PRECIPITATION MODELING IN MOUNTAINOUS AREAS FOR THE NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM[1]

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I. INTRODUCTION

The National Weather Service (NWS) is in the process of replacing empirical flood forecasting procedures with conceptual hydrologic models. The National Weather Service River Forecast System (NWSRFS) will eventually be used by most River Forecast Centers (RFC) to develop operational river forecast procedures for continuous hydrologic forecasts (Sittner 1973, Monro 1974).

Measurements of precipitation are a major input for hydrologic models. Point precipitation data are often converted to some form of mean areal precipitation (MAP) estimate for use in modeling. Present hydrologic models, to a large degree, are limited by the accuracy of the MAP estimate (Jacobi 1972).

Many factors influence the estimate of MAP, including: (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 utilized, (4) basin characteristics, (5) storm characteristics, (6) orographic effects, (7) point precipitation measurement errors, and (8) a general scarcity of precipitation gages at higher elevations in most watersheds.

The precipitation processing programs utilized in NWSRFS contain several options that are useful for adjusting precipitation data for the effects of mountainous terrain. These options, which include the use of synthetic stations, station weights, station characteristics, and various adjustment factors, will be discussed in detail. The results of applying NWSRFS in a mountainous area of New England will also be presented.

II. THE NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM (NWSRFS)

The Hydrologic Research Laboratory (HRL) of the Office of Hydrology (O/H), NWS, has for several years conducted research studies on the physical processes of the hydrologic cycle. The primary purpose of these studies was to develop suitable conceptual simulation models for use by the RFC's.

The basic river forecasting system developed by HRL is described in detail in two technical memoranda published by the National Oceanic and Atmospheric Administration (NOAA 1972, Anderson 1973). These technical memoranda describe the entire system, including the conceptual watershed model, the snow accumulation and ablation model, the processing of the basic data, and recommended calibration procedures.

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To use the hydrologic model components of the NWSRFS, the models must be calibrated for each watershed. There are 33 parameters involved in the calibration procedure. Twenty of these parameters are in the soil moisture accounting and channel routing routines while an additional 13 are in the snow accumulation and ablation model. A number of these parameters can be determined from hydrograph analysis or by physical considerations.

Two parameters provide the flexibility for the model to adjust input precipitation. The first parameter is used to adjust all precipitation input to the model. This parameter, called K1 in the model, is the ratio of average areal precipitation to the precipitation input. K1 has thus far been found to be relatively unimportant if a good estimate is made of mean areal precipitation (MAP) and for most basins is set equal to unity. The second parameter, a snow correction factor, called SCF in the model, is part of the snow accumulation and ablation model and adjusts only solid precipitation. SCF is highly dependent point-wise on gage exposure, wind speeds, gage/shield configurations, storm type, etc. In NWSRFS, SCF is an areal adjustment and therefore must be a representative value for all the gages in the basin. Anderson (Feb. 1974) and Larson (1974) have documented some of the effects of the parameter SCF in New England. It was found that SCF is quite sensitive, has a significant effect on snowpack runoff volumes, and in general is one of the more important snow model parameters.

The calibration of any hydrologic model is a lengthy and time consuming procedure. Monro (1974) and Anderson (1973, 1974) have authored a recommended calibration procedure for NWSRFS. For this discussion, it is sufficient to say that in the calibration process of the NWSRFS two major programs are utilized. These are the manual calibration and automatic calibration programs. The manual calibration program simulates an outflow hydrograph, plots observed and simulated hydrographs, calculates statistical summaries of comparisons between observed and simulated flows, etc. This program is utilized for trial-and-error calibration of the system parameters. The trial-and-error phase is normally a multi-run process. The intermediate calibration step is to utilize the automatic calibration program. This program is a pattern search optimization scheme (Monro 1971) which generally will provide optimal values for the system parameters. The final calibration step is to use the manual calibration program with parameter values determined by pattern search.

III. MEAN AREAL PRECIPITATION (MAP)

NWSRFS includes a mean areal precipitation (MAP) digital computer program. The program is needed to provide an efficient means of processing the vast 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 other locations. The MAP program estimates precipitation data at desired locations by a grid system utilizing a one over distance square weighting scheme ($1/d^2$).[1] For a more complete description of this procedure, see NOAA Technical Memorandum NWS HYDRO-14 (Hydrologic Research Laboratory Staff 1972).

[1]This procedure was developed by Mr. Walter T. Sittner, Hydrologic Research Laboratory, National Weather Service, NOAA, Silver Spring, Md. 20910.

