation could first be made for the area to be represented by synthetic stations from existing isohyetal maps. After the synthetic station's monthly station characteristics are determined, monthly and annual precipitation totals can be calculated by multiplying the station characteristic by the base station mean monthly precipitation value and then summing for the annual total. A comparison of the annual total precipitation for the area represented by synthetic station location from the isohyetal analysis and from the synthetic station will determine if further adjustments to the synthetic station's monthly station characteristics are necessary. A simple ratio of desired annual precipitation and calculated annual precipitation can be used to adjust each of the monthly station characteristic values for the synthetic station.

The objective is to insure that the entire basin is adequately covered by either real or synthetic gages and that these gages have a complete historical precipitation record which reflects their location in the basin.

The actual calculation of mean basin precipitation values in program MAP can be by any one of three methods. If either the grid point method (1/d**2) or the Thiessen weight method are used then no further analysis is required. If predetermined station weights are chosen, this is another method that can be used to influence the mean basin precipitation calculations.

The predetermined station weight method is intended as a way for the user to determine how much importance he would like placed on any particular gage. For example, perhaps in a mountainous basin a high percentage of the basin is above a given elevation but was never represented by a high elevation gage. If a synthetic high elevation gage is generated having a small Thiessen or grid point weight, the contribution of the synthetic gage could be increased by using predetermined station weights. The user could assign to the synthetic gage a weight that better reflects the area which the gage represents. The sum of all the station weights for a given basin must equal one.

After MAP is initially run, the consistency plots may reveal one or more precipitation stations which have inconsistent records. The cause for this inconsistency may be a change in location of the gage, change in exposure, change in observer or observation techniques, change in equipment or other reasons. The change in consistency of the precipitation record will appear as a definite break or change in slope of the double mass plot. If this occurs, the user can calculate the correction required for that particular record to make it consistent for the period of analysis. Each correction factor can begin with any month of the record and will continue to be used until replaced by another correction factor.

A precipitation comparison option is available to compare estimated and observed data at an individual station for the purpose of evaluating the accuracy of the estimating technique. The general procedure followed if this option is selected is that the precipitation record for the station to be replaced is set aside by MAP and not used in any calculations. A computed record for a synthetic station is then generated at the same location as the station which is being replaced.

[Next] [Previous] [Bookmarks] [Top]

Developing Station Characteristics and Station Weights

The example basin used is the Pemigewasset River Basin which is located in central New Hampshire. The portion of the basin used is upstream of Plymouth NH (Figure 1 [Bookmark]). Streamflow data were available from USGS records at Plymouth, while NCDC hourly and daily climatological data were available for several stations in or near the basin. General basin characteristics are listed in Table 1.

[Next] [Previous] [Bookmarks] [Top]

Gage Selection and Grid Orientation

Thirteen gages were chosen for use in this example. Of the 13 gages, 6 were located in the basin and 7 outside the basin (Table 2). An area elevation curve for the basin is shown in Figure 2 [Bookmark]. The X and Y coordinates were chosen by placing an 80 by 80 grid overlay on the basin map as shown in Figure 3 [Bookmark].

The Pemigewasset basin is mountainous and this influenced the grid orientation in this case. An examination of Figure 2 shows that all of the precipitation gages in the basin are located in the lower 25 percent of the basin. It was, therefore, decided to locate a synthetic station in the upper part of the basin. By orienting the grid overlay as shown in Figure 3, by locating the synthetic station as shown and by moving Cannon Mountain from its actual grid location of (36,55) to a new location (39,65) several things were accomplished. The location of the synthetic station insured that most of its generated data would come from high elevation stations. An examination of the three high elevation stations (Cannon Mountain, Mt. Washington, Pinkham Notch) showed that Cannon Mountain was at a reasonable elevation (4000 FT as opposed to Mt. Washington's 6262 FT) and had high quality records. Moving the location of Cannon Mountain into the same quadrant with the other two high elevation stations (and at the particular location chosen) insured that the magnitude of the precipitation data for the synthetic station would come from Cannon Mountain (a daily station). The added benefit was that timing of the data could come from the other two high elevation stations. The grid orientation chosen results in about 75 percent of the synthetic record being based on Cannon Mountain, 18 percent on Lincoln and 7 percent on Landaff, with no gage in quadrant IV.

The concept of moving station locations to improve or alter MAP estimates is one which should be kept in mind. In this particular example, if Cannon Mountain had not been moved, its time distribution would have been based on Landaff, a rather low elevation station. Since the synthetic station was intended as a high elevation station, timing from a low elevation station was not appropriate. Also if Cannon Mountain had not been moved into quadrant III, Mt. Washington would have been used as the estimator in that quadrant. Mt.

Washington receives very high precipitation amounts and was not felt to be representative of the Pemigewasset basin. Caution must be exercised by the user when utilizing this technique. The goal should be reasonable precipitation records at all stations, real or synthetic.

[Next] [Previous] [Bookmarks] [Top]

Station Characteristics

Since the Pemigewasset basin is mountainous, station characteristics were used in the MAP analysis. The station characteristics allow a given station to have a higher or lower point estimate of precipitation than would normally be possible with the MAP estimating scheme. The actual value of the station characteristic is not important. What is important is the relative value of characteristics between stations.

For all the stations being used, except the synthetic station, it was felt that a simple ratio of 3-month running averages of monthly precipitation for each station and the average monthly precipitation at the base station would yield reasonable results. Table 3 shows the calculations for Warren NH. West Rumney was chosen as the base station and, therefore, has a precipitation characteristic of 1.0 for each month. The resulting precipitation characteristics for all stations are shown in Table 4.

