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NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM-SNOW ACCUMULATION AND ABLATION MODEL

Eric A. Anderson

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The techniques used by the National Weather Service (NWS) for making river and flood forecasts have been changing in recent years (Sittner, 1973). Conceptual watershed models are replacing previously used empirical procedures. In 1972 the Hydrologic Research Laboratory of the Office of Hydrology, NWS, prepared a technical memorandum entitled "National Weather Service River Forecast System, Forecast Procedures" (referred to as HYDRO-14 throughout this report) as a guide for the implementation of conceptual river forecasting models by field offices. HYDRO-14 describes the techniques and computer programs needed for developing operational river forecasts based on the use of a continuous conceptual watershed model from the processing of the basic data to the preparation of the forecasts. The procedures described in HYDRO-14 did not include techniques to model snow accumulation and snowmelt. This Technical Memorandum describes a conceptual model of the snow accumulation and ablation process and the associated computer subroutines and programs which enable the model to be used in conjunction with the National Weather Service River Forecast System (NWSRFS). Guidelines and methods for determining model parameter values for a given area are also presented. Even though the snow subroutines are written for use with the NWSRFS, the snow accumulation and ablation model itself can be used with almost any soil-moisture accounting (rainfall-runoff relationship) and channel routing procedure. The output from the snow model would be the input to the soil-moisture accounting procedure. The output from the snow model is snowpack outflow (snowmelt water and rainwater leaving the snowpack) plus rain that fell on bare ground.

1.2 DATA REQUIREMENTS

The snow accumulation and ablation model uses air temperature as the sole index to energy exchange across the snow-air interface. Air temperature is the only additional data needed to use the snow model in conjunction with the NWSRFS soil-moisture accounting and channel routing models. Streamflow, precipitation, and some form of potential evapotranspiration (PE) data are needed for the NWSRFS (see chapter 2, HYDRO-14). The basic computational interval of the NWSRFS is six hours, thus, six-hourly mean areal air temperature data are required. Chapter 2 of this Technical Memorandum describes a procedure and associated computer programs for computing six-hourly mean areal air temperature from daily maximum-minimum air temperature observations Since the NWSRFS models and the snow model are continuous models, a continuous record of six-hourly mean areal air temperature data is required. However, the snow subroutines contain a provision that eliminates the requirement for valid air temperature data during periods when there is no snow on the ground

There are two basic reasons for using air temperature as the sole index to energy exchange across the snow-air interface:

a. Air temperature data are readily available throughout the United States on a real time operational basis.

b. Comparison tests conducted by the Hydrologic Research Laboratory have shown that on two experimental watersheds the temperature index method of estimating energy exchange across the snow-air interface has produced simulation results which are at least as good as those produced using a combination energy balance - aerodynamic method. The combination energy balance - aerodynamic method tested is essentially the same as the method described by Anderson (1968). The two watersheds on which these tests were made are Upper Castle Creek, Central Sierra Snow Laboratory, and Watershed W-3, Agricultural Research Service (ARS), Sleepers River Research Watershed.

The combination method will give more accurate estimates of energy exchange at a point than the temperature index method if accurate measurements of all the necessary meteorological variables are available (these variables are air temperature, dew-point, wind speed, incoming and reflected solar radiation, and atmospheric longwave radiation). However, on the two experimental watersheds the combination method results were affected by several sources of error: 1) errors in point measurements, especially in regard to incoming solar radiation, 2) errors in estimating variables which were not measured (primarily atmospheric longwave radiation), and 3) errors in estimating mean areal values of the variables (primarily determining the effect of slope, aspect, and forest cover on incoming solar and atmospheric longwave radiation, determining the areal albedo of the snowpack, and determining the mean areal wind speed). The integrated effect of these errors was estimates of energy exchange across the snow-air interface which were no better than estimates from the temperature index method on the two experimental watersheds.

It is felt that the data available at these two experimental watersheds is superior to that which is generally available on a real-time operational basis in the United States. Thus, it does not appear practicable to use a physical energy balance approach like the combination method to estimate energy exchange across the snow air interface until improved measurements of the meteorological variables affecting snowpack energy exchange are obtained and until improved methods of accounting for the effects of physiographic factors on snowpack energy exchange variables are developed.

The Hydrologic Research Laboratory is currently involved in a project to obtain the highest possible quality data for the purpose of developing and testing snowpack energy exchange equations at a point. This study is the NOAA - ARS Cooperative Snow Hydrology Project on the Sleepers River Research Watershed (Johnson and Anderson, 1968). Ultimately these measurements of the variables affecting snowpack energy exchange will be used along with data from an adjacent watershed to develop improved methods of accounting for the effect of physiographic factors, such as slope, aspect, elevation, and forest cover on the mean areal values of the meteorological variables.

Air temperature is a very good index to snowpack energy exchange in a dense coniferous forest. The only energy exchange mechanism showing much variability is longwave radiation exchange, which is a function of the difference between canopy temperature and snow surface temperature. Canopy temperature is closely related to air temperature. The other primary energy exchange mechanisms, shortwave radiation exchange, sensible heat exchange, and latent heat exchange show very little variability because there is only a slight amount of solar radiation penetrating the forest canopy and because wind movement is limited. On the other hand, in an open area there generally is a large amount of variability in solar radiation exchange, longwave radiation exchange, sensible heat exchange, and latent heat exchange. Because of this variability, air temperature is not nearly as good an index to snowpack energy exchange in an open area. Therefore, there is a greater potential for improvement in estimating snowpack energy exchange by using a physical energy balance method, rather than a temperature index method, in areas where the values of the variables affecting energy transfer can exhibit large variations. It is felt that in the near future when accurate measurements of the variables affecting snowpack energy exchange are available and when techniques of accounting for the areal variability of the variables are improved that physical energy balance equations will provide a more accurate estimate of the energy exchange across the snow-air interface.

In regard to the data period required for model parameter calibration, the recommendation given in HYDRO-14 is generally applicable to watersheds where snow is included. HYDRO-14 indicates that it is desirable to sample each mathematical relationship in the model over its maximum possible range; thus, a long data period is indicated. However, in many cases watershed characteristics change with time. For river forecasting we are interested in parameters which express the near future. Since the future cannot be sampled, a short record representing the immediate past is the second choice. Based on these considerations, HYDRO-14 recommends that "A suitable compromise seems to be the most recent 10 years of record.". For most watersheds, 10 years of record is completely adequate for determining model parameter values. However, in arid or semi-arid areas and in areas where significant snowpacks do not accumulate every year, more than 10 years of data may be required to determine adequately all the model parameters. In areas with considerable hydrologic activity and where large snowpacks accumulate every winter, less than 10 years of data may be sufficient to determine model parameter values.

1.3 TEST WATERSHEDS AND RESULTS

This Technical Memorandum does not present detailed results of tests of the snow accumulation and ablation model. However, for the benefit of potential users it is felt that a listing of the watersheds tested to date and a brief summary of the simulation results on these watersheds might be informative. Table 1-1 lists the watersheds tested and presents several statistics which summarize the comparison between observed and simulated mean daily discharge. Data from the Central Sierra Snow Laboratory were used for testing various mathematical formulations during the development stage of the snow model. The estimation of energy exchange when air temperature is below 32°F was modified based on tests using data from Sleepers River Watershed W-3. The other watersheds were used to test the applicability of the model to different size areas and to different physiographic and climatic conditions.

1.4 COMPUTER PROGRAMS AND COMPUTER REQUIREMENTS

There are three basic computer programs in the NWSRFS which include the snow accumulation and ablation model. These are: 1) the verification program (NWSRFS4) which is used to check the simulation accuracy of various sets of parameter values, 2) the optimization program (NWSRFS3) which is used to determine parameter values by an automatic optimization technique, and 3) the operational river forecasting program (NWSRFS5) which is used to prepare river discharge forecasts on an operational basis. The NWSRFS also contains a number of data processing programs (see chapter 3 of HYDRO-14). Chapter 2 of this Technical Memorandum describes three additional data processing programs for use in computing mean areal air temperature. These are: 1) the basic mean areal air temperature program (MAT Program), 2) the MAT consistency check program (Program MATCØN) which checks the consistency of each station used in the mean areal temperature analysis, and 3) the MAT temperature check program (Program TEMPCK) which compares the estimated and observed maximum and minimum temperatures at a given air temperature observation station. Table 1-2 lists the program dimensions, storage requirements, and typical run times for the six programs involving the snow accumulation and ablation model and the computation of mean areal air temperature. The programs are written in FØRTRAN IV for use on a CDC 6600 computer system. Minor revisions may be necessary for use on other computer systems.

The computer programs and test data sets described in HYDRO-14 are availat on magnetic tape from:

Acquisition Office
National Technical Information Service
U. S. Department of Commerce
Springfield, Virginia 22151

Accession number: COM 73-10298
Cost: $97.50

These programs contain all the necessary statements for use with the snow subroutines (One exception; a few changes were made to Program NWSRFS5 after preparation of the magnetic tape. The changes are only needed when the snow model is included. Appendix H lists these changes to Program NWSRFS5). Information on how to obtain the snow subroutines for programs NWSRFS3, NWSRFS4, and NWSRFS5, plus the programs for the computation of mean areal ai temperature can be obtained from:

Hydrologic Research Laboratory, W23
Office of Hydrology
National Weather Service, NOAA
Silver Spring, Maryland 20910

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REFERENCES

Anderson, E. A., "Development and Testing of Snow Pack Energy Balance Equations", Water Resources Research, Vol. 4, No. 1, February 1968, pp. 19-37.

Johnson, Martin L., and Anderson, Eric, "The Cooperative Snow Hydrology Project - ESSA Weather Bureau and ARS Sleepers River Watershed", Proceedings of the Eastern Snow Conference, 1968, pp. 13-23.

Sittner, W. T., "Modernization of National Weather Service River Forecasting Techniques", Water Resources Bulletin, Vol. 9, No. 4, August 1973.

Staff, Hydrologic Research Laboratory, "National Weather Service River Forecast System, Forecast Procedures", NOAA Technical Memorandum NWS HYDRO-14 U. S. Department of Commerce, Silver Spring, Md., December 1972.

Table 1-1.--Summary of simulation results on the watersheds tested with the snow accumulation and ablation model in conjunction with the NWSRFS as of June 1973.

Watershed	Data Period	Area mi^2	Elev. Range[1]	Number of Stations				Mean Annual Runoff Inches and CFSD	RMS Error CFSD	Correl Coef.	% Bias	Best Fit Line Obs.=a+b·Sim.	
				Precip	Elev. Range	Air Temp.	Elev. Range					a CFSD	b
Upper Castle Creek, Central Sierra Snow Laboratory	10/46-9/51	3.96	6880-9105 7050-8250	1	6890	1	6890	46.1" 13.5 CFSD	8.3	.971	-2.0	-0.4	1.05
Skyland Creek, Upper Columbia Snow Laboratory (UCSL)	10/46-9/50	8.1	4800-7610 5200-6800	1	4840	1	4840	31.5" 18.8 CFSD	6.7	.981	1.5	-0.3	1.0
Bear Creek, UCSL[2]	10/46-9/50	12.6	4480-8605 4900-6350	1	4840	1	4840	29.5" 45 CFSD	13.8	.983	0.2	-0.3	1.01
W-3, ARS Sleepers River Watershed	10/62-9/67	3.23	1140-2260 Unknown	3	1350-2200	1	1140	21.7" 5.2 CFSD	2.1	.955	1.6	0.2	0.95
W-8, ARS Sleepers River Watershed[2]	10/62-9/67	2.81	920-1680 Unknown	2	1150-1350	1	1140	17.2" 7.7 CFSD	2.2	.970	2.3	0.2	0.95
W-1, ARS Sleepers River Watershed[2]	10/62-9/67	10.54	740-2430 Unknown	4	1150-2200	1	1140	17.1" 20.9 CFSD	8.7	.964	3.5	-1.7	1.04

Table 1.1 (continued)

Passumpsic R. at Passumpsic, Vermont	10/63-9/71	436.	530-3400 780-2240	4	699-1140	3	699-1140	20.3" 653 CFSD	294.	.939	-1.5	49.	0.94
Rock River at Rock Rapids, Iowa	10/59-9/69	788.	1330-1950 Unknown	6	1350-1700	6	1350-1700	3.1" 179 CFSD	444.	.906	5.9	28.	0.80

1 First range is for the total area. Second range is for 90 percent of the area, excluding the upper and lower 5 percent. All elevation ranges are in feet above m.s.l.

2 Streamgage is downstream from another calibrated watershed. Local area was calibrated using observed upstream inflows. Area, elevation range, and station information are for local area only. Mean daily discharge comparisons are based on the total flow at the streamgage.

Table 1-2.--Program dimensions, storage requirements[1], and typical run times[1] for NWSRFS programs using the snow model and programs for computing mean areal air temperature.

Program	Dimensions	Storage Requirements Decimal Words	Typical Run Times
Verification Program (NWSRFS4)	5 snowpack and soil-moisture accounting areas. 5 streamflow points. 3 upstream inflow points. 2 PE stations	39K	2 sec./year for each snowpack and soil-moisture accounting area, plus 3 sec./year for each streamflow point
Optimization Program (NWSRFS3)	2 snowpack and soil-moisture accounting areas. 1 streamflow point. 4 upstream inflow points. 2 PE stations 50 months of data	32K for program, plus 75K for data storage	5.5 sec./50 months for each snowpack and soil-moisture accounting area, plus 1 sec./50 months for the streamflow point
Operational River Forecasting Program (NWSRFS5)	10 snowpack and soil-moisture accounting areas. 10 streamflow points. 5 upstream inflow points. 3 PE stations. 14 days of data.	29K To enlarge river system requires approx. 350 words/snowpack and soil-moisture accounting area, plus 600 words/streamflow point	1 sec./14 days for each streamflow point
Mean Areal Air Temperature Program (MAT Program)	40 maximum-minimum air temperature stations 10 areas to compute mean areal temperature 4800 months of data storage	37K for program, plus 744 words of random access data storage per station year	7 sec./year for an analysis involving 10 stations

Table 1-2. (continued)

MAT Consistency Check Program (Program MATCON)	40 maximum-minimum air temperature stations 5 groups for double mass analysis 25 years of record	33K for program, plus 24 words of data storage per station year (data are generated by MAT Program)	1 sec./year for an analysis involving 10 stations
Program TEMPCK		40K for program, plus 1488 words of data storage per year (data are generated by MAT Program)	0.5 sec./year

1 Storage requirements and run times are based on a CDC 6600 computer system.

CHAPTER 2. DATA PROCESSING

2.1 INTRODUCTION

In order to calibrate a conceptual model for use in forecasting streamflow in a river system, large amounts of continuous hydrologic data are required. The conversion of the raw data into the form required for model calibration must be accomplished in an efficient manner.