The computation of mean areal precipitation is accomplished within MAP by estimating all missing hourly and daily precipitation values for all stations being utilized. Daily precipitation is then distributed as an hourly series on the basis of hourly precipitation. MAP is computed by multiplying hourly precipitation by suitable station weights for all stations within the area of interest and summing these results in 1-, 3-, or 6-hour increments. Station weights can be predetermined subjective judgments developed by the user, grid point weights ($1/d^2$), or Thiessen weights.

Most techniques used to estimate areal precipitation values are acceptable for relatively flat areas. In this situation a reasonable level of accuracy can be achieved assuming "enough" precipitation gages exist and that they are reasonably distributed. However, a major problem arises in situations where the basin in question is mountainous and where most of the precipitation gages are located in the lower portions of the basin (a common occurrence). 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). This situation is currently handled in NWSRFS through the generation of synthetic precipitation stations.

The one over distance square ($1/d^2$) procedure for estimating missing point data from surrounding stations is used to generate the precipitation record at the synthetic station. Station characteristic adjustments can be used to modify the generation of precipitation data. Station characteristic adjustments are monthly values which allow generated precipitation data for any location to be adjusted so that, as an example, a synthetic precipitation station at a high elevation could have a precipitation estimate greater than any surrounding observed station. The amount of adjustment can vary from month to month to take into account seasonal effects such as changing storm tracks, etc.

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

IV. UTILIZING MAP IN MOUNTAINOUS AREAS

The following general techniques have been utilized by the HRL when applying NWSRFS in mountainous areas. The techniques as listed are only guides and will no doubt be changed and modified as more experience is gained in precipitation modeling in mountainous areas.

All daily and hourly precipitation stations which are in or near the basin of interest should be located and examined in terms of areal and elevation representativeness. If the user feels that there is good gage dispersion 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 data available for a basin due to mountainous terrain, the first option in MAP to utilize would be station characteristics. Examine monthly normal precipitation values for all stations.

A station should be selected as a "base station." The criteria for a base station is that it should be a station which has a long-term reliable climatological record and is representative of a large portion of the basin. This base station will serve as a guide for determining station characteristics. Monthly characteristics for each station can be determined by a process as simple as a ratio of normal monthly precipitation:

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

i = given station
j = 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. Monthly characteristics can also be arbitrarily chosen to reflect a particular basin characteristic such as seasonal storm patterns, etc.

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

The number of synthetic stations and their locations are subjective judgments by the user. 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. Also, the synthetic station elevation does not have to match the actual elevation for any particular 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 utilized 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 utilized 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 utilized for the station characteristics of the synthetic station. A possible approach is to plot the average monthly characteristics versus time, smooth the curve, and utilize these values for the synthetic station characteristics.

Isohyetal analysis can be utilized to refine the synthetic station precipitation characteristics. For example, if a high elevation synthetic station is desired, an estimate of monthly or annual precipitation could first be made for the intended area to be represented by synthetic stations from existing isohyetal maps. After the synthetic station 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 station characteristic method will determine if further adjustments to the synthetic stations 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.

All of the effort up to this point has been 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 the MAP program can be by any one of three methods. If either the grid point method ($1/d^2$) or the Thiessen weight method are utilized then no further analysis is required prior to utilizing MAP. If the third method is chosen, predetermined station weights, then the user has an additional tool with which to use his subjective judgment to influence the mean basin precipitation calculations.

The station weight procedure is intended as a way for the user to determine how much importance he would like placed on any particular gage in the MAP process. 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. A synthetic high elevation gage is generated but the criteria for locating it for estimation purposes results in a small Thiessen or gird point weight. In this situation, the importance of the synthetic gage could be increased by utilizing the station weight procedure and assigning to the synthetic gage a weight that more truly reflects the area which the gage represented. The sum of all the station weights for a given basin must equal unity.

V. APPLICATION OF NWSRFS IN THE PEMIGEWASSET BASIN OF NEW ENGLAND

The Pemigewasset River Basin is located in central New Hampshire. The portion of the basin fit by NWSRFS for this example is upstream of Plymouth, N.H., an area of approximately 622 miles (1611 km^2) (fig. 1). Streamflow data are available from USGS records at Plymouth while hourly and daily climatological data are available for several stations in or near the basin from the National Climatic Center at Asheville, N.C. During the test period (1965-71), it was found that the mean annual precipitation for the basin was 48.9 inches (124.2 cms), the mean annual snowfall was 16.2 inches water equivalent (41.2 cms), and the mean annual discharge was 26.8 inches (68.2 cms). Thirteen gages were chosen for use in this example. Of the 13 gages, 6 are in the basin and 7 are located outside the basin. An area elevation curve for the basin is shown in figure 2.