Precipitation characteristics for the synthetic station in this example were based on precipitation characteristics from other high elevation stations (Pinkham Notch and Cannon Mountain). The techniques used to develop the characteristics for the synthetic station are subjective. It is important that the synthetic station characteristics should reflect the area which the synthetic station is to represent.

One technique would be to use an average of monthly precipitation ratios from other high elevation stations such as Pinkham Notch and Cannon Mountain. Mt. Washington was not used in this example because its high monthly characteristics were not felt to be representative of the area the synthetic station was meant to represent. A smoothed approximation of these data would probably be a good representation of precipitation characteristics for the synthetic station. An alternate technique would be to use a plot of 3-month running averages of characteristics for one or more high elevation stations such as Cannon Mountain. Another technique would be to develop an idealized curve of precipitation characteristics for the synthetic station. The idealized curve could be based on the user's knowledge of a particular area and could reflect area peculiarities which may not be fairly represented in a running average plot, etc.

For this example, the station characteristics from a idealized curve were used for the initial estimates for the synthetic station. Again, many possible techniques could be used to generate a curve of precipitation characteristics for the synthetic station. No single procedure is the 'correct' procedure. The user must determine what is the 'best' approach for his particular situation.

Monthly precipitation characteristics for the synthetic station picked from the idealized curve are listed in column 2 of Table 5. These precipitation characteristics when multiplied by the base station monthly precipitation averages result in a mean annual precipitation value of 55.7 IN for the synthetic station.

Isohyetal maps of the basin indicated that the average annual precipitation above 1600 FT elevation would be about 54.5 IN. Ideally, the isohyetal maps should cover the period of record being used for calibration purposes. The isohyetal maps in this case were published in 1955, however and the period of record for this analysis was 1964 to 1971. In order to make some adjustment for this discrepancy, a comparison was made between average annual precipitation for the period of record (1964 to 1971) and the average annual precipitation from the isohyetal maps for six individual stations. The results indicated that the isohyetal map may be high by about 3.5 IN and, therefore, a final estimate of mean basin precipitation in the Pemigewasset above 1600 FT (488 M) elevation for 1964 to 1971 was 54.5 IN minus 3.5 IN or 51.0 IN (130 CM).

[Next] [Previous] [Bookmarks] [Top]

Station Weights

As was discussed previously, after all the precipitation data are distributed and/or estimated, mean areal precipitation is calculated by multiplying hourly precipitation values by station weights and then summing in 1 hour, 3 hour or 6 hour intervals. The station weights themselves can be predetermined by the user or calculated by program MAP (i.e., grid point weights or Thiessen weights). In areas where precipitation does not show great variability with location (such as areas with a limited range of elevation), Thiessen weights or grid point weights computed from a grid map are adequate.

In this example, because of the mountainous nature of the basin, predetermined station weights were used. Table 6 shows these weights. Three MAP values were calculated, one for the upper basin (greater than 1600 FT) one for the lower (less than 1600 FT) and one for the total basin. Three sets of station weights were required. For the total basin, since the synthetic station represented about half the basin area, it was given a weight of 0.5. The total weight must equal 1.0 in each case, so the other .5 weight was distributed among the other 6 gages in the basin. When MAP for only the upper basin was being calculated, the total weight of 1.0 was given to the synthetic station since it was the only gage in the basin located above 1600 FT elevation. When MAP for the lower basin was being calculated, the synthetic station was given zero weight and the total weight was distributed fairly uniformly among the other gages in the basin.

For comparison purposes the grid point weights and Thiessen weights were calculated for these stations and are listed in Table 6. It can be seen that the grid point weights and Thiessen weights are quite similar. However the grid point system tends to give at least small weights to nearly every station. In both cases weight is given to stations outside the basin. Also in both cases less weight is placed on the synthetic station than in the predetermined weight method. MAP was run using the three station weighting schemes and the results for water year 1965 are shown in Table 7 for comparison purposes. It can be seen that the MAP results using the grid weights and Thiessen weights are nearly identical (less than 1 percent differences over the total year). MAP results using the predetermined station weights are higher by about 9 percent and this is the result of the high weight given the synthetic station. The predetermined weight for the synthetic station was .5 while the grid point weight was .14 and the Thiessen weight was .13 (see Table 6).

[Next] [Previous] [Bookmarks] [Top]

Importance of Synthetic Stations and Station Locations in the Calibration Process

At this point MAP could be run with the time series data being written to a data file. This was done for the Pemigewasset basin in order to estimate the value of synthetic stations and the relative importance of hand and/or low elevation stations.

The calibration of the Pemigewasset watershed for this example involved several Manual Calibration Program (MCP) and Automatic Parameter Optimization Program (OPT) runs to arrive at the 'optimum' parameter values. A multi-year statistical summary of some of these runs is presented in Table 8. The final simulation run resulted in a correlation coefficient of 0.94 and a bias of -0.5 percent between observed and simulated daily flows.

Model parameters were initially optimized utilizing high and low elevation precipitation stations. However a simulation run utilizing precipitation data from only low elevation stations gave the following results:

- o the correlation coefficient decreased (0.94 to 0.92)
- o the root-mean-square (RMS) increased by 22.2 percent (636.2 to 777.7)
- o the bias changed from -0.5 percent to -23.2 percent

This indicates that it would not be desirable to calibrate a model on one network of gages and then forecast operationally on a network of gages with vastly different spatial and elevation characteristics.