HYDRO-14 (Appendix B) describes the format of data tapes containing raw hydrologic data which can be obtained from the National Climatic Center (NCC) at Asheville, North Carolina. Tapes containing two types of data are available: 1) hourly precipitation data, and 2) daily observations (precipitation, maximum-minimum air temperature, snowfall, snow on ground, water-equivalent of snow on ground, wind movement, and evaporation). HYDRO-14 (Chapter 3) also describes a method of estimating point values, for periods of missing data or locations having no data, and for computing areal means of precipitation. The computer program which utilizes this method and the NCC data tapes to compute mean areal precipitation is also described.

This chapter discusses the methods and the computer programs needed to compute mean areal air temperature for use in the calibration of the snow accumulation and ablation model. In addition, two supplementary data programs for the tabulation of monthly and annual means of precipitation, air temperature, wind movement, and evaporation are described. A summary of the necessary steps to process the raw data into the form required by the NWSRFS model calibration programs concludes the chapter.

2.2 ESTIMATION OF POINT VALUES OF AIR TEMPERATURE

2.2.1 INTRODUCTION

Since maximum-minimum air temperature data are measured as point values, the use of the data to compute mean areal values involves, implicitly or explicitly, inferences concerning the air temperature at all other points within the area. This section outlines a method of estimating the maximum and minimum daily air temperature at any point as a function of that at surrounding points. The method is objective in non-mountainous areas and quasi-objective in mountainous areas. The method can easily be programmed for use in computing mean areal air temperature for a long period of record. The program will use a minimum of computer time.

2.2.2 THEORY OF ESTIMATION

Referring to Figure 2-1, let point X be the point at which the maximum or minimum air temperature is to be estimated. Points A through G are points at which the maximum or minimum temperature is known.

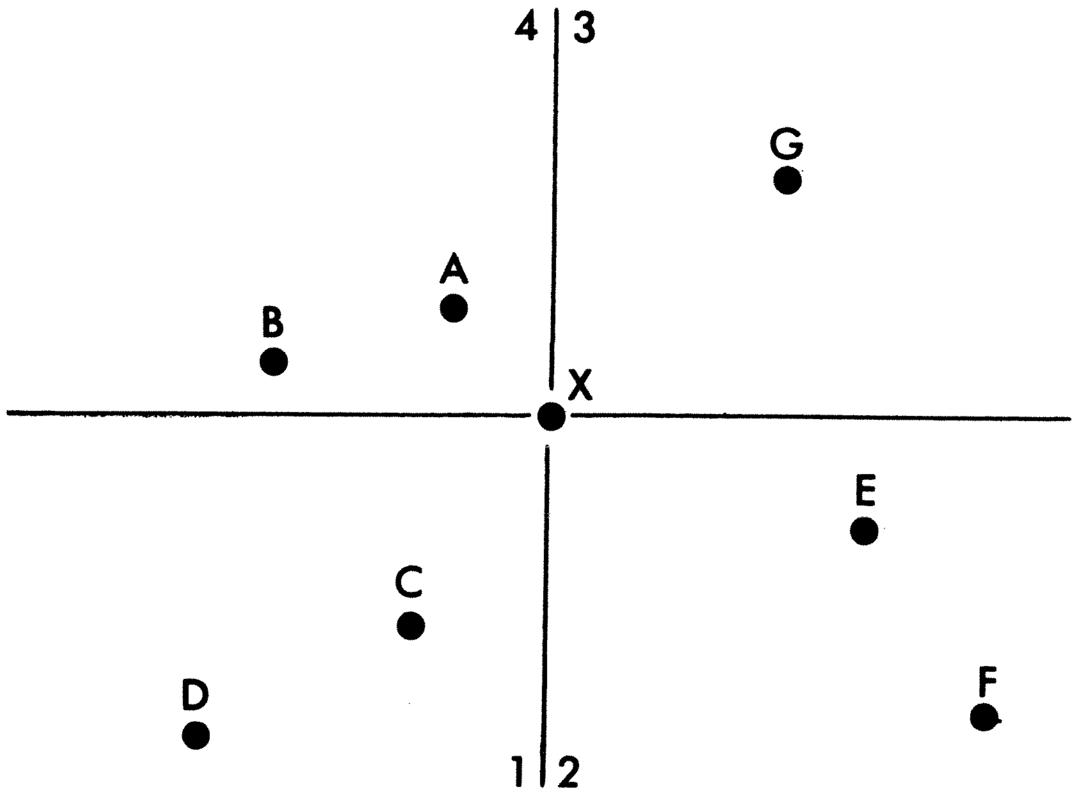


Figure 2-1.--Station location and quadrants for the estimation of air temperature at station X.

Perpendicular lines through point X divide the surrounding area into fou quadrants. It should be noted that perpendicular axes of any orientation can be used.

The estimate of temperature at X is now computed as a weighted average o "adjusted" station temperatures, using the station within each quadrant wi the largest station weight. Thus, the estimate of the temperature at any point X can be expressed as:

$$T_x = \frac{\sum_{i=1}^{i=n} [AT_i \cdot W_i]}{\sum_{i=1}^{i=n} W_i}, \qquad (2.1)$$

where: T_x = maximum or minimum temperature at the station being estimated.
i = the station used as an estimator,
n = number of estimators (the station with the largest station weight in each quadrant is used as an estimator),
AT_i = "adjusted" maximum or minimum temperature at station i, and
W_i = **weight function** for station i.

The procedure used to calculate "adjusted" station temperatures and the weight functions depends on whether the area is mountainous or non-mountainous

2.2.2.1 Non-mountainous Areas

As far as temperature estimation is concerned, a non-mountainous area is an area where topography does not appear to affect temperature variations and the gradients observed are approximately a linear function of distance. The weight function in this case is equal to the reciprocal of the distance from the station to point X. The "adjusted" temperature for each station used to estimate point X is then the same as the measured temperature at that station. Thus, the estimation equation for non-mountainous areas is:

$$T_x = \frac{\sum_{i=1}^{i=n} [T_i \cdot \frac{1.0}{d_{i,x}}]}{\sum_{i=1}^{i=n} \frac{1.0}{d_{i,x}}} , \qquad (2.2)$$

where: T_i = maximum or minimum temperature at estimator station i, and
$d_{i,x}$ = the distance from the station being estimated to the estimator station i, in terms of map coordinates.

2.2.2.2 Mountainous Areas

In reality, the differences in temperature between a number of stations in a mountainous region can vary from day to day depending on the meteorological situation. Operationally, the temperature differences between stations could be expressed as a function of a number of topographic and meteorological variables. However, in calibrating a conceptual hydrologic model, due to retrieval and processing problems, it is generally not feasible to use any additional meteorological data other than air temperature measurements. Experience has shown that the differences between station means are a good indication of the typical variations in temperature that exist over a mountainous area. In some cases, these differences are small (e.g., stations at approximately the same elevation may have slightly different means because of the exposure of the thermometers) and for practical purposes can be ignored. However, in other cases, especially in areas with significant topographic variation, these differences between stations are important and must be accounted for. Thus, as far as temperature estimation is concerned, a mountainous area is an area over which considerable variations in temperature usually exist.

Because of seasonal variations, a procedure for estimating point values in mountainous regions should use the mean monthly maximum and minimum temperature for each station as indices. Therefore, the "adjusted" station temperature can be expressed as:

$$AT_i = T_i + (N_x - N_i), \qquad (2.3)$$

where: N_x = mean maximum or minimum temperature at the station being estimated, and

N_i = mean maximum or minimum temperature at the estimator station i.

By substituting Eq. 2.3 for AT_i and rearranging the terms, Eq. 2.1 can be expressed as:

$$T_x - N_x = \frac{\sum_{i=1}^{i=n} [(T_i - N_i) \cdot W_i]}{\sum_{i=1}^{i=n} W_i} \quad . \qquad (2.4)$$

Thus, it can be seen readily that for a mountainous area the deviation of temperature at point X from the mean at the same point can be estimated from the deviation of temperatures at surrounding stations from their respective means.

In regard to station weights, the most important factors in mountainous areas are probably distance and elevation. If two stations are equi-dista from station X, studies have shown that the one closest in terms of elevat is usually the best estimator. This suggests that the weight function use in the estimation scheme should include elevation difference as a paramete A functional form for W_i which has produced improved estimates of temperature is:

$$W_i = \frac{1.0}{G_1 \cdot d_{i,x} + F_e \cdot \Delta E_{i,x}} \quad , \qquad (2.5)$$

where:
- $d_{i,x}$ = the distance between stations X and i expressed in map coordinates,
- G_1 = a scale factor to convert map coordinates to miles,
- $\Delta E_{i,x}$ = the absolute difference in elevation, expressed in 1,000 feet, between stations X and i, and
- F_e = an arbitrarily selected elevation weighting factor (if F_e = 10, then two stations, one which is 10 miles further from station X in distance, but 1,000 feet closer in elevation, would have the same station weight).

When either $\Delta E_{i,x}$ is zero or F_e selected to be zero, Eq. 2.5 is, of course equivalent to the weight function used in Eq. 2.2.

The final equation for the estimation of maximum or minimum air temperature at a point in a mountainous area can be determined by the substitutio of Eqs. 2.3 and 2.5 into Eq. 2.1. This substitution yields:

$$T_x = \frac{\sum_{i=1}^{i=n} \left\{[T_i + (N_x - N_i)] \cdot \left[\frac{1.0}{G_1 \cdot d_{i,x} + F_e \cdot \Delta E_{i,x}}\right]\right\}}{\sum_{i=1}^{i=n} \left[\frac{1.0}{G_1 \cdot d_{i,x} + F_e \cdot \Delta E_{i,x}}\right]} \qquad (2.6)$$

2.2.3 DETERMINATION OF F_e

It can be seen readily from Eq. 2.6 that F_e affects the station weight of each station being used to estimate the temperature at point X. Increasing F_e will give more weight to stations with the smallest values of $\Delta E_{i,x}$ and less weight to stations with the largest values of $\Delta E_{i,x}$. The estimate of temperature at point X is computed using the station within each quadrant with the largest station weight. Thus, as F_e is increased, the stations used to estimate the temperature at point X may change. Changes will occur if the station weight of more distant stations in each quadrant becomes greater than the station weight of stations which are closer to point X. This will occur as F_e increases if the distant stations have a smaller value of $\Delta E_{i,x}$. The dominant effect of F_e in most cases is the effect it has on the selection of the stations used to estimate temperature at point X.

Eq. 2.6 is used in mountainous areas for two purposes: (1) to estimate periods of missing data at an air temperature observation station, and (2) to estimate the maximum-minimum air temperature at a location which has no observed data. To estimate periods of missing data, the optimum value of F_e can be determined through a cut-and-try (iterative) technique, utilizing the available valid data from the station. To estimate air temperature at a location which has no observed data, the magnitude of F_e must be arbitrarily selected. F_e values for other stations in the area may provide a guideline for the selection. However, it should be noted that the optimum value of F_e for a station is dependent on the location of the stations being used to make the estimate (e.g., the magnitude of F_e could vary considerably depending on whether distant stations had large values of $\Delta E_{i,x}$ or small values of $\Delta E_{i,x}$ relative to stations that are close to point X).

A computer program is provided for determining the optimum value of F_e at any selected temperature observation station (program is described in section 2.4.4). The program compares the estimated and observed maximum and minimum air temperatures. By varying the magnitude of F_e, the effect of F_e on the results can be determined. The root-mean-square (RMS) error (square root of the sum of the squares of the observed minus estimated values) is used to compare results. Figs. 2-2 and 2-3 show the effect of various values of F_e on RMS for two locations; one in Arizona, and the other in New Hampshire. These figures suggest that the magnitude of F_e for estimating maximum temperatures should be different from the magnitude of F_e for estimating minimum temperatures.

If a plot of RMS versus F_e is not prepared and thus the magnitude of F_e is selected arbitrarily, experience would indicate the following guidelines:

1. If the stations that are closest to point X also have the smallest values of $\Delta E_{i,x}$, the magnitude of F_e is not critical. $F_e = 0.0$ would be appropriate.

2. If the stations that are closest to point X have the largest values of $\Delta E_{i,x}$, a value of F_e in the range 10.0 to 30.0 would be appropriate.

It should be noted that these guidelines are based on a limited amount of testing of the temperature estimation procedure on data from Arizona, Vermont, and New Hampshire.

2.2.4 TYPICAL ESTIMATION RESULTS

In order to give the user a feel for the accuracy that can be expected from Eq. 2.6, a summary of typical results is given in Table 2-1. In all cases F_e was arbitrarily selected as 10.0. In addition to the station elevations, the observation times should be noted. For stations taking their observations in the afternoon (including midnight) the maximum and minimum are assumed to have occurred on the day of observation. For stations taking morning observations the minimum is assumed to have occurred on the day of observation while the maximum is assumed to have occurred on the previous day. In reality these assumptions do not always hold, thus, a group of stations with mixed observation times can have mismatched maximums and minimums on some days. In addition to the RMS error, the standard deviation of the observed temperatures about the monthly mean is also given. If the RMS error exceeds the standard deviation, no intelligence is imparted by the technique, as the monthly mean would make a better daily estimate. Table 2-1 shows only the RMS error and standard deviation for the total test period. The monthly ratios of the RMS error to the standard deviation were similar to those for the total test period. However, in most cases both figures are greater during cold periods than during warm periods.

2.3 COMPUTATION OF MEAN AREAL AIR TEMPERATURE

2.3.1 INTRODUCTION

Mean areal air temperature is computed by utilizing stations within or close to the area and in some cases other available meteorological information. The basic procedure consists of: 1) examine the available maximum-minimum air temperature data to determine if the available data adequately represents all portions of the area, 2) if the available data does not represent all portions of the area, assign "dummy" stations to those portion that are not represented, 3) determine the mean monthly maximum and minimum temperature for each "dummy" station, 4) determine station area weights for all stations, 5) estimate daily maximum and minimum temperature at all stati having missing periods of record, and 6) multiply station temperatures by station area weights to get mean areal air temperature. This section elaborates on the use of this basic procedure in non-mountainous and mountainous areas.

2.3.2 NON-MOUNTAINOUS AREAS

Since temperature varies linearly with distance in non-mountainous areas, "dummy" stations are not needed. Any area weight assigned to a "dummy" station could be proportioned to the stations used to estimate the temperature at the "dummy" station. Thus, the use of "dummy" stations would not change the estimate of mean areal temperature.

Several procedures could be used for computing station area weights in non-mountainous areas. One method is the use of grid point weights (section 3.3.4 of HYDRO-14) where the grid points correspond to the X, Y coordinate system used to locate the stations. For temperature the reciprocal of the distance is used rather than the reciprocal of the distance squared as with precipitation. Other methods would include Thiessen weights or an arithmetic average, if stations are distributed in a reasonably uniform manner.

Missing data should be estimated using Equation 2.2. It should be noted that to get a good estimate for missing data periods at stations near the border of the area, it is usually necessary to include additional outlying stations.

2.3.3 MOUNTAINOUS AREAS

In some cases there is an adequate distribution of temperature observation stations to represent all portions of a mountainous area. However, for most mountainous areas this is not the case. This is especially true for the high elevation portions of most mountainous areas. Thus, it is usually necessary to create "dummy" stations to represent those portions of a mountainous area for which actual data does not exist.