The precipitation characteristics developed for each station are shown in table 1. All were developed with West Rumney as the base station. The monthly characteristics for the synthetic station were developed initially from Pinkham Notch and Cannon Mountain stations (both over 1600 feet (488 m) elevation). Isohyetal maps (which ideally should cover the period of record being utilized for calibration purposes) indicated that average annual precipitation above 1600 feet (488 m) elevation in the Pemigewasset basin should be about 51 inches (130 cms). The initial precipitation characteristics for the synthetic station multiplied by the base station mean monthly precipitation values resulted in a mean annual precipitation value of 55.7 inches (141.5 cms). Characteristics were then adjusted for the synthetic station by a .915 adjustment factor so that the mean annual precipitation value for the synthetic station would equal 51 inches (130 cms).

The calibration of the Pemigewasset watershed involved several simulation and optimization runs to arrive at the "optimum" parameter values. A multi-year statistical summary of some of these runs is presented in table 2. The "best" fit, of course, was achieved in the basin when both low and high elevation gages were utilized. 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. The correlation coefficient decreased (0.94 to 0.92), the root-mean-square (RMS) increased by 22.2 percent (636.2 to 777.7), and 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 reoptimized (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. The correlation coefficient dropped slightly (0.94 to 0.93), the RMS increased by 5 percent, and the bias changed from -0.5 percent to -2.7 percent. The best RMS obtainable in this situation 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 substantially more improvement would result in those basins where the monthly precipitation characteristics for a high elevation station 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.

Table 3 lists some of the model parameters, their optimized values, and a brief explanation of their function in the model. It is interesting to note how the optimized values of these parameters change as different elevation gages are used. For example, if only low elevation gages are used, K1 changes from 1.0 to 1.03. K1 adjusts all precipitation input so this change increased precipitation input to the basin from low elevation stations by 3 percent. Two other parameter values "warped" to compensate for too little precipitation. EHIGH dropped from 1.15 to 0.95 thereby effectively reducing evapotranspiration. SCF increased from 1.30 to 1.32 slightly increasing solid precipitation. Opposite adjustments occurred to these parameter values when only the high elevation stations were used.

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 will be necessary to explain the reasons for many of the parameter value changes.

VI. CONCLUSIONS

Lack of precipitation data from the higher elevations of mountainous areas is a detriment in utilizing conceptual hydrologic models for hydrograph simulations. The judicious utilization of synthetic precipitation stations, station characteristics, station weights, etc., as available in MAP and precipitation adjustment parameters (Kl, SCF, etc.) as provided in the manual calibration program, will enable the users of NWSRFS to reduce the adverse effects of mountainous terrain on precipitation modeling.

The practical application of and experience with these techniques and procedures in mountainous areas is limited at this point in time. The limitations of these techniques are recognized by the authors. In the future, other techniques may provide additional skill for the analysis of precipitation data in mountainous areas (Peck 1972). NWSRFS is a dynamic and changing system and will incorporate improved techniques and procedures when they become available.

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Table 1.--Monthly precipitation characteristics

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	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 2.--Calibration results, multi-year statistical summary, Pemigewasset River, 1964-71

Precipitation gages used in run	Observed mean flow (CFSD)	Simulated mean flow (CFSD)	Correlation coefficient	Percent bias	RMS
All gages	1228.0	1221.9	0.94	-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

[1]Model parameters reoptimized based on low elevation gages only.
[2]Model parameters reoptimized based on high elevation gages only.

Table 3.--Optimized model parameters

Parameter	All precipitation gages	Low elev. gages only	High elev. gages only	Purpose
UZSN	0.250	0.230	0.327	Nominal upper zone storage
CB	.22	.21	.24	Infiltration index
POWER	2.08	1.84	1.78	Exponent in infiltration curve
KV	1.00	1.42	.58	Weighting factor for variable groundwater recession rates
K24EL	.171	.081	.249	Percent of watershed in stream surfaces and riparian vegetation
A	.045	.051	.051	Percent impervious area
EPXM	.350	.410	.285	Maximum interception storage
K1	1.00	1.03	.95	Ratio of areal precipitation to precipitation input
K3	.170	.170	.170	Evapotranspiration opportunity index for lower zone
MFMAX	.028	.022	.040	Maximum non-rain melt factor
MFMIN	.008	.007	.011	Minimum non-rain melt factor
SI	14.3	16.9	21.6	Areal water equivalent above which 100 percent snow cover always exists
DAYGM	.010	.008	.012	Daily melt at snow-soil interface
EHIGH	1.15	.95	1.63	Maximum adjustment factor for evapotranspiration
NEP	180	180	180	Day when evapotranspiration reaches maximum
NDUR	60	32	55	Number of days at which evapotranspiration is maximum
SCF	1.30	1.32	1.28	Snow correction factor for precipitation gages