Model parameters were then re-optimized (i.e., allowed to readjust to the different network) using only low elevation gages. Simulation runs were then made using only low elevation precipitation data with the following results:

- o the correlation coefficient dropped slightly (0.94 to 0.93)
- o the RMS increased by 5 percent

- the bias changed from -0.5 percent to -2.7 percent

The best RMS obtained in this configuration was 667.1. The addition of a high elevation station, which in this case was a synthetic station, reduced the RMS to 636.2, thus improving the model fit by nearly 5 percent in this particular situation.

It is anticipated that substantial improvement would result in those basins where the monthly precipitation characteristics for a high elevation station that has a seasonal pattern significantly different from the low elevation stations. In this example, the seasonal pattern for low elevation stations closely followed the synthetic station monthly characteristics.

It is interesting to note how the optimized values of some parameters changed as different elevation gages were used. For example, when only low elevation gages were used, PXADJ (in MCP) changed from 1.0 to 1.03, increasing precipitation input to the basin from low elevation stations by 3 percent. SCF (in MCP) increased from 1.30 to 1.32 slightly increasing solid precipitation. A more detailed discussion of both PXADJ and SCF follows.

The values of several other parameters changed for each simulation configuration. Since there is a great deal of interrelationship in the models and parameter values, additional investigations would be necessary to fully explain the reasons for many of the parameter value changes.

Lack of precipitation data from the higher elevations of mountainous areas would seem to be a detriment in using conceptual hydrologic models for hydrograph simulations. The judicious use of synthetic precipitation stations, station characteristics, station weights, etc., as available in MAP and of precipitation adjustment parameters (PXADJ, SCF, etc.) as provided in MCP, will enable users to reduce the adverse effects of mountainous terrain on precipitation modeling.

[Next] [Previous] [Bookmarks] [Top]

USE OF PRECIPITATION ADJUSTMENT FACTOR PXADJ AND SCF

For areas which receive considerable amounts of solid precipitation, one of the more important items to consider may be the precipitation gage catch deficiency due to wind (Peck, 1972). This section describes the problem and the options available for dealing with it.

[Next] [Previous] [Bookmarks] [Top]

Review of Previous Studies

Numerous of articles have been published on this subject from the mid eighteenth century to the present. Kurtyka (1953), Israelson (1967) and Larson (June 1971) have each published comprehensive literature reviews containing a total of some 1600 references in the general field of precipitation measurements. More recently, the World Meteorological Organization (1973) has published an annotated bibliography in the same subject area.

While most studies vary as far as the magnitudes of gage catch deficiencies due to wind are concerned, they all reach the same general conclusions that wind is the major cause of error in precipitation gage measurements. This error increases with gage site wind speed and is larger for solid than for liquid precipitation. A generally accepted theory is that, in addition to site turbulence, much of the total measurement error is the result of turbulence and increased wind speed in the vicinity of the gage orifice resulting from the obstacle of the gage itself to the windstream. As the air rises to pass over the gage, precipitation particles which would have passed through the gage orifice are instead deflected and carried further downwind, thus resulting in gage catch deficiencies (Peck, 1972; Robinson, 1969; Chou, 1968; Green 1972).

In order to minimize gage catch deficiencies, wind speed and eddy effects should be reduced in the vicinity of the gage (NOAA, 1972). The most successful method of accomplishing this has been to place the precipitation gage in a well protected natural site to reduce the adverse effects of wind in the vicinity of the gage (Brown, 1962). The Commission for Instruments and Methods of Observation (CIMO) of the World Meteorological Organization (WMO) has stated that no single item is more important in the measurement of precipitation, especially snowfall, than the exposure or physical surroundings of the gage (WMO, 1969). For good exposure a gage should have protection in all directions by objects of uniform height, with the height of this protection up to a height approximately equal to the distance from the gage to the protection. Care must also be exercised to prevent 'overprotecting' the gage.

Much work has been done in the past to develop shields for gages which will compensate for the adverse effect of wind (Weiss, 1957). It has been shown that shields can have a beneficial effect on gage performance, especially for solid precipitation (Warnick, 1956). Unfortunately, gage shields generally are not effective much beyond wind speeds of 20 MPH (32 KM/HR). Gage shields generally function by directing wind currents down and around the gage, thus reducing the general turbulence and upward wind movement in the gage orifice vicinity. However no combination of gage and shield will entirely eliminate the adverse effect of wind on gage catch.

Past studies have indicated a wide range of catch deficiencies for solid precipitation. Black (1954) stated that a precipitation gage at Barrow, Alaska, recorded 4 IN (10 CM) annual precipitation while the true value was estimated at 16 IN (41 CM). Thus, wind caused a catch deficiency of at least 75 percent. Kurtyka (1953) estimated gage catch deficiencies as high as 80 percent due to exposure. Sansborg (1972) estimated losses in the catch of snow at 40 to 50 percent for a gage at 1.5 M above the snow surface. Warnick (1956) estimated that for a wind speed of 20 MPH (32 KM/HR), an unshielded gage could be expected to catch only 20 percent of 'true' catch. Warnick also estimated that the addition of a shield to the gage would increase its catch to 35 percent of 'true' catch at 20 mph. Larson (Aug 1971) has found that at wind speeds of approximately 12 MPH (19 KM/HR) an unshielded gage would catch 66 to 75 percent of 'true' catch.