If "dummy" stations are needed, the next step is to determine the mean monthly maximum and minimum temperature for each "dummy" station. An analysis to determine these values would include an examination of the variation in monthly means for stations with actual data that are within the area, an examination of monthly means for stations with actual data in the surrounding area, especially high elevation stations, and possibly an examination of other meteorological information, such as radiosonde data. If radiosonde data are used, the difference in the thermal gradient up the side of a mountain and the lapse rate in the atmosphere must be considered.

The station area weight for each station in a mountainous area is equal to the portion of the area that the station represents.

Missing daily maximum and minimum temperatures at all stations should be estimated using Eq. 2.6. This will complete the data record at all actual stations, plus create a data record for each "dummy" station (since a "dummy" station is just a station with all missing data).

2.4 COMPUTER PROGRAMS FOR COMPUTING MEAN AREAL TEMPERATURE

2.4.1 INTRODUCTION

A computer program has been written which uses the techniques described in previous sections of this chapter to compute mean areal air temperature. The basic computational interval of the NWSRFS is six hours, thus, the final product of the program is six hourly mean areal temperature. In addition to the basic program to compute mean areal temperature, there are two programs to aid in preliminary analysis, a program to check the consistency of the basic temperature data, and a program to compare estimated and observed data at an individual station.

2.4.2 PROGRAMS TO AID IN PRELIMINARY ANALYSIS

To aid in station selection and to provide helpful data for isohyetal, temperature variation, and model calibration analyses, two preliminary data processing programs are provided to summarize the data on the NWSRFS-NCC tapes. In each program the stations and the period of record to be summarized are preselected. A brief description of the tasks performed by each program is as follows:

a. Daily observation tape program (Program PRELIM2).
   1. Lists snowfall and snow on ground for each month that there was snowfall or snow on ground.
   2. Computes average daily evaporation and wind movement for each month at stations that make pan evaporation measurements.
   3. Computes mean monthly and mean annual precipitation, maximum temperature, minimum temperature, evaporation, and wind movement for the period being summarized.
   4. Writes the data for the selected stations and for the selected period onto a new tape. The format of the new tape is exactly the same as the original NWSRFS-NCC tape. Thus, the daily data for a reasonably large area (maximum number of stations equal 75), which may encompass several states, can be placed on a single tape. This will save on tape reading and tape handling costs during the computation of mean areal temperature and precipitation.

b. Hourly precipitation data tape program (Program PRELIM1).
   1. Computes mean monthly and mean annual precipitation.
   2. Writes the selected data onto a new tape.

A listing of programs PRELIM1 and PRELIM2 are given in Appendix A.

2.4.3 MEAN AREAL TEMPERATURE PROGRAM

The Mean Areal Temperature (MAT) program provides an efficient means to process air temperature data for use in the snow accumulation and ablation model. The program is described in sequential order of the major steps involved in the computation of MAT.

2.4.3.1 Input Data

The program uses maximum-minimum temperature observations to compute areal means. The maximum-minimum temperature data are input in NWSRFS-NCC daily observation tape format (Appendix B.2.3, HYDRO-14). In addition to the raw temperature data, station and areal information is also needed. Appendix B.: contains the input summary for the MAT program.

2.4.3.2 Estimation of Missing Maximum-Minimum Temperature Data

The MAT program uses Eq. 2.2 for non-mountainous areas and Eq. 2.6 for mountainous areas to estimate missing data at each station. When using Eq. 2.6, the program allows for different values of F_e for maximum temperatu and minimum temperature at each individual station. The program is written so that no estimated value will be used in the estimation of another missing value. If all the stations are missing on a given day, the temperature at each remains as a missing value and a message is printed. The six hourly means resulting from periods when all the maximums or minimums are missing will also be missing and must be estimated later by hand. To avoid cases of missing data remaining in the program output, a reasonable number of stations should always be included in the analysis. When more than five stations are used, cases of missing data in the program output will probably never occur.

2.4.3.3 Conversion of Maximum-Minimum Temperature Data to Six-hourly

In the MAT program, the maximum temperature is assumed to occur in the afternoon and the minimum near sunrise. The relationship between each six-hour period and the maximum and minimum temperature varies throughout the year because of variations in the number of daylight hours. In snow computations, the most important time of the year is the spring melt period. The relationships used in the MAT program were derived from maximum-minimum and hourly air temperature data available for the spring snowmelt period from the Central Sierra Snow Laboratory near Donner Summit, California and the NOAA-ARS Cooperative Snow Research Station near Danville, Vermont. The relationships used in the MAT program are:

a. Midnight to 6 a.m.

$$T_6 = 0.95 \cdot T_{min_n} + 0.05 \cdot T_{max_{n-1}} \qquad (2.7)$$

b. 6 a.m. to noon

$$T_6 = 0.40 \cdot T_{min_n} + 0.60 \cdot T_{max_n} \qquad (2.8)$$

c. Noon to 6 p.m.

$$T_6 = 0.925 \cdot T_{max_n} + 0.025 \cdot T_{min_n} + 0.05 \cdot T_{min_{n+1}} \qquad (2.9)$$

d. 6 p.m. to midnight

$$T_6 = 0.33 \cdot T_{max_n} + 0.67 \cdot T_{min_{n+1}} \qquad (2.10)$$

where: T_6 = Mean six-hourly air temperature,
T_{min} = Minimum air temperature,
T_{max} = Maximum air temperature, and
n = Current day.

2.4.3.4 Computation of Areal Means

The computation of six-hour areal means is simply a matter of multiplying the six-hourly temperatures for each station by the station weight for that station. Station area weights for MAT computations can be predetermined, based on the portion of the area represented by each station, or grid point weights can be computed within the program. It is strongly recommended that predetermined station area weights be used in mountainous areas. The final product, six-hourly mean areal air temperature, can be output onto tape in

NWSRFS Standard Tape Format (section 3.7.2 in HYDRO-14) or on Office of Hydrology Standard Format cards (Appendix A in HYDRO-14) with a field length equal to three.

2.4.3.5 Consistency Checks

A separate program to be used in conjunction with the MAT program is prc vided to check the consistency of the basic maximum-minimum temperature data. The data needed for the consistency checks are written onto a disk scratch tape in the MAT program. The consistency check program is then executed immediately after the MAT program. The consistency check prograr has no input other than that given it by the MAT program.

The difference in monthly mean temperature between two stations should t nearly constant, though in some cases the difference may exhibit a seasone variation. Thus, a double-mass plot showing the deviation of the cumulati mean monthly temperature at an individual station from the average cumulat mean temperature at a group of stations should be a good check on the cons tency of the temperature data at the individual station. For a consistent record the double-mass plot should be a straight line, or a straight line waves on it if a seasonal variation between stations exists. Figure 2-4 shows some typical consistency check plots. Stations A and B are consiste over the period while station C is not. The consistency check program produces such a plot for both maximum and minimum temperatures at all the stations used in the areal analysis.

In addition to the consistency of the record, the plots also give some insight as to how representative certain stations are. For example, if there are a number of stations within the same area at a similar elevatior their consistency plots should be fairly similar. If the plot for one station shows large negative deviations from the others, it is likely that the station is influenced significantly by cold air drainage and, thus, may not be a representative station.

2.4.3.6 Correcting Inconsistent Stations

The initial run of the MAT program and the consistency check program may show that certain stations have inconsistent records while others may not be representative of the portion of the area that they are supposed to represent. Thus, the program needs to be rerun to correct these deficienc Unrepresentative stations can be dropped from the analysis, or their stati weight can be revised, or they can be corrected by the addition or subtrac tion of a constant temperature so that their data will be representative. Inconsistent stations need to be corrected so that their record will be consistent. For example, in Fig. 2-4 station C could be made consistent t applying a correction of -1°F to all observations from November 1965 throu April 1968. A provision for making such corrections is included in the in to the MAT program. It should be noted that when applying a correction it is necessary to adjust the mean station temperature if the data being corrected were used to compute the station mean.

2.4.3.7 Sample Input and Output

A set of sample input cards for the computation of mean areal temperature for the Passumpsic River at Passumpsic, Vermont for the period October 1963 through September 1971 is listed in Appendix B.2. A map of the Passumpsic basin, showing station location, is shown in Figure 2-5. Appendix B.3 contains examples of the output from the MAT program and the consistency check program.

2.4.4 TEMPERATURE ESTIMATION COMPARISON PROGRAM

A program is provided to compare estimated and observed data at an individual station for the purpose of checking the accuracy of the estimatic technique or to determine the magnitude of F_e. This program (TEMPCK) must be run in conjunction with the MAT program. A "dummy" station is positionec at exactly the same coordinate location as the actual station for which the comparison is to be made. The MAT program estimates the daily maximum and minimum temperatures for the "dummy" station using Eq. 2.2 or Eq. 2.6, depending on the type of area. The MAT program then writes the daily maximu and minimum temperatures for the "dummy" station and its real counterpart or a disk or tape. Program TEMPCK uses these data to compare the estimated anc observed temperatures. The comparison is summarized by a plot of estimated versus observed maximum and minimum temperatures and by a table of the RMS error and the standard deviation of the observed maximum and minimum temperatures for each month and for the total period that was compared.

The input for the MAT program varies slightly from that listed in Appendix B.1 when the MAT program is being used to prepare input for TEMPCK. The changes are as follows:

Card No.	Changes
1	Punch a zero in column 30. Column 40 has no effect. Punch the run number in columns 56-60 of the actual station for which the comparison of observed versus estimated temperatures is to be made. Run number is determined by the station input order as defined by card 3.
4 & 5	F_e should be the same for the "dummy" station and its real counterpart.
6-8	Do not input these cards.

In addition to the data prepared by the MAT program, program TEMPCK requires one input card. The form of this card is as follows:

Format	Contents
I5	Initial ordinate for estimated versus observed maximum temperature plot. Plots are 120°F by 120°F, thus, if initial ordinate is -9°F, then

Format	Contents
	observed and estimated values from -9°F to +110°F will be plotted.
I5	Initial ordinate for estimated versus observed minimum temperature plot.
F5.0	EMAX. When the estimated temperature varies by more than EMAX degrees from the observed, program TEMPCK prints a message listing the observed temperature, the estimated temperature, and the date of occurrence.

Appendix B.4 lists a set of sample input for using program TEMPCK in conjunction with the MAT program. Appendix B.5 contains sample output from program TEMPCK.

2.5 SUMMARY OF STEPS IN DATA PROCESSING

As a reference for users of the data processing programs presented in this chapter and in chapter 3 of HYDRO-14, the steps required to prepare the data necessary for model calibration are summarized. To illustrate the steps a typical basin is used as an example; the Passumpsic River at Passumpsic, Vermont. Data were prepared for the period October 1963 through September 1971.

a. Obtain NWSRFS-NCC hourly and daily data tapes, including table of contents, for all states involved in the analysis from the National Climatic Center, Asheville, North Carolina. (Tapes described in Appendix B of HYDRO-14) In this case, tapes were obtained for Vermont and New Hampshire.

b. With the aid of the Annual Summaries of Climatological Data published by the Environmental Data Service, NOAA, and the tape table of contents, select all the stations which could possibly be useful in the analysis. In this case, 40 daily stations and 21 hourly stations were selected for use in calibration of the Passumpsic River and for future analysis of the Ammonoosuc and White River basins.

c. Run programs PRELIM1 and PRELIM2 for the selected stations.

d. Determine changes in location of all stations from the Annual Summaries of Climatological Data and observation times for daily stations from monthly Climatological Data bulletins.

e. Perform an isohyetal analysis to determine "characteristic precipitation" (section 3.3.2 in HYDRO-14) for each station if the area is mountainous. Also locate "dummy" precipitation stations if they are needed. For the Passumpsic basin "characteristic precipitation" was determined from the mean monthly precipitation values computed by programs PRELIM1and PRELIM2 and from an isohyetal analysis performed by Knox and Nordenson (1955).

f. Run the Mean Basin Precipitation program (section 3.4 in HYDRO-14). For the Passumpsic, mean areal precipitation was computed for three areas; the basin as a whole, the area below 1,330 feet elevation, and the area above 1,330 feet elevation. The output was put onto tape.

g. Examine the available maximum-minimum air temperature data to determine if the available data adequately represents all portions of the area. If the available data does not represent all portions of the area, assign "dummy" stations to those portions that are not represented. Determine the mean monthly maximum and minimum temperature for each "dummy" station from available actual temperature records or possibly other meteorological information. For the Passumpsic basin temperature records for stations within or near the basin, plus several high elevation stations in northern New England, were used to determine the mean monthly maximum and minimum temperature for the assigned "dummy" station.

h. Run the Meán Areal Temperature program. For the Passumpsic basin mean temperature was computed for the same areas as was precipitation. The output was put onto tape.

i. Obtain mean daily discharge records. In the case of the Passumpsic River, daily discharge was punched directly from the U.S.G.S. Water Supply Papers and converted to Office of Hydrology Standard Format Cards (Appendix A in HYDRO-14). The data could also have been obtained from the U.S.G.S. on magnetic tape and converted to Office of Hydrology Standard Format Cards with program DAILYF (Appendix D in HYDRO-14).

j. Determine daily potential evapotranspiration (PE) and put the results on Office of Hydrology Standard Format Cards. For the Passumpsic basin daily PE was computed from meteorological variables (Equations given in section 3.5 of HYDRO-14) collected by NOAA and the Agricultural Research Service near Danville, Vermont. For periods when the meteorological variables were not available, daily PE was estimated from mean monthly PE computed for Burlington, Vermont.

k. Put all data currently on Office of Hydrology Standard Format Cards onto tape in NWSRFS Standard Tape Format. Program NWSRFS2 (Appendix E.1 in HYDRO-14) performs this task. For the Passumpsic basin PE and mean daily discharge data were converted from cards to tape.

l. Combine the basic data from individual tapes onto one master tape for use in model calibration. Program SUPERTP (Appendix E.2 in HYDRO-14) is used to merge tapes. For the Passumpsic basin the three individua tapes; one containing mean areal precipitation, one containing mean areal temperature, and one containing PE and mean daily discharge, were combined.