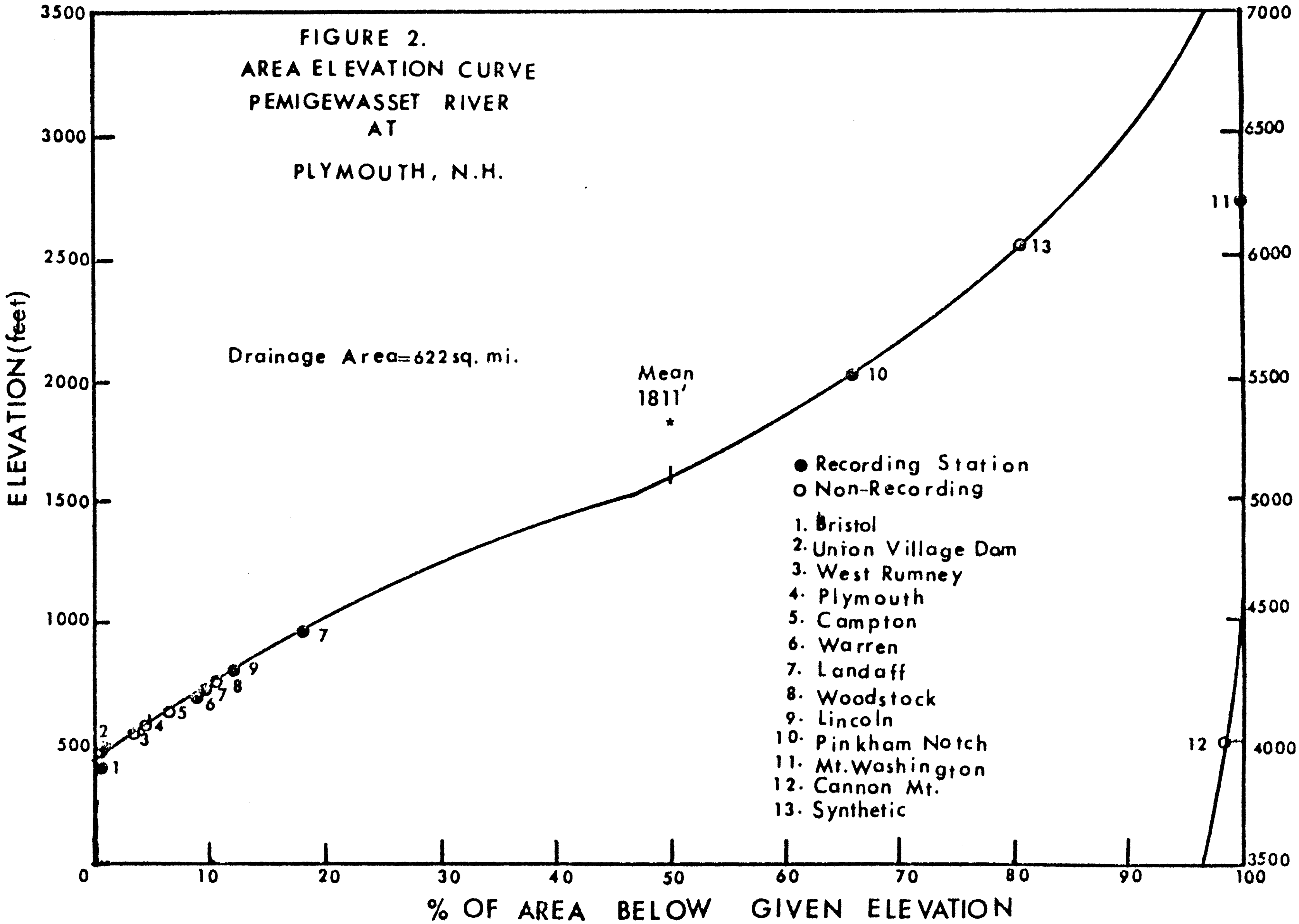
FIGURE 2.
AREA ELEVATION CURVE
PEMIGEWASSET RIVER
AT
PLYMOUTH, N.H.
Drainage Area=622 sq. mi.
Mean
1811'
ELEVATION (feet)
% OF AREA BELOW GIVEN ELEVATION
● Recording Station
o Non-Recording
1. Bristol
2. Union Village Dam
3. West Rumney
4. Plymouth
5. Campton
6. Warren
7. Landaff
8. Woodstock
9. Lincoln
10. Pinkham Notch
11. Mt.Washington
12. Cannon Mt.
13. Synthetic