Gage catch deficiencies are much smaller for liquid than for solid precipitation. Green (1969) has estimated that for liquid precipitation, if wind speed at the gage orifice is 20 to 30 percent of that at a height of 6 FT (2 M), then the gage will catch within 1 percent of 'true' catch. Lindsley (1958) shows gage catch deficiency for rain at 10 MPH (16 KM/HR) to be approximately 15 percent. Bratzev (1963) has estimated the wind-caused measurement error for liquid precipitation to be about 5 percent per m/sec (2 mph) wind speed. Struzer (1968) has estimated the mean error due to wind for liquid precipitation at 10 to 20 percent. The use of shields on precipitation gages for liquid precipitation is less effective than for solid precipitation. Chou (1968) has reported an increase in rainfall catch of 2 percent when utilizing a shielded gage. Larson (Aug 1971) reports no significant difference in rainfall catch between shielded and unshielded gages.

A fundamental problem underlying all of these types of studies is that the determination of ‘ground true’, to a large measure, determines the value of the entire study. It is not too surprising that the comparison of results from various studies shows a rather wide range of gage catch deficiencies for any given situation. The following general conclusions however will probably summarize most precipitation measurement error studies:

- o Point measurements of precipitation can have considerable deficiencies due to wind. These errors increase with wind speed and are much greater for solid than for liquid precipitation.

- o The most important factor in obtaining reliable precipitation measurements is proper site selection. A well protected site can reduce measurement errors due to wind considerably.

- o Gage shields can reduce gage catch deficiencies and are much more effective for snow than for rain. No combination of gage and shield however will entirely eliminate the adverse effect of wind on catch. In addition the shields themselves are not too effective at wind speeds above 20 MPH (32 KM/HR).

[Next] [Previous] [Bookmarks] [Top]

Current Gage Catch Studies

The Hydrologic Research Lab has run several precipitation research projects which have as one of their primary goals an evaluation of gage catch deficiencies (primarily for solid precipitation). One of the sites is located near Danville, Vermont, while a second site is located near Laramie, Wyoming. Both of these sites have been described in detail in other reports (Larson, Aug 1971; Larson, Feb 1972; Larson, Apr 1972).

Gage catch deficiencies for solid precipitation have been determined for shielded and unshielded gage configurations at both sites. For the Wyoming site, it was found that at 10 MPH (16 KM/HR) the gage catch deficiency was about 45 percent for solid precipitation and at 20 MPH (32 KM/HR) it increased to about 70 percent. With the addition of a free-swinging Alter shield to the gage, the deficiency at 10 MPH (16 KM/HR) was reduced to about 28 percent while at 20 MPH (32 KM/HR) the deficiency was 45 percent for solid precipitation. For the Danville site, an unshielded gage at wind speeds of 10 MPH (16 KM/HR) also had a catch deficiency of about 45 percent. A shielded gage at this site at 10 MPH (16 KM/HR) had a deficiency of about 24 percent. Data from the Danville site indicates that at wind speeds of 10 MPH (16 KM/HR) a deficiency in rainfall catch of about 10 percent can be expected. It was also found that the shielded gage caught little more rainfall than the unshielded gage at the wind speeds experienced at this site (about 1 percent more at 5 MPH (8 KM/HR) wind).

A summary of gage catch deficiencies versus wind speed are presented in Figure 4 [Bookmark#1]. Curves are shown for liquid precipitation (the catch of shielded and unshielded gages are nearly equal), solid precipitation (unshielded gage) and solid precipitation (shielded gage). When measuring precipitation, the following approximate results can be expected:

- For solid precipitation, a 45 percent deficiency at 10 MPH (16 KM/HR) and a 70 percent deficiency at 20 MPH (32 KM/HR). A shield can reduce solid precipitation measurement errors by about 33 to 50 percent.

- For liquid precipitation, a 10 percent deficiency at 10 MPH (16 KM/HR). A shield has little beneficial effect for liquid precipitation measurements.

[Next] [Previous] [Bookmarks] [Top]

Precipitation Adjustment Factors

Two parameters provide the flexibility for the calibration model to adjust precipitation. The first parameter (PXADJ) is used to adjust all precipitation input to the model and is the ratio of average areal precipitation to the precipitation input. PXADJ has thus far been found to be relatively unimportant if a good estimate is made for mean basin precipitation and is usually set equal to one. The second parameter (SCF) is part of the snow accumulation and ablation model and adjusts only solid precipitation. The snow correction factor (SCF) is highly dependent point-wise on gage exposure, wind speeds, gage/shield configurations, storm type, etc. SCF is an areal adjustment and, therefore, must be a representative value for all the gages in the basin. Anderson (Feb 1974) documented some of the effects of the parameter SCF in the Passumpsic River basin in Vermont. It was found that SCF is quite sensitive, has a significant effect on snowpack runoff volumes and is one of the more important snow model parameters.

[Next] [Previous] [Bookmarks] [Top]

Initial Estimate of SCF

Several different techniques were tried in order to estimate a starting value for the parameter SCF prior to calibrating the Pemigewasset basin.

The first approach tried was to compare the precipitation catch of shielded and unshielded gages in or near the Pemigewasset River basin. Only one shielded gage existed in the basin above Plymouth (Warren NH). A second shielded gage was located just south of the basin (Bristol NH). Two unshielded gages in similar orographic locations and at comparable elevations were then chosen for catch comparison with the shielded gages. One of the unshielded gages is located in the basin (Woodstock NH) while the second is just south of the basin (Lakeport NH). A plot of the sum of the monthly precipitation catch for the shielded gages versus the sum of the monthly precipitation catch of the unshielded gages for the calibration period (1964 to 71) showed that during the predominantly solid precipitation months (November to March), the shielded gages caught more precipitation than the unshielded gages. During predominantly liquid precipitation months (April to October), there was little or no difference in precipitation catch between the shielded and unshielded gages.