Reference:

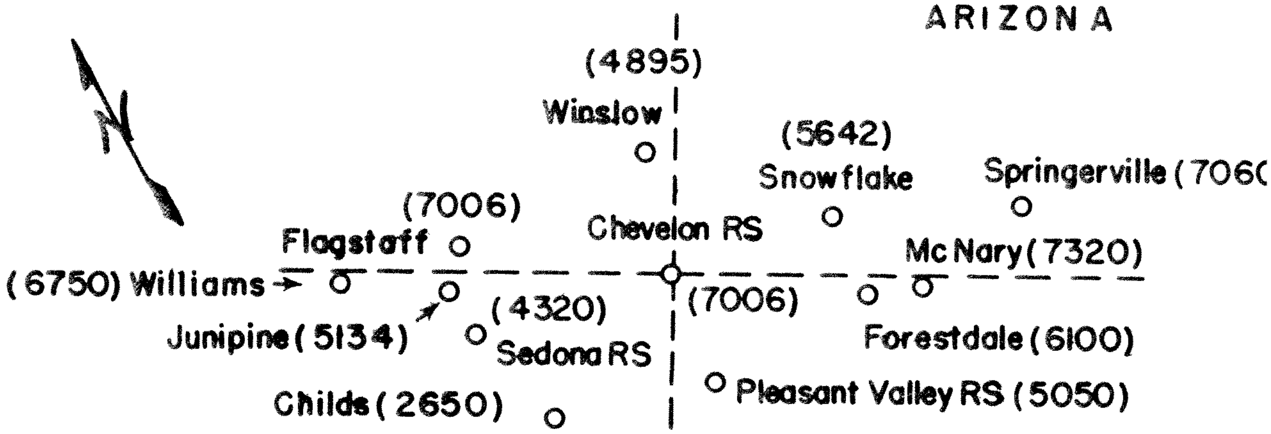
Knox, C. E. and Nordenson, T. J.,"Average Annual Runoff and Precipitatio in the New England-New York Area,"Hydrologic Investigations Atlas HA7, Department of the Interior, United States Geological Survey, 1955.

TABLE 2-1 Accuracy of point temperature estimates from Eq. 2.6 with F_e = 10.0

Case	Estimated Station Elevation, Observation Time and Test Period	Stations Used for Estimate-- Elevation and Observation Time	RMS-°F Max	RMS-°F Min	Standard Deviation °F Max	Standard Deviation °F Min
High elevation station estimated from stations at or below it.	Flagstaff, Arizona 7006' 12PM 10/63 - 9/71	Chevelon RS 7006' 5PM Cottonwood 3360' 6PM Groom Creek 6100' 5PM Williams 6750' 5PM Winslow 4895' 12PM Wupatki N.M. 4908' 5PM	3.4	4.4	8.6	7.5
	Flagstaff, Arizona 7006' 12PM 10/63 - 9/71	Chevelon RS 7006' 5PM Cottonwood 3360' 6PM Fort Valley 7347' 8AM Groom Creek 6100' 5PM Winslow 4895' 12PM Wupatki N.M. 4908' 5PM	3.7	4.8	8.6	7.5
	Fort Valley, Arizona 7347' 8AM 10/63 - 9/71	Chevelon RS 7006' 5PM Cottonwood 3360' 6PM Groom Creek 6100' 5PM Williams 6750' 5PM Winslow 4895' 12PM Wupatki N.M. 4908' 5PM	5.0	5.8	8.5	8.2
Middle elevation station estimated from stations above and below it.	Junipine, Arizona 5134' 6PM 10/63 - 9/71	Cottonwood 3360' 6PM Flagstaff 7006' 12PM Montezuma Castle 3180' 6PM Williams 6750' 5PM	2.1	2.8	8.1	5.8

TABLE 2-1 (continued)

High elevation station estimated from low elevation stations	Palisade RS, Arizona 7945' 5PM 1/65 - 9/71	Oracle 2SE Sabino Canyon San Manuel	4540' 2640' 3560'	6PM 5PM 6PM	3.9	4.6	7.4	6.7
	Palisade RS, Arizona 7945' 5PM 1/65 - 9/71	Sabino Canyon San Manuel Willow Springs Ranch	2640' 3560' 3690'	5PM 6PM 5AM	3.9	4.8	7.4	6.7
	Mt. Washington, N.H. 6262' 12PM 10/63 - 9/71	Bethelehem 10/63 - 11/65 12/65 - 9/71 Fabyan Pinkham Notch 10/63 - 9/64 10/64 - 9/71 Woodstock	1380' 1620' 2029' 720'	 7AM 5PM 7PM 7PM 7AM 6PM	5.6	8.4	9.9	10.5
	Mt. Mansfield, Vt. 3950' 5PM 10/63 - 9/71	Burlington WSO Montpelier Morrisville	332' 1126' 680'	12PM 12PM 5PM	4.4	6.6	9.8	10.1
Station estimated from other stations at nearly the same elevation	North Danville, Vt. 1140' 12PM 10/63 - 9/71	Newport St. Johnsbury West Burke	766' 699' 900'	12PM 4PM 7AM	3.1	4.8	9.7	10.1



STATION LOCATION MAP WITH ELEVATIONS IN PARENTHESES

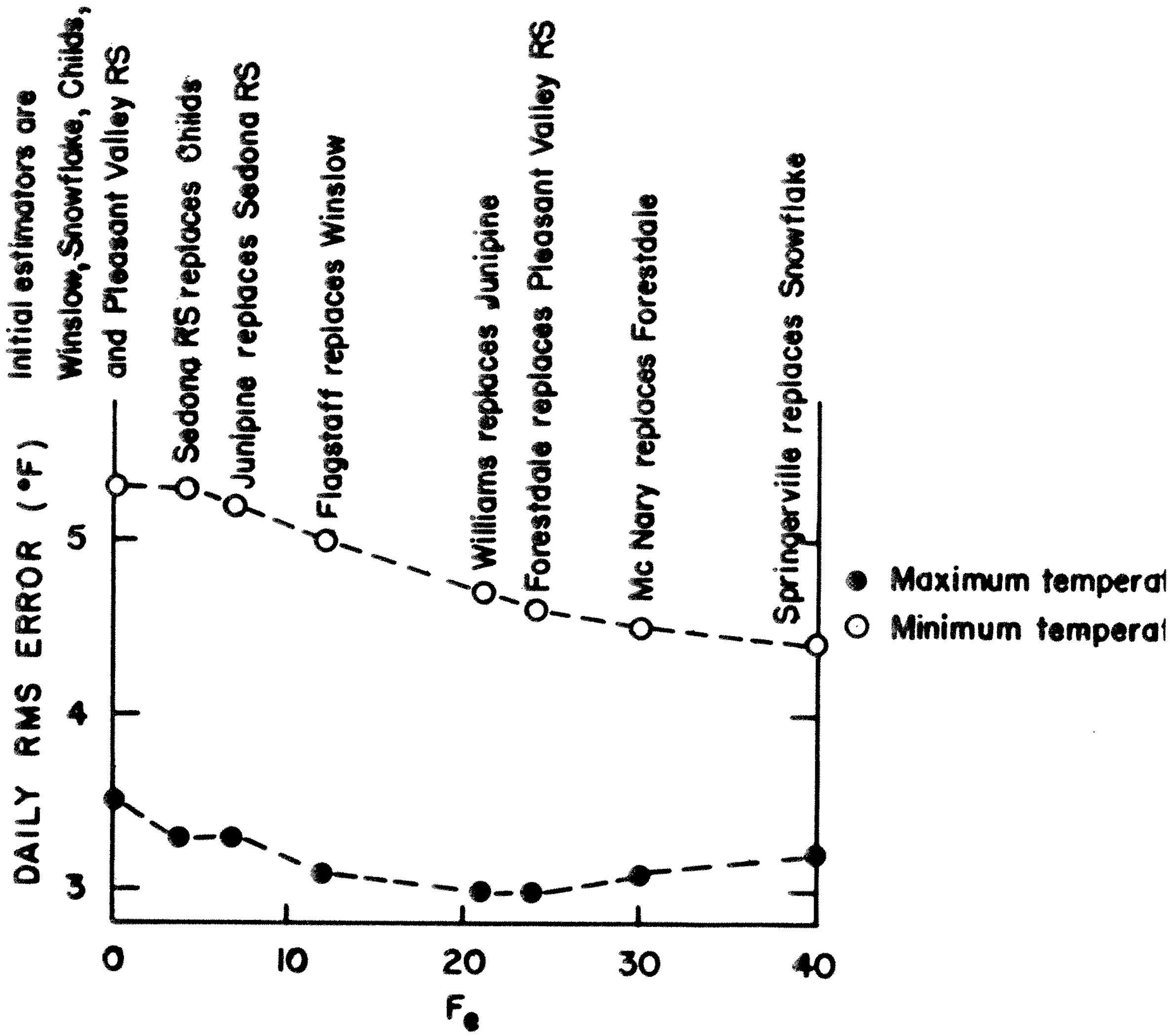
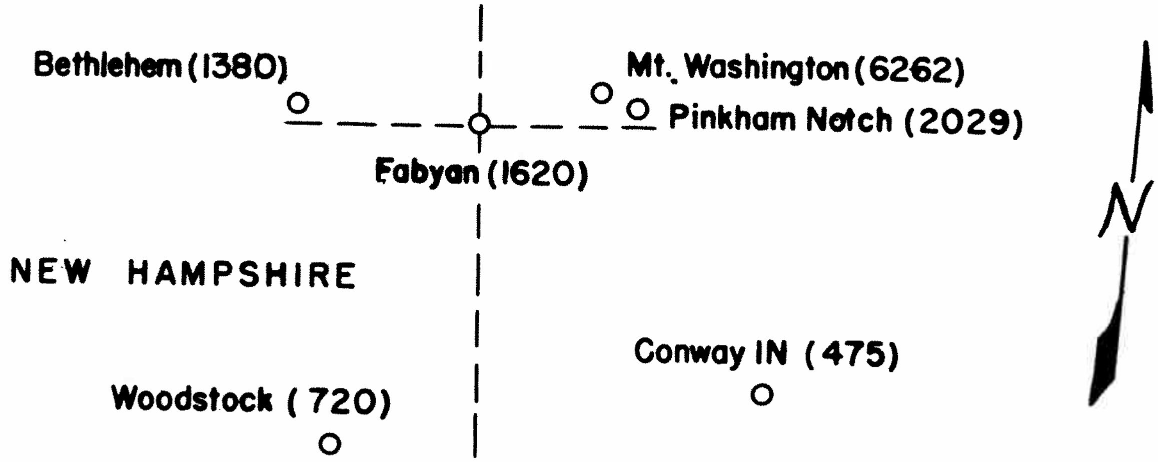


Figure 2-2. F_e versus RMS error plot for Chevelon Ranger Station, Arizona, 10/63 - 9/



STATION LOCATION MAP WITH ELEVATIONS IN PARENTHESES

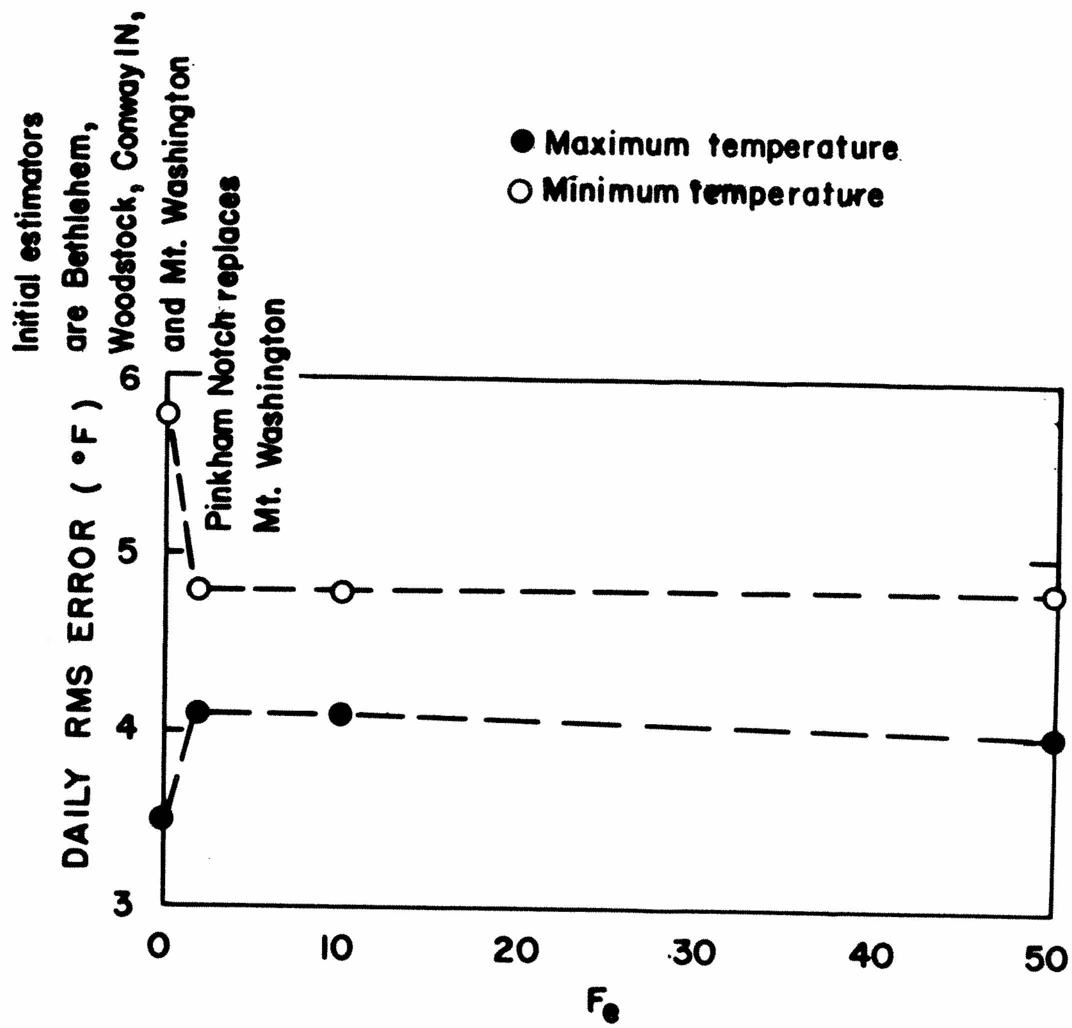


Figure 2-3. F_e versus RMS error plot for Fabyan, New Hampshire, 10/63 - 7/70.