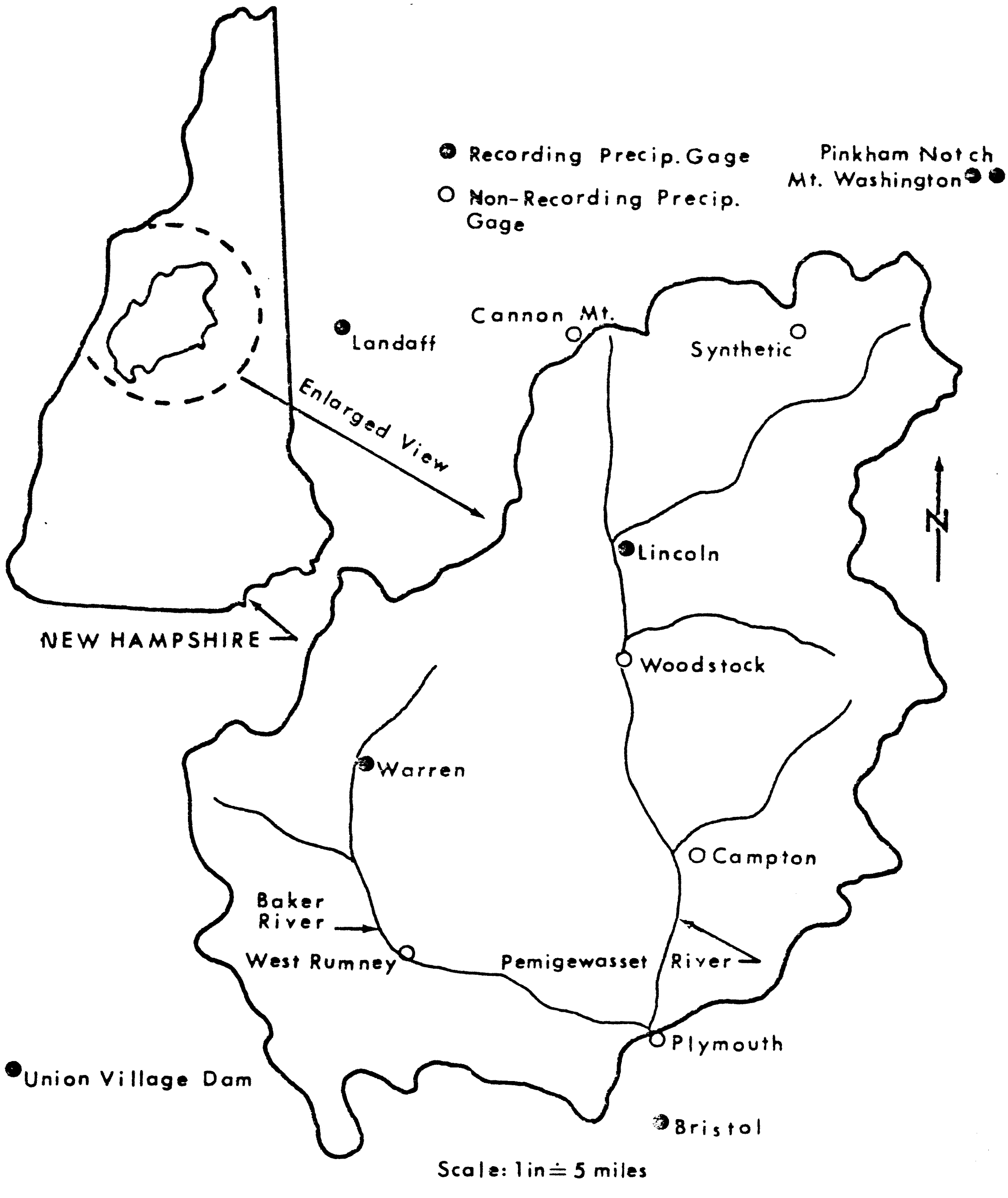

FIGURE 1. PEMIGEWASSET BASIN ABOVE PLYMOUTH, N.H.