In order to estimate a value for SCF, a comparison was made between the winter catch (November to March) for the pairs of shielded and unshielded gages. The total winter catch for these shielded gages was 260.72 IN (662.22 CM) while the unshielded gages caught 229.15 IN (582.04 CM). Figure 4 [Bookmark#2] shows that a shield reduces the solid precipitation measurement error of an unshielded gage by 33 to 50 percent. Thus, the difference between the total winter catch of the pairs of gages can be used to obtain an estimate of the 'true' winter catch. In this case, the estimate of the 'true' precipitation would range from 292 IN (742 CM) to 324 IN (823 CM). The resulting correction factor for unshielded gages would range from 1.27 to 1.41. This analysis assumes that the exposure of all four sites is similar and that the differences in the catch are due primarily to the shields and not to some site peculiarity.

A second approach to estimating a value for SCF was to use basin wind speeds. This approach assumes that:

- o mean point wind is indicative of mean areal wind
- o the precipitation gages are exposed to mean areal wind
- o mean wind is indicative of storm wind

The second assumption is primarily dependent upon the site or location of each individual gage. Gages with poor exposure may be exposed to higher than average winds, while gages with good exposure may be exposed to less than average winds. In order to minimize the effects of these types of assumptions, it would be preferable to have storm wind data from many points within the basin. In addition, it would be desirable for each user to be aware of the location and exposure of each precipitation gage used in any particular analysis.

The nearest available wind data were from Concord NH, south of

Plymouth NH. During the winter months, the mean wind speed at this location and at gage orifice height was estimated to be approximately 5.5 MPH (8.8 KM/HR). This would correspond to a SCF of about 1.37 for unshielded gages and solid precipitation. This estimate of SCF is in the range of SCF values previously determined by gage catch comparison. Thus, a reasonable estimate of SCF based both on gage catch comparisons and wind speed measurements would be a value in the range of 1.27 to 1.41.

[Next] [Previous] [Bookmarks] [Top]

Evaluation of the Parameter SCF

To evaluate the parameter SCF in the Pemigewasset watershed, several verification and optimization runs were made to arrive at the 'optimum' parameter values. The optimization scheme at the time of this study was limited to 50 months of data. Therefore, the final step in the calibration procedure was to optimize first on the initial 50 months of data and, second, on the last 50 months. The mean of the two sets of optimized parameters was then used in the final verification run. A multi-year statistical summary of some of these runs is presented in Table 9.

The calibration procedure was begun with an initial SCF of 1.15. This value was chosen because it would be a reasonable minimal starting value for calibrating any watershed with winter snowcover if no other data (i.e., wind or shielded/unshielded gage comparisons) were available. The calibration process ultimately resulted in a final optimized value for SCF of 1.30. This is in the range of values previously established for SCF. Thus, it would seem that a good initial estimate of SCF can be made prior to the calibration process using available wind and/or solid precipitation records.

After the model was calibrated satisfactorily to the Pemigewasset basin, the sensitivity of SCF was investigated. The first step was to hold all parameters at their optimized values while SCF was varied from 1.0 to 1.5. Some of the results of this process are presented in Figure 5 [Bookmark]. It can be seen that a minimum root mean square (RMS) and a maximum correlation coefficient (r) occur with a SCF=1.3. The percent mean snowmelt period bias (March, April, May) increases steadily from a large negative bias with SCF=1.0 to a large positive bias with SCF=1.5. A zero monthly bias is achieved with SCF=1.27 while at the optimized value of SCF=1.3 a slight positive bias exists (approximately +2.5 percent).

A logical question is whether or not a snow correction factor is necessary in a complete conceptual hydrologic model. That is, can other parameters in the model be adjusted to compensate for the wind-caused solid precipitation measurement errors which occur during the snow accumulation process. To answer this question, parameter SCF was fixed at one. The model was again optimized on the initial and final 50 months of the calibration period. Other parameters were allowed to readjust themselves to compensate for the lack of snow correction factor. The optimization scheme, in an attempt to compensate for reduced input from winter precipitation with SCF=1.0, adjusted parameters to redistribute runoff from summer, fall and winter months to the spring runoff months. The statistical results of the final verification with SCF set to one are listed in Table 9 under run A. It can be seen that eliminating SCF, even though other parameters were reoptimized to compensate for it, has resulted in a poorer model fit. For the verification period, the correlation coefficient decreased from .94 to .92 while RMS increased over 10 percent (636.2 to 708.1).

[Next] [Previous] [Bookmarks] [Top]

References

Anderson, Eric A., 'Conceptual Streamflow Forecasting Model Applied to Northern New England Rivers', Eastern Snow Conference, Ottawa, Ontario, Feb. 7-8, 1974.

Anderson, Eric, 'National Weather Service River Forecast System, Snow Accumulation and Ablation Model', NOAA Tech Memo NWS Hydro-17, Silver Spring, MD., 1974.

Black, Robert F., 'Precipitation at Barrow, Alaska, Greater than Recorded', Trans. AGU, Vol. 35, No. 2, April 1954.

Bratzev, A. P., 'Influence of Wind Speed on the Quantity of Measured Precipitation', Soviet Hydrology Papers, AGU, No. 4, pp. 414-417, 1963.

Brown, Merle J. and Eugene L. Peck, 'Reliability of Precipitation Measurements as Related to Exposure', Journal of Applied Meteorology, Vol. 1, No.2, June 1962, pp. 203-207.

Green, M. J., 'Effects of Exposure on the Catch of Rain Gauges', T. P. 67, The Water Research Association, Medmenham, Marlow, Buckinghamshire, England, July, 1969.