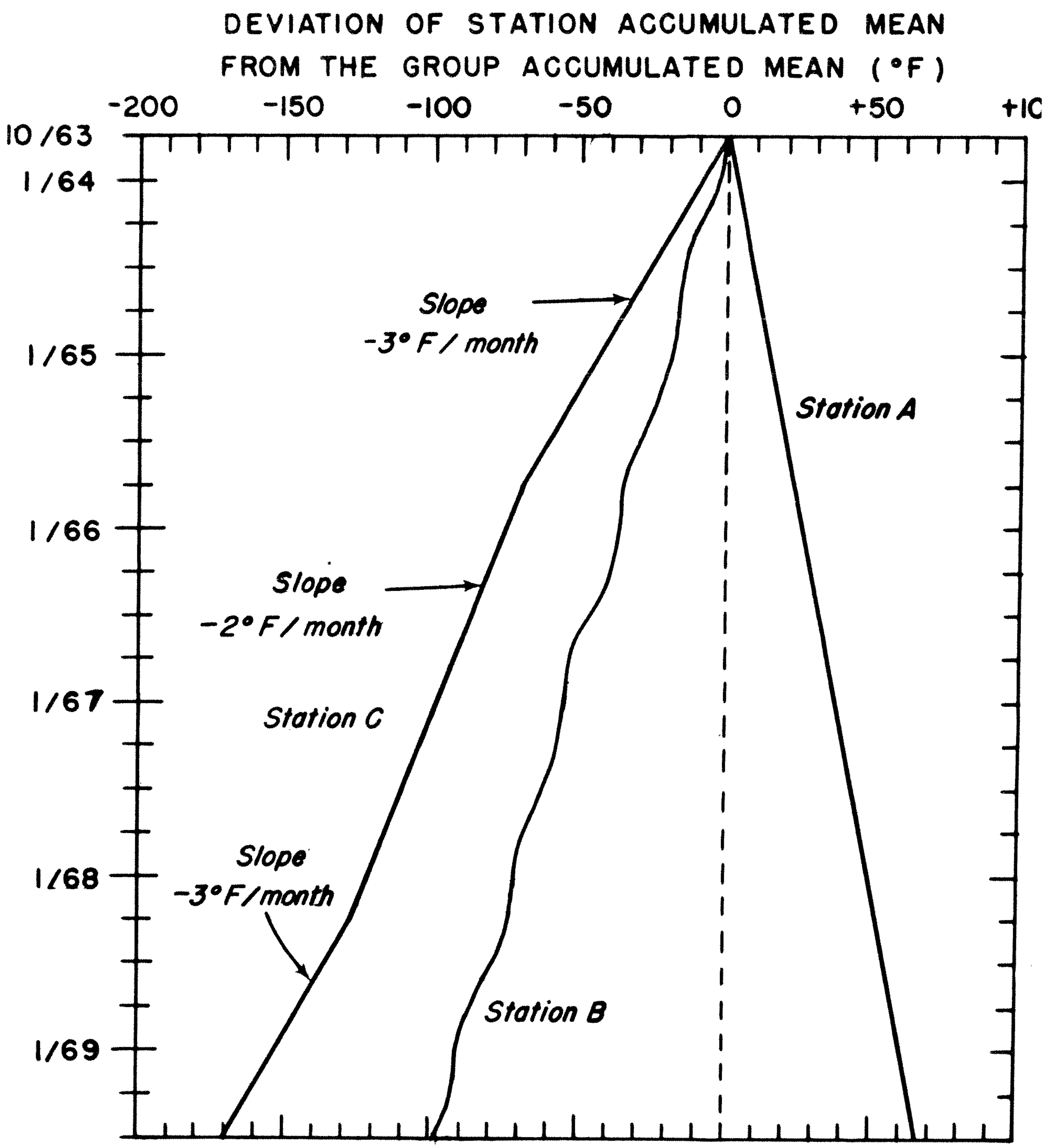
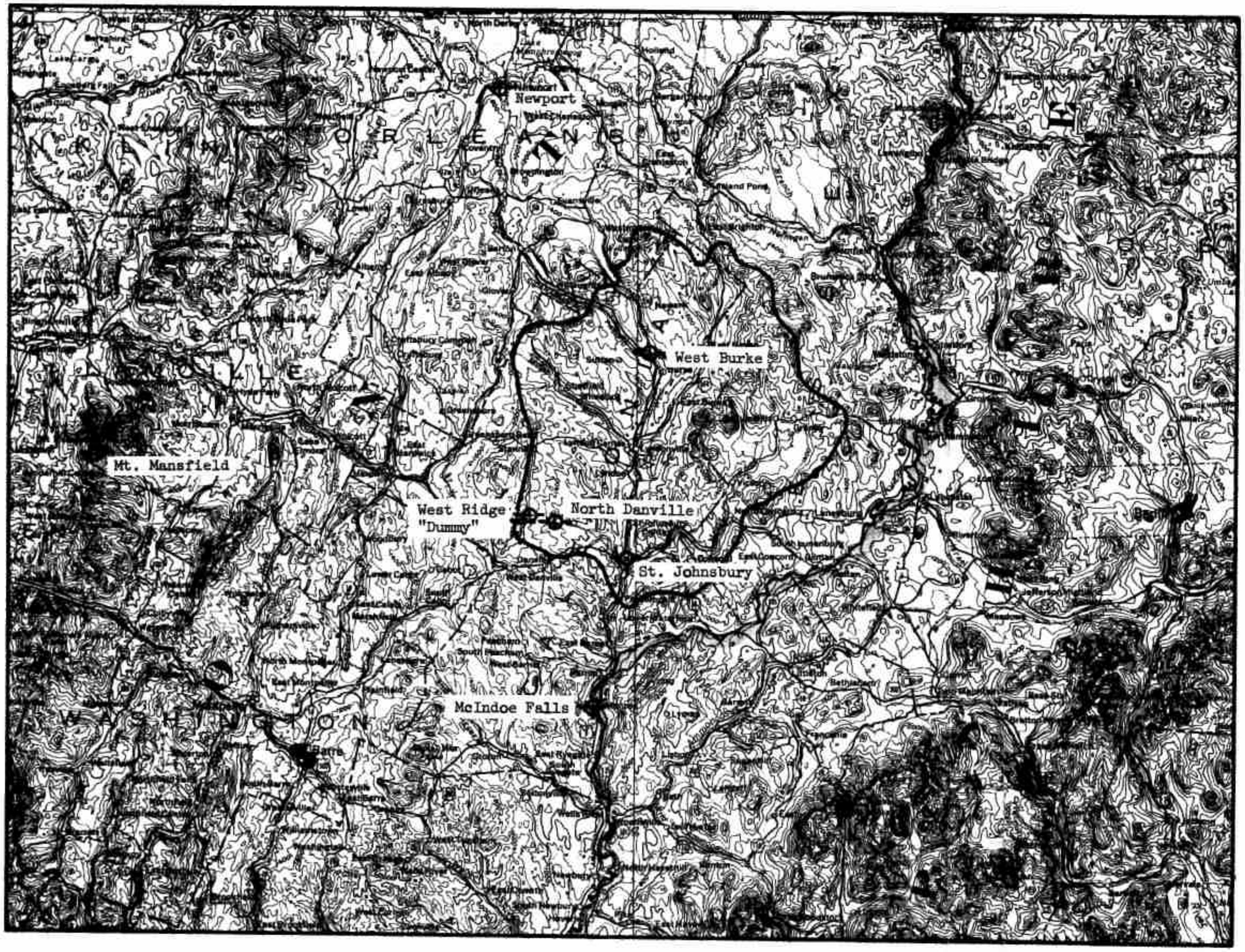


Figure 2-4. Typical temperature consistency check plot.



Scale: 1:500,000

Contour Interval 200 feet

CHAPTER 3. SNOW ACCUMULATION AND ABLATION MODEL

3.1 INTRODUCTION

This chapter describes the basic model representing the physical processes which are needed to simulate the accumulation and ablation of a snowpack. The basic philosophy of the model is that each significant physical componen be represented separately, rather than to use a single index to explain several processes, e.g., the use of degree-day-factors as described by Linsley et al. (1958). As noted in Chapter 1, air temperature and precipitation are the only meteorological variables that are required for this model. Guidelines for determining model parameters are not included in this chapter. Model parameter guidelines are inclyded in the discussion of model calibration in Chapter 5.

3.2 FLOWCHART

Figure 3-1 shows a flowchart of the snow accumulation and ablation model. This flowchart shows each of the physical components which are represented in the model. These include, accumulation of the snowpack, heat exchange at the air-snow interface, areal extent of snow cover, heat storage within the snowpack, liquid-water retention and transmission, and heat exchange at the soil-snow interface.

3.3 DESCRIPTION OF MODEL COMPONENTS

This section describes the mathematical relationships which are used to model each of the basic components of the snow accumulation and ablation process. It should be noted that in the model all snowpack variables are expressed in terms of mean values over the entire area. Thus, if the total snowpack water equivalent is computed as 6.30 inches and the areal extent of snow cover is 50 percent, then the mean water equivalent over the area actually covered by snow is 12.60 inches.

3.3.1 ACCUMULATION OF THE SNOWPACK

The first decision which must be made is whether precipitation entering the model is in the form of rain or snow. Air temperature is used as the index to the form of precipitation. The parameter PXTEMP is the delineatior point between rain and snow.

$TA > PXTEMP$ Precipitation is rain, and
$TA \leq PXTEMP$ Precipitation is snow,

where:

TA is the air temperature in degrees F, and
PXTEMP is in degrees F.

For heat storage computations or for computing the melt caused by rain water, the temperature of the precipitation is assumed to be equal to the air temperature. When snow is falling at air temperatures greater than 32°F, the temperature of the snow is set to 32°F.

In order to simulate the accumulation of the snowpack correctly, not on does the form of precipitation need to be determined, but the amount of precipitation must be reasonably accurate. The catch of a precipitation gage can be in error by a considerable amount during snowfall events; especially if the gage is not shielded or if the gage is exposed to high winds. The parameter SCF is used to correct for gage catch deficiency during snowfall, i.e.,

$$PX_a = SCF \cdot PX_g, \quad (3\cdot$$

where:

PX_g is the precipitation as recorded by the gage in inches, and
PX_a is the actual water equivalent of the snowfall in inches.

In this model SCF is a mean gage catch deficiency correction factor. For individual storm PX_a can be in error because of variations in wind speed and direction. However, as the number of storms contributing to the snov pack becomes large, the errors from individual storms will tend to cancel each other.

3.3.2 HEAT EXCHANGE AT THE AIR-SNOW INTERFACE

The heat exchange at the air-snow interface is the most critical factor controlling the ablation of a snowpack. This model uses air temperature ε the index to the heat exchange mechanisms which control heat flow into or out of the snowpack. There are two basic situations for which heat exchar needs to be estimated: (1) when the air is warm enough so that melt takes place at the snow surface, and (2) when the air is too cold for melt to occ

3.3.2.1 Melt at Snow Surface

The model assumes melt can occur at the snow surface when the air temper ture is above 32°F. The relative importance of various heat exchange mech anisms varies with meteorological conditions. Since only air temperatur and precipitation are assumed known in this model, it is impossible to distinguish each condition. However, the rate of melt during rain can be separated from the rate of melt during other conditions. In the model the equation for melt during rain is used when the amount of rain exceeds 0.1 inch in six hours.

a. Melt during rain. During rain several assumptions are made so that melt can be computed from an energy balance equation. The assumptions are: (1) solar radiation is zero, (2) incoming longwa radiation equals the blackbody radiation at the ambient air tempe ature, (3) snow surface temperature is 32°F, (4) dew point is equ to ambient air temperature, and (5) temperature of the rain water equal to the ambient air temperature.

A brief derivation of the energy balance equation is as follows:

1. The energy balance of a melting snowpack can be expressed as:

$$M = Q_n + Q_e + Q_h + Q_{P_X} , \qquad (3.1)$$

where: Q_n = net radiative heat transfer,
Q_e = latent heat transfer,
Q_h = sensible heat transfer,
Q_{P_X} = heat transfer by rain water, and
M = amount of melt.

Units of all quantities are inches water equivalent.

2. Based on the preceding assumptions, net radiative transfer during rain on a melting snowpack is:

$$Q_n = \sigma \cdot T_{aK}^4 - \sigma \cdot T_{sK}^4 , \qquad (3.2)$$

where: σ = Stefan Boltzmann constant (5.78×10^{-10} inches of melt $\cdot$ day^{-1} $\cdot$ $^{\circ}K^{-4}$),
T_{aK} = ambient air temperature $^{\circ}K$, and
T_{sK} = snow surface temperature $^{\circ}K$ (in this case $T_{sK} = 273^{\circ}K$).

Assuming linearity of $\sigma \cdot T_{aK}^4$ over the temperature region of main interest, Eq. 3.2 can be expressed as:

$$Q_n = 0.007 \cdot (T_a - 32) , \qquad (3.3)$$

where: T_a is the ambient air temperature, $^{\circ}F$, and Q_n is in terms of inches/6 hr.

Eq. 3.3 yields values within 5 percent of Eq. 3.2 over the temperature range $32^{\circ} < T_a < 75^{\circ}F$.

3. A Dalton-type equation is commonly used to compute vapor transfer. During a rain on snow event, condensation will occur, thus the equation for vapor transfer would be:

$$V = f(u) \cdot (e_a - e_s), \qquad (3.4)$$

where: V = condensation - inches/6 hr.,
f(u) = wind function - inches/(inches H_g $\cdot$ 6 hr.),

e_a = vapor pressure of air - inches H_g, and
e_s = vapor pressure of snow surface - inches H_g (assumed to be the saturation vapor pressure at the snow surface temperature = 0.18 in. H_g at 32°F).

Thus, the latent heat transfer during a rain on snow event is:

$$Q_e = L_V \cdot V \,, \tag{3.5}$$

where: L_V = latent heat of vaporization (7.5 inches of melt/inch of condensate).

Combining Eqs. 3.4 and 3.5, the equation for latent heat transfer during a rain on snow event is:

$$Q_e = 7.5 \cdot f(u) \cdot (e_a - 0.18), \tag{3.6}$$

where: Q_e is in inches/6 hr.

However, for every 7.5 inches of latent heat melt, one inch of condensate is also added to the snowpack. Thus, the total amount of liquid water produced by latent heat exchange during a rain on snow event (W_{Q_e}) is:

$$W_{Q_e} = 8.5 \cdot f(u) \cdot (e_a - 0.18), \tag{3.7}$$

where: W_{Q_e} is in inches/6 hr.

4. If it is assumed that the eddy transfer coefficients for heat and vapor are equal, then the ratio of Q_h/Q_e, commonly referred to as Bowen's ratio, can be expressed as:

$$\frac{Q_h}{Q_e} = \gamma \cdot \frac{T_a - T_s}{e_a - e_s} \,, \tag{3.8}$$

where: γ is the psychrometric constant - inches H_g/°F (γ = 0.000359·PA where PA is atmospheric pressure - in. H_g), and T_s is the snow surface temperature - °F.

Substituting Eq. 3.6 for Q_e, the expression for sensible heat transfer becomes:

$$Q_h = 7.5 \cdot \gamma \cdot f(u) \cdot (T_a - 32) \ . \qquad (3.9)$$

5. The heat transferred by rain water to the snow is the difference between the initial and final heat content of the rain water. This can be expressed as:

$$Q_{px} = C_p \cdot P_x \cdot T_a - C_p \cdot P_x \cdot 32^\circ F, \qquad (3.10)$$

where: C_p = specific heat of water, 0.007 inches water equivalent/ °F, and
P_x = amount of precipitation - inches.