Green, M. J. and P. R. Helliwell, 'The Effect of Wind on Rainfall Catch', The Water Research Association, Ferry Lane, Medmenham, Marlow, Buckinghamshire, England, Feb., 1972.

Hydrologic Research Laboratory Staff, 'National Weather Service River Forecast System Forecast Procedures', NOAA Tech Memo NWS HYDRO-14, National Weather Service, Silver Spring, MD., Dec. 1972.

Israelson, C. Earl, 'Reliability of Can-Type Precipitation Gage Measurements', Utah Water Research Laboratory, Utah State University, Logan, Utah, July 1967.

Jacobi, Sven and David R. Dawdy, 'The Relation of Rainfall Network Density to Accuracy of Runoff Prediction in a Mountainous Basin', Symposium on the Distribution of Precipitation in Mountainous Areas, Ceilo, Norway, Vol. II, Technical Papers, WMO/OMM No. 326, Geneva, Switzerland, Aug. 1972.

Kurtyka, John C., 'Precipitation Measurements Study', Report of Invest. #20, State Water Survey Division, Urbana, Illinois, 1953.

Larson, Lee W., 'Precipitation and Its Measurement, A State of the Art', Water Resource Series #24, WRRI, Univ. of Wyoming, Laramie, Wyoming, June, 1971.

Larson, Lee W., 'Shielding Precipitation Gages from Adverse Wind Effects with Snow Fences', Water Resources No. 25, WRRI, Univ. of Wyoming, Laramie, Wyoming, Aug., 1971.

Larson, Lee W., 'Approaches to Measuring 'True' Snowfall', 29th Eastern Snow Conference, Oswego, New York, Feb. 3-4, 1972.

Larson, Lee W., 'An Application of the Dual-Gage Approach for Calculation of 'True' Solid Precipitation', 53rd Annual Meeting, AGU, Washington, D.C., April, 1972.

Larson, Lee W. and Eugene L. Peck, 'Accuracy of Precipitation Measurements for Hydrologic Modeling', Water Resources Research, Vol. 10, No. 4., Aug. 1974.

Monro, John C. and Eric A. Anderson, 'National Weather Service River Forecasting System', ASCE, Hydraulics Division, Vol. 100, HY5, May, 1974.

NOAA, 'Substation Observations, U.S. Department of Commerce, Weather Bureau Observing Handbook No. 2', Silver Spring, Md., Data Acquisition Division, Office of Meteorological Operations, 1972.

Peck, Eugene L., 'Relation of Orographic Precipitation Patterns to Meteorological Parameters', Symposium on the Distribution of Precipitation in Mountainous Areas, Geilo, Norway, Vol. II, Technical Papers, WMO/OMM no. 326, Geneva, Switzerland, Aug. 1972.

Peck, Eugene L., 'Snow Measurement Predicament', Water Resources Research, Vol. 8, No. 1, Feb., 1972.

Robinson, A. C. and J. C. Rodda, 'Rain, Wind and the Aerodynamic Characterisics of Rain-Gauges', Meteorological Magazine, 98, 1969, 113.

Sandsborg, John, 'Precipitation Measurements with Various Gauge Installations', Nordic Hydrology 3, pp. 80-106, 1972.

Sittner, W. T., 'Modernization of National Weather Service River Forecasting Techniques', Water Resources Bulletin, Vol. 9, No. 4, Aug. 1973.

Struzer, L. R., et al., 'Correction of Precipitation Normals, Glavoraiageofizicheskiaia observatoriia', Trudy, No. 215, Leningrad, pp. 3-15, 1968 (in Russian).

Warnick, C. C., 'Influence of Wind on Precipitation Measurements at High Altitude', Univ. of Idaho, Exp. Sta. Bull. #10, Moscow, Idaho, 1956.

Weiss, L. L. and W. T. Wilson, 'Precipitation Gage Shields', International Union of Geodesy and Geophysics, Assemblie General de Toronto, 1:462-484, 1957.

World Meteorological Organization, 'Guide to Meteorological Instrument and Observing Practices', No. 8, T.P. 3, Geneva, 1969.

World Meteorological Organization, 'Annotated Bibliography on Precipitation Measurement Instruments', Report #17, WMO-No-343, Geneva, 1973.

Table 1. Pemigewasset River at Plymouth NH

Area: 622 MI2 (1610 KM2)

Mean Elevation: 1811 FT (533 M)

Elevation Range: 457 to 5,249 FT (139 to 1,600 M)

Number of Stations and Elevation Range:

- For computing mean precipitation:

  6 stations
  elevation range: 457 to 810 FT (139 to 247 M)

- For computing mean temperature:

  3 stations
  elevation range: 457 to 720 FT (139 to 220 M)

Mean Annual Values for Test Period (1964-1971):

- Discharge - 26.8 IN (68.2 CM)
- Precipitation - 48.9 IN (124.2 CM)
- Snow water equivalent - 16.2 IN (41.2 CM)

Table 2. Precipitation stations used in MAP analysis

Station	Elevation	In/out of Basin	X,Y Coordinate
Hourly:			
Union Village Dam VT	463	out	36,24
Bristol NH	430	out	60,33
Landaff (1) NH	960	out	28,48
Landaff (2) NH	810	out	28,49
Lincoln NH	800	out	40,51
Mt. Washington NH	6262	out	38,74
Pinkham Notch NH	2029	out	40,74
Warren NH	700	in	40,40
Daily:			
Campton NH	620	in	49,46
Cannon Mt. NH	4000	out	39,65
Synthetic Station	1811	in	38,60
Plymouth NH	560	in	53,41
West Rumney NH	560	in	46,36
Woodstock NH	720	in	43,49

Table 3. Calculations of monthly precipitation characteristics for Warren NH

Month	Average Monthly Precipitation	3-Month Running Average	Precipitation At Base Station	Monthly Precipitation Characteristic
Jan	1.95	2.94	2.28	1.29
Feb	3.03	2.50	3.33	.75
Mar	2.52	2.76	3.16	.87
Apr	2.74	2.81	3.00	.94
May	3.16	3.05	3.72	.82
Jun	3.69	3.37	3.34	1.01
Jul	3.69	3.63	3.66	1.00
Aug	3.93	3.38	3.75	.90
Sep	2.53	2.85	3.16	.90
Oct	2.10	2.84	2.70	1.05
Nov	3.88	3.28	4.96	.66
Dec	3.85	3.21	4.29	.75

Table 4. Monthly precipitation characteristics

	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Union Village Dam	1.04	0.64	0.77	0.96	0.82	1.02	0.97	0.95	0.96	1.14	0.62	0.69
2	Bristol	1.44	.83	.94	.93	.79	.87	.79	.79	.89	1.28	.77	.88
3	Landaff	.83	.55	.60	.83	.71	.88	.83	.79	.85	.89	.48	.53
4	Lincoln	1.57	.99	.89	.87	.80	.94	1.00	.81	.91	1.15	.74	.96
5	Mt. Washington	4.00	2.55	2.57	2.32	1.76	2.12	1.98	1.93	2.16	2.81	1.74	2.06
6	Pinkham Notch	1.40	1.39	1.31	1.19	1.16	1.25	1.26	1.34	1.34	1.53	1.48	1.47
7	Warren	1.29	.75	.87	.94	.82	1.01	1.00	.90	.90	1.05	.66	.75
8	Campton	.85	.88	.84	.89	.97	.89	.87	.83	.91	.96	.88	.92
9	Cannon Mt.	1.22	1.19	1.11	1.16	1.26	1.34	1.42	1.41	1.37	1.26	1.20	1.23
10	Synthetic	1.12	1.14	1.20	1.26	1.31	1.37	1.37	1.31	1.26	1.20	1.14	1.12
11	Plymouth	1.03	1.02	.95	.94	.95	.99	.97	.97	.93	.96	.96	1.02
12	West Rumney	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
13	Woodstock	.85	.84	.95	1.02	1.12	1.14	1.20	1.18	1.16	1.06	1.00	.90

Table 5. Precipitation characteristics for synthetic station (IN)

Column 1	Column 2	Column 3	Column 4	Column 5	
Month	Initial estimate of characteristic	Base station mean monthly precipitation	Column 2 times Column 3	Column 2 times 0.915 1/	Column 5 times Column 3
Jan	1.22	2.28	2.78	1.12	2.54
Feb	1.25	3.33	4.16	1.14	3.81
Mar	1.31	3.16	4.14	1.20	3.74
Apr	1.38	3.00	4.14	1.26	3.79
May	1.43	3.72	5.32	1.31	4.87
Jun	1.50	3.34	5.01	1.37	4.58
Jul	1.50	3.66	5.49	1.37	5.02
Aug	1.43	3.75	5.36	1.31	4.91
Sep	1.38	3.16	4.36	1.26	3.99
Oct	1.31	2.70	3.54	1.20	3.24
Nov	1.25	4.96	6.20	1.14	5.67
Dec	1.22	4.29	5.23	1.12	4.79
			55.73 2/		51.0 3/

= ——— = ——— =

Notes:

1/ Column 5 is final monthly precipitation characteristics for synthetic station.
2/ Average annual precipitation for the synthetic station based on initial precipitation characteristics.
3/ Average annual precipitation for the synthetic station based on adjusted precipitation characteristics.

Table 6. Comparison of station weight options

Station 1/	Predetermined Weights 2/			Grid Point Weights 2/			Thiessen Weights 2/		
	Tot	Upr	Lwr	Tot	Upr	Lwr	Tot	Upr	Lwr
1	.0	.0	.0	.02	.01	.02	.0	.0	.0
2	.0	.0	.0	.01	.0	.02	.0	.0	.0
3	.0	.0	.0	.03	.04	.02	.01	.01	.01
4	.05	.0	.1	.13	.16	.10	.13	.17	.09
5	.0	.0	.0	.0	.0	.0	.0	.0	.0
6	.0	.0	.0	.0	.0	.0	.0	.0	.0
7	.1	.0	.2	.15	.12	.18	.18	.14	.22
8	.05	.0	.1	.15	.12	.19	.16	.11	.21
9	.0	.0	.0	.04	.10	.0	.05	.11	.0
10	.5	1.0	.0	.14	.26	.03	.13	.25	.02
11	.1	.0	.2	.08	.03	.11	.07	.0	.12
12	.1	.0	.2	.13	.06	.19	.15	.07	.21
13	.1	.0	.2	.12	.10	.14	.13	.14	.13

Notes:

1/ Station order corresponds to Table 2.
2/ Tot = total basin
Upr = upper basin (greater than 1600 FT)
Lwr = lower basin (less than 1600 FT)

Table 7. MAP estimates for total Pemigewasset Basin for water year 1965 (MM)

Year	Month	Grid Point Weights 1/	Thiessen Weights 1/	Predetermined Weights 1/
1964	Oct	55.50	56.18	62.04
	Nov	102.43	103.42	110.57
	Dec	99.39	100.61	105.14
1965	Jan	40.07	41.01	40.90
	Feb	91.19	92.88	94.47
	Mar	21.27	21.61	30.43
	Apr	60.77	61.57	64.82
	May	23.64	23.92	25.75
	June	115.26	113.48	135.26
	July	85.70	86.05	85.76
	Aug	74.36	72.97	86.53
	Sept	149.99	148.71	158.19
		919.57	922.41	999.86
		(36.20 IN)	(36.31 IN)	(39.36 IN)

Note:

1/ Station weights used are listed in Table 6.