Thus, the melt caused by rain water is:

$$Q_{px} = 0.007 \cdot P_x \cdot (T_a - 32). \qquad (3.11)$$

Substituting Eq. 3.3, 3.6, 3.9 and 3.11 into Eq. 3.1 and including the amount of condensate, the equation used in the model for melt during a rain on snow event becomes:

$$M = 0.007 \cdot (T_a - 32) + 7.5 \cdot \gamma \cdot UADJ \cdot (T_a - 32), \qquad (3.12)$$
$$+ 8.5 \cdot UADJ \cdot (e_a - 0.18) + 0.007 \cdot P_x \cdot (T_a - 32),$$

where: UADJ is a parameter representing the average six-hour wind function during rain on snow events, and M is in units of inches/6 hr.

b. Melt during non-rain periods. During non-rain periods melt at the snow surface is assumed to be linearily related to the difference between the air temperature and a base temperature, MBASE (units are °F). The most commonly used base temperature is 32°F. Thus, melt during non-rain periods can be expressed as:

$$M = M_f \cdot (T_a - MBASE), \qquad (3.13)$$

where: M_f = melt factor - inches/(6 hr. · °F).

This relationship is adequate for any single period of the snow season. However, the melt factor for one portion of the snow season differs from the melt factor for other portions because of the changing relationship between the meteorological factors which affect melt and the quantity (T_a - MBASE). Thus, the model uses a seasonally varying melt-factor. The minimum melt factor (MFMIN) is assumed to occur on December 21 and the maximum melt factor (MFMAX) on June 21. A sine curve is used to extrapolate melt factors for other dates, as shown in Figure 3-2.

3.3.2.2 Heat Exchange During Non-Melt Periods

When the air temperature is below 32°F the model assumes melt does not occur. In this situation the heat exchange can be positive (snowpack gaining heat) or negative (snowpack losing heat). The direction of heat flow depends on whether the air is warmer or colder than the surface layer of the snowpack. An antecedent temperature index (ATI) is used as an index to the temperature of the surface layer of the snowpack. This index is computed as follows:

$$ATI_2 = ATI_1 + TIPM \cdot (T_{a_2} - ATI_1), \qquad (3.14)$$

where: subscripts refer to time period one and two. TIPM is an anteceden temperature index parameter ($0.0 < TIPM \leq 1.0$).

Exceptions to Eq. 3.14 are:

a. When ATI is greater than 32°F, ATI is set to 32°F.
b. When the snowpack is isothermal at 32°F, ATI is set to 32°F.
c. When more than 0.2 inches water equivalent of snowfall occurs in six hours then ATI is set equal to the temperature of the new sno since the new snow is now the surface layer.

The heat exchange during a non-melt period is assumed proportional to the temperature gradient defined by air temperature and the antecedent tempera ture index. Thus the change in the heat storage of the snowpack when $T_a < 32°F$ is:

$$\Delta HS_2 = NM_f \cdot (T_{a_2} - ATI_1), \qquad (3.15)$$

where: ΔHS = change in snowpack heat storage - inches water equivalent/ 6 hr., and
NM_f = negative melt factor - inches/(6 hr. · °F).

Subscripts refer to time periods and indicate that ΔHS is calculat using the value of ATI at the end of the previous six-hour period.

The conduction of heat into or out of the snowpack is primarily a functi of snow density in addition to the temperature gradient. The density of the upper layer of the snowpack is variable, but tends to increase as the snow "ripens" and melt progresses. Thus, the negative melt factor should vary seasonally. Since heat transfer during non-melt periods is much less significant than during melt periods, additional mathematical relationshir and parameters to describe this seasonal variation are not warranted. In this model the same seasonal variation used for the non-rain melt factor is used for the negative melt factor. Therefore, the only parameter needed for non-melt heat exchange is NMF, the maximum negative melt factor. The minimum negative melt factor (NMF_{min}) is:

$$NMF_{min} = NMF \cdot \frac{MFMIN}{MFMAX} \tag{3.16}$$

and the seasonal variation is the same as for the non-rain melt factor, as shown in Figure 3-2.

To conclude this section, Table 3-1 summarizes the calculation of heat exchange at the air-snow interface for each heat exchange situation.

3.3.3 AREAL EXTENT OF SNOW COVER

The percent of the area which is covered by snow must be estimated to determine the area over which heat exchange is taking place and, in the case of rain on snow, to determine how much rain falls on bare ground. The areal depletion of snow is predominantly a function of how much of the original water-equivalent of the snowpack remains. Because of a similarity in accumulation versus elevation and vegetal cover and a similarity in drift patterns from year to year, each area should have a reasonably unique areal depletion curve. An areal depletion curve, as used in the model, is a plot of the areal extent of snow cover versus the ratio of mean areal water equivalent to an index value, A_i (units are inches water equivalent). The index value, A_i, is the smaller of: 1) the maximum water equivalent since snow began to accumulate, or 2) a preset maximum (SI). SI is thus the mean areal water equivalent above which there is always 100 percent snow cover. A typical areal depletion curve is shown in Figure 3-3.

The one problem that remains is the case when new snow occurs over an area that is partially bare. In this case, the area reverts to 100 percent cover for a period of time, then returns to the point where it was on the areal depletion curve before the snowfall occurred. The method of modeling this situation also is shown on Figure 3-3. The variables are defined as follows:

SBAESC = the areal extent of snow cover from the areal depletion curve just prior to the new snowfall;
SB = the areal water equivalent just prior to the new snowfall;
S = the amount of the new snowfall - inches water equivalent; and
SBWS = the amount of water equivalent above which 100 percent areal snow cover temporarily exists.

SBWS is computed as:

$$SBWS = SB + 0.75 \cdot S. \tag{3.17}$$

Thus, the areal extent of snow cover remains at 100 percent until 25 percent of the new snow melts. In reality this 25 percent figure varies from area to area, but the magnitude of the variation and the effect on model results do not warrant the inclusion of another parameter.

3.3.4 SNOWPACK HEAT STORAGE

The model keeps a continuous accounting (on a six-hour basis) of the heat storage of the snowpack. The upper limit for heat storage computations is 32°F. Thus, when the snowpack is isothermal at 32°F, the snowpack heat storage is assumed to be zero. When heat is transferred from the snow to the air, heat storage becomes negative. This is called negative heat storage (NEGHS) in the model. Enough heat must be added to bring negative heat storage back to zero before surface melt water or rain water can contribute to liquid water storage or snowpack outflow. Negative heat storage can physically consist of snow at a temperature less than 32°F or refrozen liquid water or a combination of these. It makes no difference what the physical form of negative heat storage is, it is the total amount of the heat deficit that is important.

3.3.5 LIQUID-WATER RETENTION AND TRANSMISSION

Snow crystals retain liquid-water similar to soil particles. In the model the maximum amount of liquid-water (LIQWMX - inches) that the snowpack can hold is:

$$LIQWMX = PLWHC \cdot WE, \tag{3.18}$$

where: PLWHC = percent (decimal) liquid-water holding capacity; and
WE = water equivalent of the solid portion of the snowpack in inches.

The model assumes PLWHC is a constant for all snowpack conditions, since variations of liquid-water holding capacity with regard to density and crystal structure are not well defined. The amount of liquid-water that exists within the snowpack at any time is LIQW (units are also inches).

Equations for the transmission of excess liquid-water through the snowpack were developed with data obtained from the Central Sierra Snow Laboratory Lysimeter during April and May of 1954. The equations apply to a "ripe" snowpack (well-aged snow with a spherical crystalline structure). However, they are used under all conditions since there is a lack of data and knowledge on the transmission of water through fresh snow. The excess liquid-water is first lagged and then attenuated. The equation for lag is (shown graphically on Figure 3-4):

$$LAG = 5.33 \cdot [1.0 - \exp(-0.03 \cdot WE/EXCESS)], \tag{3.19}$$

where: LAG = lag in hours, and
EXCESS = excess liquid water in inches/six hours.

The equation for attenuation is (shown graphically on Figure 3-5):

$$PACKRO = (S + I_1)/[0.5 \cdot \exp(-83.5 \cdot I_1/WE^{1.3}) + 1.0], \qquad (3.20)$$

where: PACKRO = snowpack outflow in inches/six hours;
S = the amount of excess liquid-water in storage in the snowpack at the beginning of the period - inches, and
I_1 = the amount of lagged inflow for the current period - inches/six hours.

The functional forms of Eqs. 3.19 and 3.20 were developed by plotting the experimental data. Final coefficient values were determined by minimizing the squared error between simulated and observed snowpack outflow from the lysimeter.

3.3.6 HEAT EXCHANGE AT THE SOIL-SNOW INTERFACE

Heat exchange at the soil-snow interface is usually negligible compared to heat exchange at the air-snow interface. In some watersheds a small amount of melt takes place continuously at the bottom of the snowpack and is enough to sustain base flow throughout the winter. The model assumes that a constant amount of melt takes place at the soil-snow interface. This constant rate of melt is defined by the parameter DAYGM which has units of inches of water equivalent/day.

3.3.7 COMPONENTS NOT INCLUDED

Neither snowpack sublimation or interception are explicitly included in the model for the following reasons.

a. To calculate snowpack sublimation with reasonable accuracy, dew point and wind data are needed. In this model, neither of those quantities are known. Snowpack sublimation is usually of the same order of magnitude from one snow season to the next for a given watershed. Thus, to some extent the value of SCF would reflect sublimation losses as well as precipitation gage catch deficiencies.

b. Interception of snow by vegetation and any subsequent loss are complex processes. During a storm, interception storage increases until some maximum is reached. After the storm, some of the intercepted snow falls to the ground, some melts and runs down the tree trunks, and some sublimates. Many studies have represented the seasonal loss by interception as a percentage of the total seasonal snowfall. If this is a valid assumption, which it seems to be, then it would be very difficult to separate interception effects from gage catch deficiency effects.

c. In most watersheds the magnitude of sublimation losses and interception losses are much less than the magnitude of precipitation gage catch deficiencies.

3.4 SUMMARY OF MODEL PARAMETERS

Following is a list of the parameters used in the snow accumulation and ablation model and their definitions for use as a reference:

a.	PXTEMP	Temperature above which precipitation is assumed to be rain (°F).
b.	SCF	Multiplying factor to correct for precipitation gage catch deficiency during periods of snowfall.
c.	MBASE	Base temperature for melt computations during non-rain periods (°F).
d.	UADJ	Average six-hour wind function during rain on snow events [inches/(in. H_g · 6 hr.)].
e.	MFMAX	Maximum non-rain melt factor which occurs on June 21 [inches/(6 hr.·°F)].
f.	MFMIN	Minimum non-rain melt factor which occurs on December 21 [inches/(6 hr.·°F)].
g.	TIPM	Antecedent temperature index parameter ($0.0 < \text{TIPM} \leq 1.0$).
h.	NMF	Maximum value of negative melt factor which occurs June 21 [inches/(6 hr.·°F)].
i.	SI	Mean areal water-equivalent above which 100 percent areal snow cover always exists (inches).
j.	PLWHC	Percent (decimal) liquid water holding capacity.
k.	DAYGM	Daily melt at the soil-snow interface (inches).
l.	EFC	Percent (decimal) of area over which evapotranspiration occurs when there is 100 percent snow cover. [Evapotranspiration is modified when snow is on the ground by:

$$EP = EFC \cdot P_e + (1.0 - EFC) \cdot (1.0 - AESC) \cdot P_e, \qquad (3.21)$$

where:

P_e is watershed potential evapotranspiration modified for snow cover (inches), and AESC is percent (decimal) areal extent of snow cover].

Reference:

Linsley, R. K., Kohler, M. A. and Paulhus, J. L. H., Hydrology for Engineers, McGraw-Hill, New York, 1958, 340 pp.

TABLE 3-1

SNOW-AIR INTERFACE HEAT EXCHANGE SUMMARY

A. AIR TEMPERATURE > 32°F

1. No rain or light rain (<0.1"/ 6 hr)

Heat Exchange = $(T_a - MBASE) \cdot$ Melt factor

2. Rain (≥0.1"/ 6 hr)

assume : no solar radiation
longwave equals blackbody radiation at air temperature
dew-point = air temperature
temp. of rain = air temperature

$$\text{Heat exchange} = 0.007 \cdot (T_a - 32) + 7.5 \cdot \gamma \cdot f(\mu) \cdot (T_a - 32) + 8.5 \cdot f(\mu) \cdot (e_a - 0.18) + 0.007 \cdot \text{Rain} \cdot (T_a - 32)$$

γ = psychrometric constant, e_a = vapor pressure
$f(\mu)$ = wind function

B. AIR TEMPERATURE ≤ 32 °F

Heat Exchange = $(T_{a_2} - ATI_1) \cdot$ Negative melt factor

ATI is antecedent temperature index

$ATI_2 = ATI_1 + TIPM \cdot (T_{a_2} - ATI_1)$

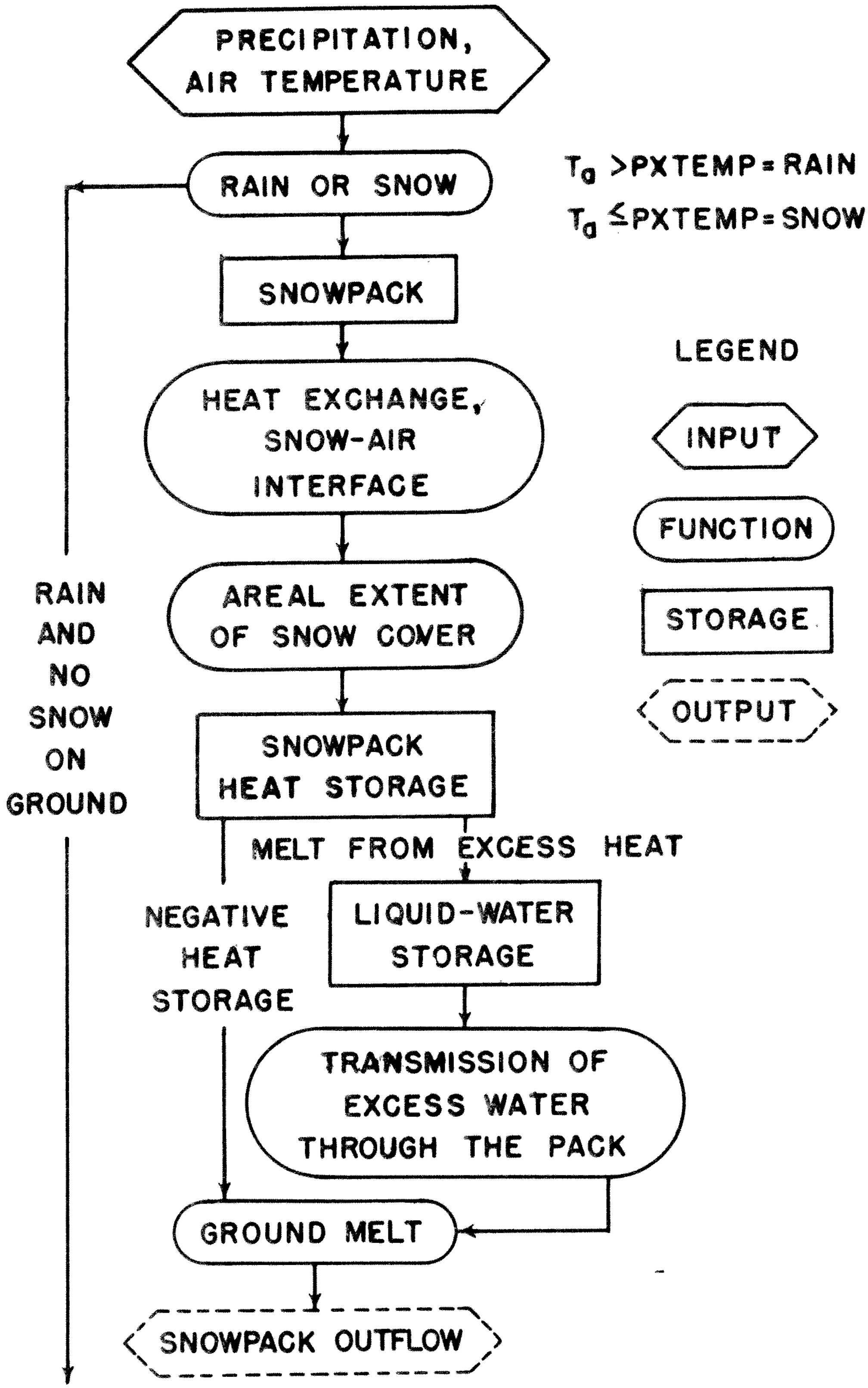


Figure 3-1. - Flow chart of snow accumulation and ablation model.