Table 8. Multi-year calibration statistical summary for the Pemigewasset River 1964-1971

Precipitation gages used	Observed mean flow (CFSD)	Simulated mean flow (SFSD)	Correlation coefficient	Percent bias	RMS
All gages	1228.0	1221.9	.94	-0.5	636.2
Low elevation	1228.0	943.6	.92	-23.2	777.7
High elevation	1228.0	1516.8	.90	23.5	1030.1
Low elevation 1/	1228.0	1194.5	.93	-2.7	667.1
High elevation 2/	1228.0	1048.1	.90	-14.7	808.1

Notes:

1/ Model parameters re-optimized based on low elevation gages only.
2/ Model parameters based on high elevation gages only.

Table 9. Multi-year calibration statistical summary for the Pemigewasset River 1964-1971

Run Number	Observed Mean Flow (CFSD)	Simulated Mean Flow (CFSD)	RMS	Correlation Coefficient	Percent Bias
2	1228.0	1162.5	1064.2	.82	-5.3
7	1228.0	1195.2	813.6	.90	-2.7
11	1228.0	1205.9	762.9	.91	-1.8
12 1/	1228.0	1213.9	699.8	.93	-1.2
13 2/	1228.0	1231.8	637.1	.94	+0.3
14 3/	1228.0	1221.9	636.2	.94	-0.5
A 4/	1228.0	1201.7	708.1	.92	-2.1

Notes:

1/ Parameters optimized on first 50 months.
2/ Parameters optimized on last 50 months.
3/ Mean of both sets of optimized parameters used.
4/ 'BEST' simulation results with SCF set equal to one.

Figure 1. Pemigewasset River basin above Plymouth NH

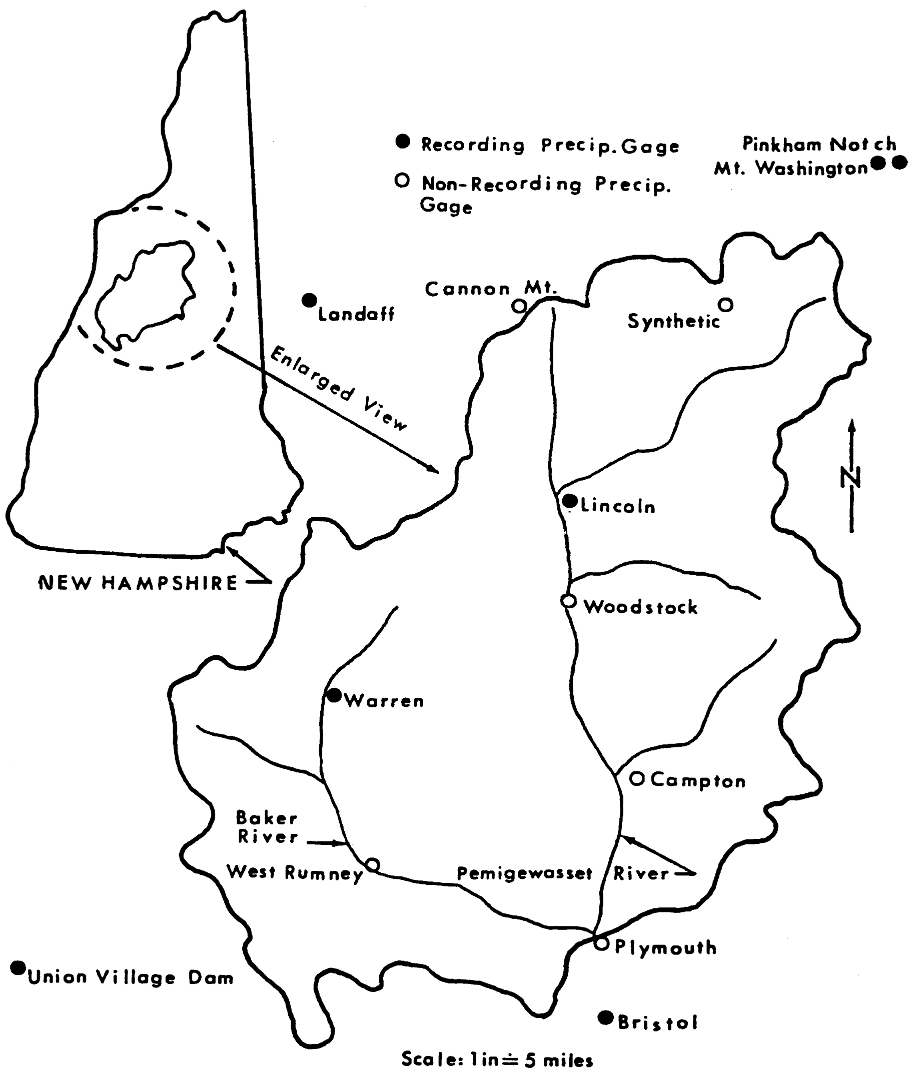

FIGURE 1. PEMIGEWASSET BASIN ABOVE PLYMOUTH, N.H.

Figure 2. Area elevation curve

Figure 3. Pemigewasset River basin above Plymouth NH with grid

Figure 4. Gage catch deficiencies versus wind speed

Figure 5. Snow correction factor sensitivity plot