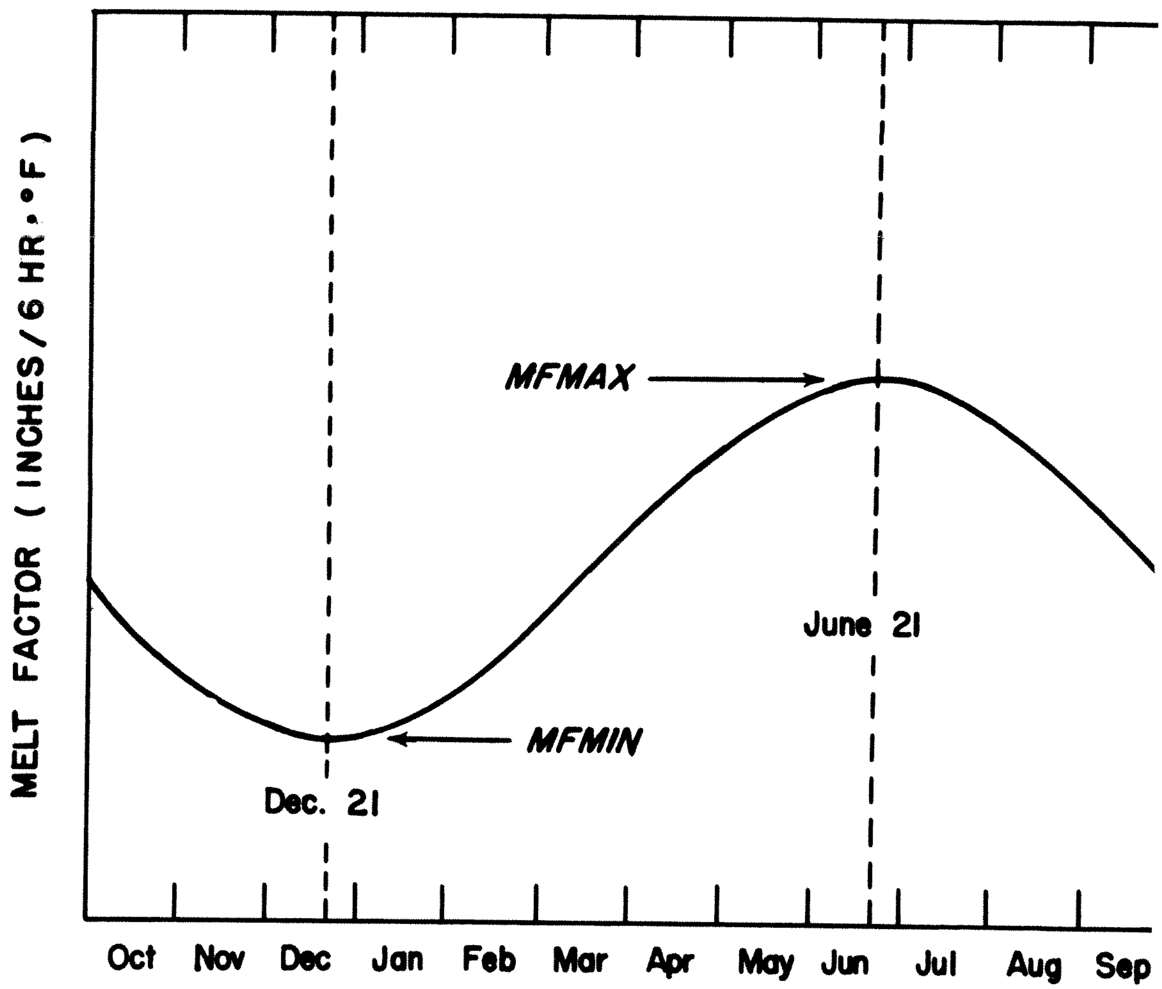


Figure 3-2. - Seasonal variation in melt factors.

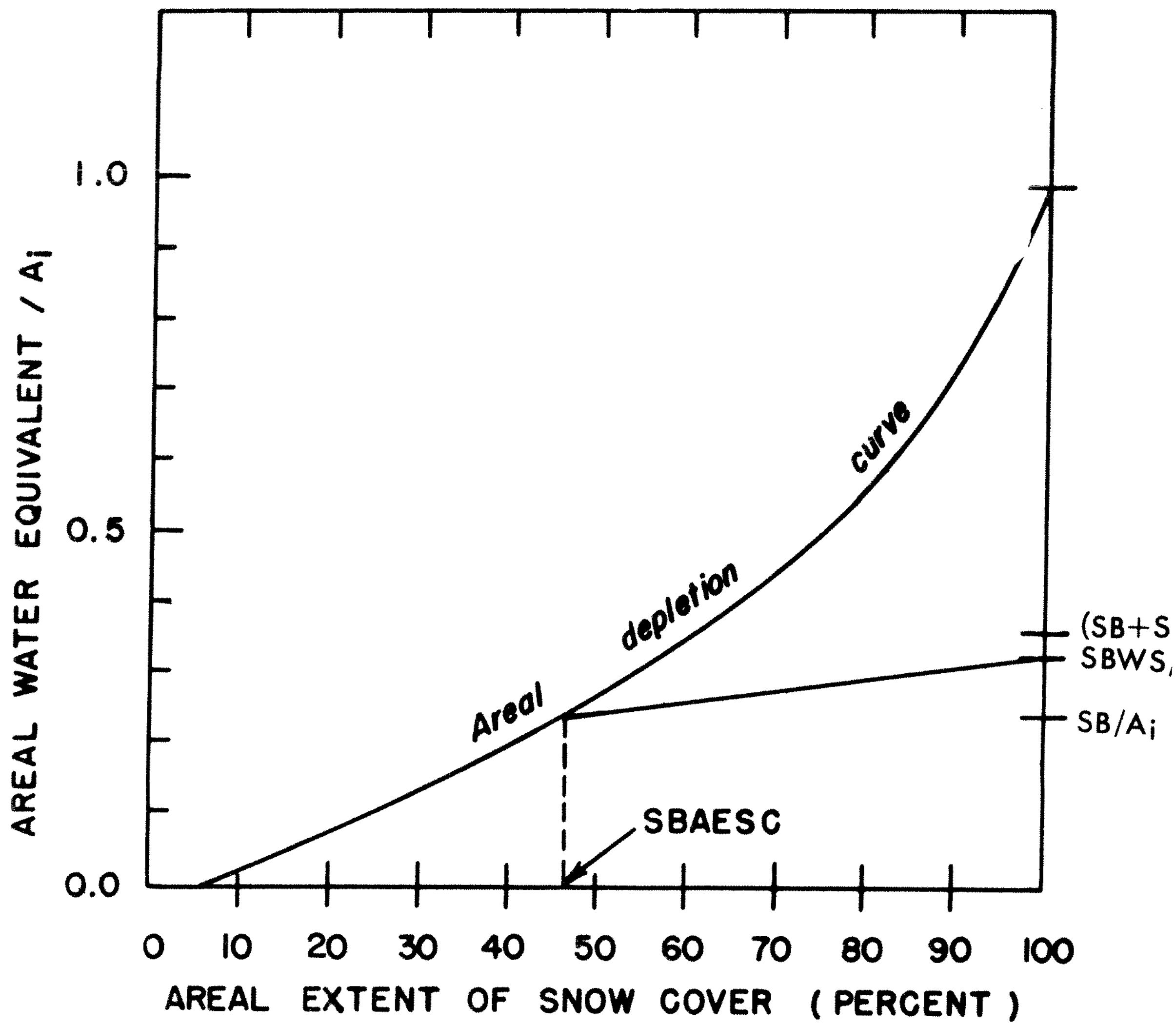


Figure 3-3. - Snow cover areal depletion curve.

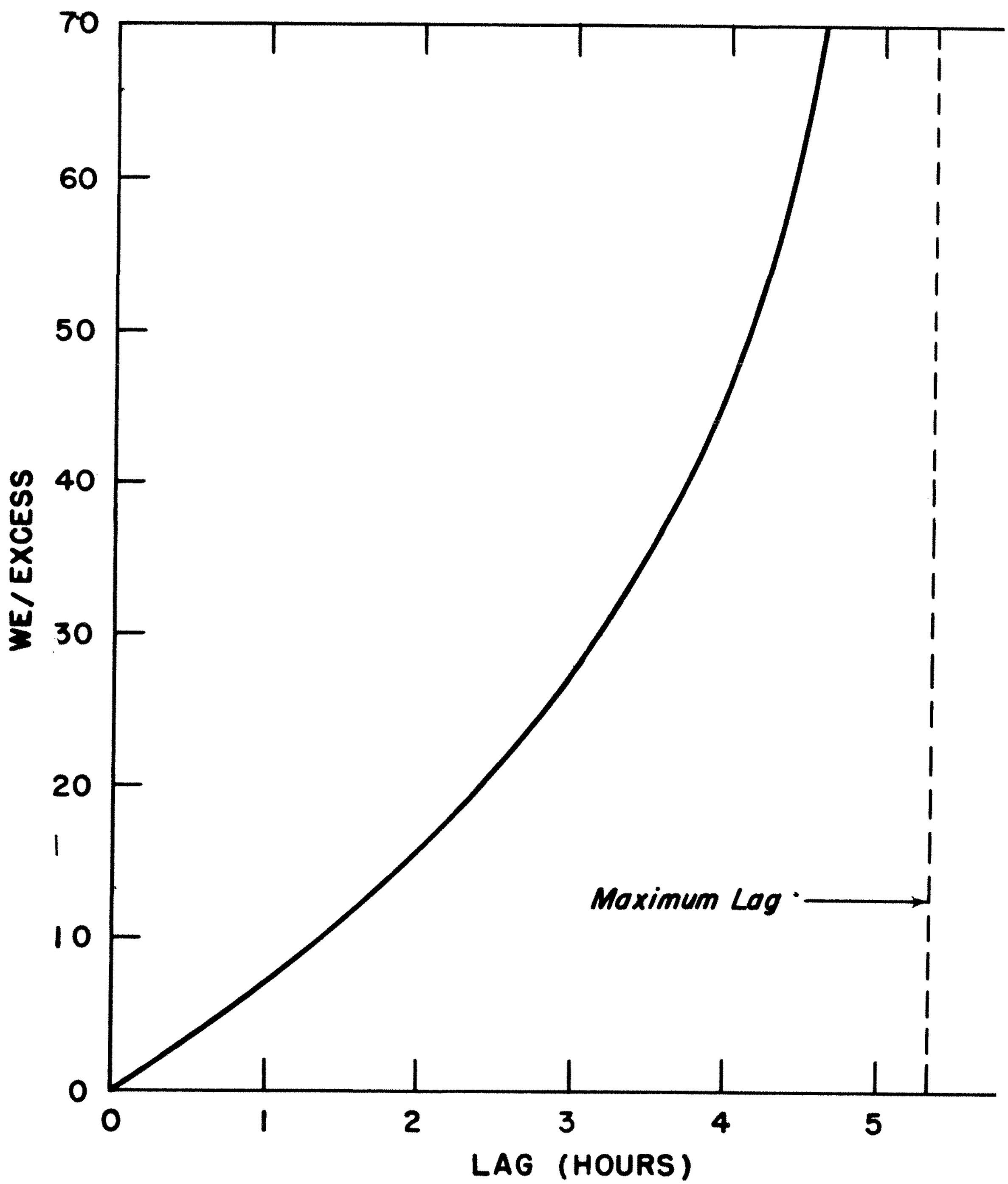


Figure 3-4. - Lag applied to excess liquid-water moving through a snowpack.

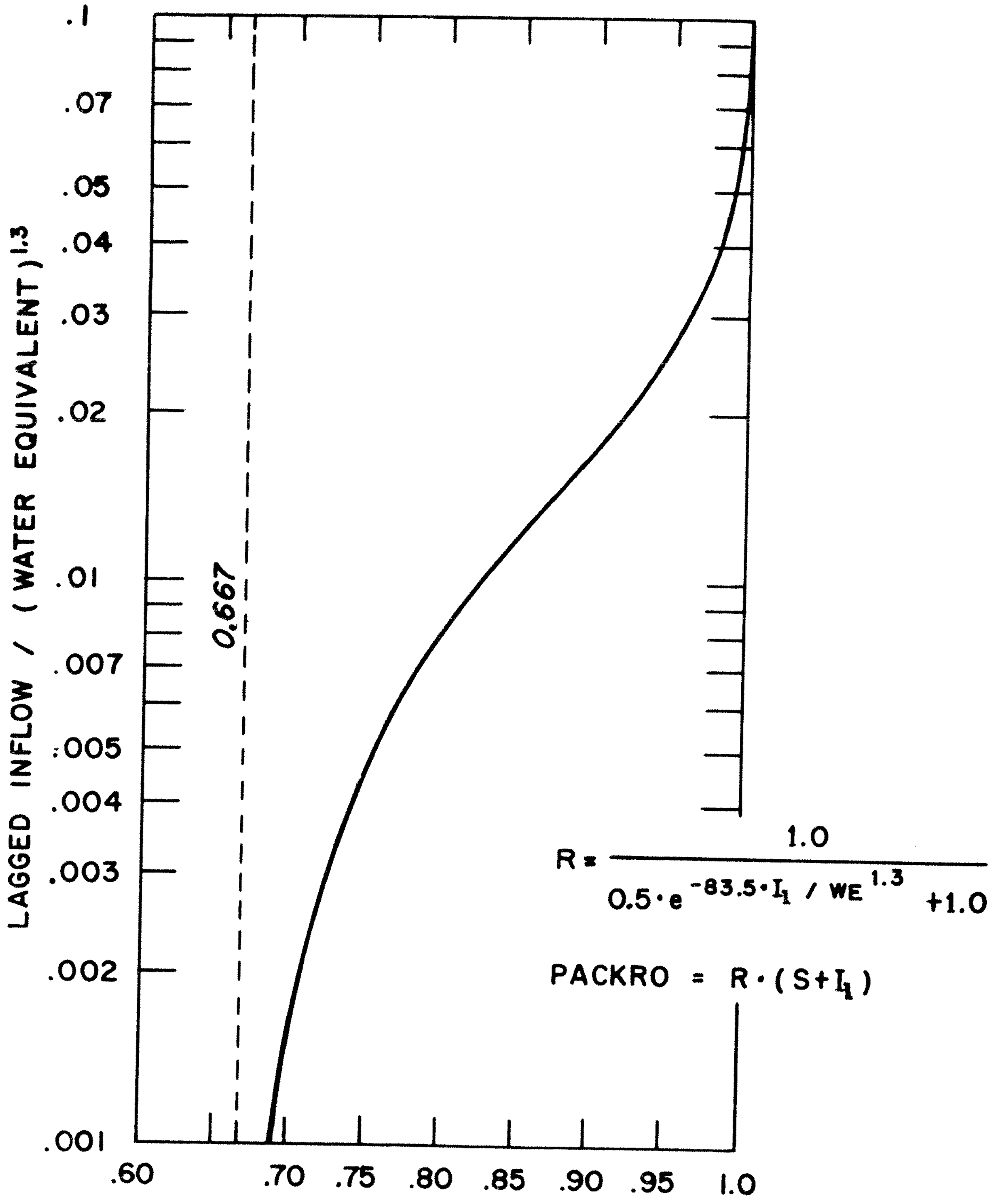


Figure 3-5. - Attenuation of excess liquid water moving through a snowpack.

CHAPTER 4. DESCRIPTION OF COMPUTER SUBROUTINES FOR THE SNOW ACCUMULATION AND ABLATION MODEL

4.1 INTRODUCTION

This chapter describes the computer subroutines which are needed to use the snow accumulation and ablation model in conjunction with the NWSRFS. The NWSRFS programs, as described in HYDRO-14, contain all the statements that are needed to communicate with the snow subroutines, i.e., subroutine CALL statements, COMMON blocks, and initialization of variables. Snow subroutines are provided for all three NWSRFS programs involving hydrograph simulation; the verification program (NWSRFS4), the optimization program (NWSRFS3), and the operational river forecasting program (NWSRFS5).

4.2 SUBROUTINES

There are four snow subroutines for the verification program, three for the optimization program, and three for the operational river forecasting program. Following is a brief description of the function of each subroutine:

a. Subroutines included in the verification, optimization, and operational programs.

   1) SNOWPM inputs snow parameters and initial values of snowpack storages and variables for each sub-area for which channel inflow is to be computed. Soil-moisture accounting sub-areas and snowpack accounting sub-areas are identical. The subroutine also outputs the parameters and initial values for future reference.

   2) PACK is the subroutine that simulates the accumulation and ablation of the snowpack, as described in Chapter 3. As a reference for those readers who are interested in the snow accumulation and ablation model, but do not want to obtain all the NWSRFS programs, a listing of subroutine PACK, from the verification program, is contained in appendix C.

b. Subroutine included in the verification and optimization programs.

   SNOWIN inputs six-hour air temperature data from tape. In additio observed daily water-equivalent of the snowpack can be input from tape if such data are available. Observed water-equivalent data are not used in the computations, but are printed out so that a visual check between observed and computed water-equivalent can be made. (Note. In using the data processing programs from appendix E of HYDRO-14 to load observed water-equivalent data onto tape, observed water equivalent is treated as if it were mean daily flow data. For example, if two observed water equivalent stations and four mean daily flow stations were being loaded, the data processir programs would be instructed to load six mean daily flow stations. The observed water-equivalent stations must be placed before the mean daily flow stations in the input queue.) All data are input month at a time. All snow data must be on the same tape. The subroutine contains the flexibility that if more stations or area are on tape than are needed for a particular run, only that info mation that is requested is read. Thus, one data tape can be set up for a large river system and be used for running any segm of the system.

c. Subroutine included in the verification program only.

SNOWOT is a short subroutine which outputs total monthly snowfal rain, and snowpack outflow, plus a water balance of the snowpack a check on PACK subroutine computations.

d. Subroutine included in the operational program only.

UPSNOW allows for the input of adjustments to snowpack parameters and variables which may be needed operationally to adjust the snow model so that simulated conditions agree with observed conditions. A description of the adjustments is included later in this chapter under section 4.5.3.

4.3 VERIFICATION SNOW SUBROUTINES

This section describes the options, input required, and output produced by the snow subroutines which are used in conjunction with the verification program (NWSRFS4).

4.3.1 SUBROUTINE OPTIONS

There are three optional features in regard to data input and computer output with the verification snow subroutines.

a. As mentioned previously, observed daily water-equivalent data can be input and printed for comparative purposes. If observed water-equivalent data are not available, which is usually the case, the input of such data are eliminated.

b. The verification program contains the flexibility that the snow subroutines do not have to be used every month. Thus, during months when there is no snowfall and no snow on the ground, the program can bypass the snow subroutines. This feature eliminates the need for valid air temperature data during non-snow months. Thus, during non-snow months the air temperature records on the basic data tape can be loaded as missing data. Missing air temperature data are signified by 999.0.

c. During calibration it is important in many cases to monitor daily changes in snowpack conditions. This is necessary to answer questions such as: Was the runoff caused by melt, rain on snow, or just rain? What is the areal extent of snow cover during a certain period? What is the amount of negative heat storage and liquid-water retention before a certain event? Was the precipitation assumed to be rain or snow? When did melt occur? When did the snowpack disappear? To answer such questions the subroutines contain the option that snowpack variables can be output on a daily basis for each sub-area.

4.3.2 INPUT SUMMARY

Appendix D.1 contains a listing of the input needed to run the verification program with snow included.

4.3.3 SAMPLE INPUT

Appendix D.2 lists the input for an eight-year run of the verification program on the Passumpsic River at Passumpsic, Vermont.

4.3.4 SAMPLE OUTPUT

Appendix D.3 lists examples of the output from the run of the verification program which used the sample input data for the Passumpsic River. To conserve space, the entire output is not listed, but only examples of each type of printout.

4.4 OPTIMIZATION SNOW SUBROUTINES

This section describes the options, input required and output produced by the snow subroutines which are used in conjunction with the optimization program (NWSRFS3).

4.4.1 SUBROUTINE OPTIONS

There are two options in regard to snow computations included in the optimization program. The standard options of the optimization program are described in chapter 7 of HYDRO-14.

a. As in the verification program, the program can be instructed to bypass the snow subroutines during months with no snowfall and no snow on the ground.

b. The optimization program can be used for either one or two snow and soil-moisture accounting sub-areas (see section 7.4.3 of HYDRO-14). As the optimization program is currently written, soil-moisture accounting parameters are the same for each area when two sub-areas are used. In the snow subroutines different parameter values can be used for each sub-area. The use of different parameter values for each sub-area is intended for use during the optimization of a mountain watershed with two elevation zones. Care should be exercised for two reasons if this option is used: 1) geographical factors which would suggest the use of different snow parameters for each area also would generally suggest the use of different soil-moisture accounting parameters, and 2) unless variables such as water-equivalent and areal snow cover are available for each sub-area as a check on simulation results, the addition of twice as many snow parameters may allow for an improved hydrograph simulation, but at the expense of an unreasonable simulation of snow accumulation and ablation within each area. A further discussion of the use of elevation zones in mountainous areas is contained in section 5.8.1.

4.4.2 INPUT SUMMARY

Appendix E.1 contains a listing of the input needed to run the optimizat: program with snow included.

4.4.3 SAMPLE INPUT AND OUTPUT FOR OPTIMIZATION RUN

Appendix E.2 lists the input and the output for an optimization run on tl Passumpsic River at Passumpsic, Vermont.

4.4.4 SAMPLE INPUT AND OUTPUT FOR SENSITIVITY RUN

As described in chapter 7 of HYDRO-14, the optimization program can also operated in a sensitivity mode. Appendix E.3 lists the input and output fo a sensitivity run on the Passumpsic River.

4.5 OPERATIONAL SNOW SUBROUTINES

This section describes program features, input required, and the output produced by the snow subroutines which are used in conjunction with the operational river forecasting program (NWSRFS5).

4.5.1 INPUT OF AIR TEMPERATURE DATA

In the operational program all data are input through subroutine DATAIN (see section 6.2 of HYDRO-14). This includes the input of six-hour air temperature data; both air temperatures that have been observed and those that are predicted to occur in the future. The determination of six-hour mean areal air temperature from point observations and possibly other meteorological data is left to the user. Since each river forecast office has different data networks, it would be extremely difficult to write a generalized operational data processing program that would fit the needs of all forecast offices. Thus, the task of writing an operational data processing program (i.e., a program to compute mean areal precipitation from point observations or other meteorological data, compute an estimate of evapotranspiration, compute mean areal air temperature from point values ar other meteorological data, and compute discharge from river stage observations or reservoir levels) is left to the user.

In the case of air temperature, the point should be made that data other than maximum-minimum temperature observations will be available on an operational basis to compute six-hour mean areal air temperature. There will also be more data available to delineate whether precipitation is rair fall or snowfall. However the number of air temperature observation statio available operationally may be considerably less than the number used for n calibration. The effect of the operational temperature data network on sin tion results should be random, as long as there is not a significant bias between the operational mean areal air temperature estimation procedure and the mean areal temperature procedure used in calibration.

4.5.2 INCLUSION OF SNOW IN AN OPERATIONAL RUN

On each run of the operational program the user must tell the program if snow is to be included. If there is no snowfall and no snow on the ground, the snow subroutines are not needed. This feature not only saves computer time during non-snow periods, but also eliminates the need for observed and predicted mean areal air temperature data. Snow parameters and initial values are retained on the carryover tape (see section 6.6 of HYDRO-14) so that they are available when the next snowfall occurs. However, the user must remember to input snow parameters on the initial run of the operationa program or on another run subsequent to the first occurrence of snow. Once snow parameters are input they will be retained for use whenever snow occur

4.5.3 SNOWPACK ADJUSTMENTS

Several snowpack variables and parameters can be adjusted so that simulated conditions will agree with observed conditions. These adjustments fall into two categories: 1) adjustments to make snowpack variables such as water-equivalent and areal extent of snow cover agree with observed values, and 2) adjustments to correct for deviations between the simulated and observed hydrographs. In making hydrograph adjustments a major consideration is to determine the most likely cause of the error so that the correction will minimize future deviations of the hydrographs. A set of decision rules to accomplish this is an area for considerable future research. For the present, the program supplies only the methods of adjusting; the hydrologist must decide which adjustment to use. The following snowpack adjustments are available.

a. Adjustments to snowpack variables.

   1) Areal water-equivalent can be adjusted at any time by reading in a new areal water-equivalent value for those sub-areas whic are in error. New areal water-equivalent values will usually be based on field measurements of water-equivalent. However, in some cases, water-equivalent adjustments may be based on deviations between simulated and observed hydrographs. In the operational program the following rules are used for adjusting areal water-equivalent:

      a) The new value is input in terms of total water-equivalent, i.e., solid plus liquid-water content of the snowpack.

      b) The percent liquid-water in the new snowpack is the same as in the old one.

      c) Areal extent of snow cover remains the same.

Subroutine UPSNOW changes the solid and liquid portions of the snowpack so that the percent liquid-water remains the same. Subroutine UPSNOW also computes an adjustment factor (AWEADJ) which keeps the areal extent of snow cover (AESC) the same:

$$AWEADJ = \frac{AESC_1}{AESC_2}, \qquad (4.1)$$

where: $AESC_1$ is the areal extent of snow cover computed from the basic areal depletion curve using the old value of areal water-equivalent, and $AESC_2$ is the areal extent of snow cover computed from the basic areal depletion curve using the new value of areal water-equivalent. (The basic areal depletion curve is the curve that was determined during model calibration.)

This adjustment factor remains in effect until the areal water-equivalent is adjusted again. The effect of AWEADJ is to temporarily shift the areal depletion curve. This effect is illustrated in figure 4.2.

2) Areal extent of snow cover can also be adjusted at any time by reading in a new value of areal snow cover for those sub-areas which are in error. Areal snow cover adjustments also will be based generally on observations of area snow cover, but could also be used to adjust the simulated hydrograph in some situations. Subroutine UPSNOW computes an adjustment factor (AEADJ) which temporarily shifts the areal depletion curve in a manner similar to AWEADJ:

$$AEADJ = \frac{AESC\ new}{AESC\ old} \qquad (4.2)$$

This adjustment factor remains in effect until the areal extent of snow cover is adjusted again. The effect of AEADJ on the areal depletion curve is illustrated in figure 4-2. It should be noted that to remain on the basic areal depletion curve that both areal water-equivalent and areal extent of snow cover must be adjusted.

3) The gage catch deficiency factor (SCF) for snowfall varies from storm to storm primarily as a function of wind. Operationally, wind data may be available and thus the user may want to estimate SCF for each storm rather than use a mean catch deficiency factor for all storms. An adjusted value of SCF can be input for any or all sub-areas. The adjusted value of SCF is not retained for future use, but is used only for the present storm. The mean snowfall correction factor is retained on the carryover tape.

b. Adjustments to correct hydrograph deviations.

1) The volume of snowmelt can be adjusted by applying a multiplying factor to the computation of melt. Since melt is computed differently during rain on snow and non-rain periods, two adjustments are needed:

a) During non-rain periods the melt factor (M_f) can be multiplied by a correction factor.

b) During rain on snow events, the average wind function (UADJ) can be multiplied by a correction factor.

Both of these corrections are only applied to observed data. The corrections do not apply to the forecast period (future period for which predicted data are used). If several days of observed data are included in the computer run, the same multiplication factor applies to each day. The only method available to adjust different days by different amounts is to adjust the mean areal air temperature data.

2) The amount of negative heat storage can also be adjusted. This adjustment would probably not be used very often, but could be helpful during the early portion of snowmelt when the snowpack is becoming "ripe" and runoff is beginning to occur. The negative heat storage adjustment is also useful during mid-winter rain on snow events to partition the rain between that which is released and that which is retained within the snowpack. Even though negative heat storage is a snowpack variable, it is listed under hydrograph adjustments, since the adjustment to negative heat storage would almost always be based on deviations between observed and simulated hydrographs rather than on measurements of the variable itself.

4.5.4 INPUT SUMMARY

Appendix F.1 contains a listing of the input needed to run the operational river forecasting program with snow included.

4.5.5 SAMPLE INPUT AND OUTPUT FOR OPERATIONAL PROGRAM

Appendices F.2, F.3 and F.4 list the input and output for three runs of the operational program on the Rock River at Rock Rapids, Iowa. Appendix F.2 lists the initial run of the program to illustrate how to get the program started and how to create the initial carryover tape. Appendix F.3 shows the preliminary run on a major flood. Appendix F.4 illustrates the use of several adjustments to revise the preliminary run for the same major flood.

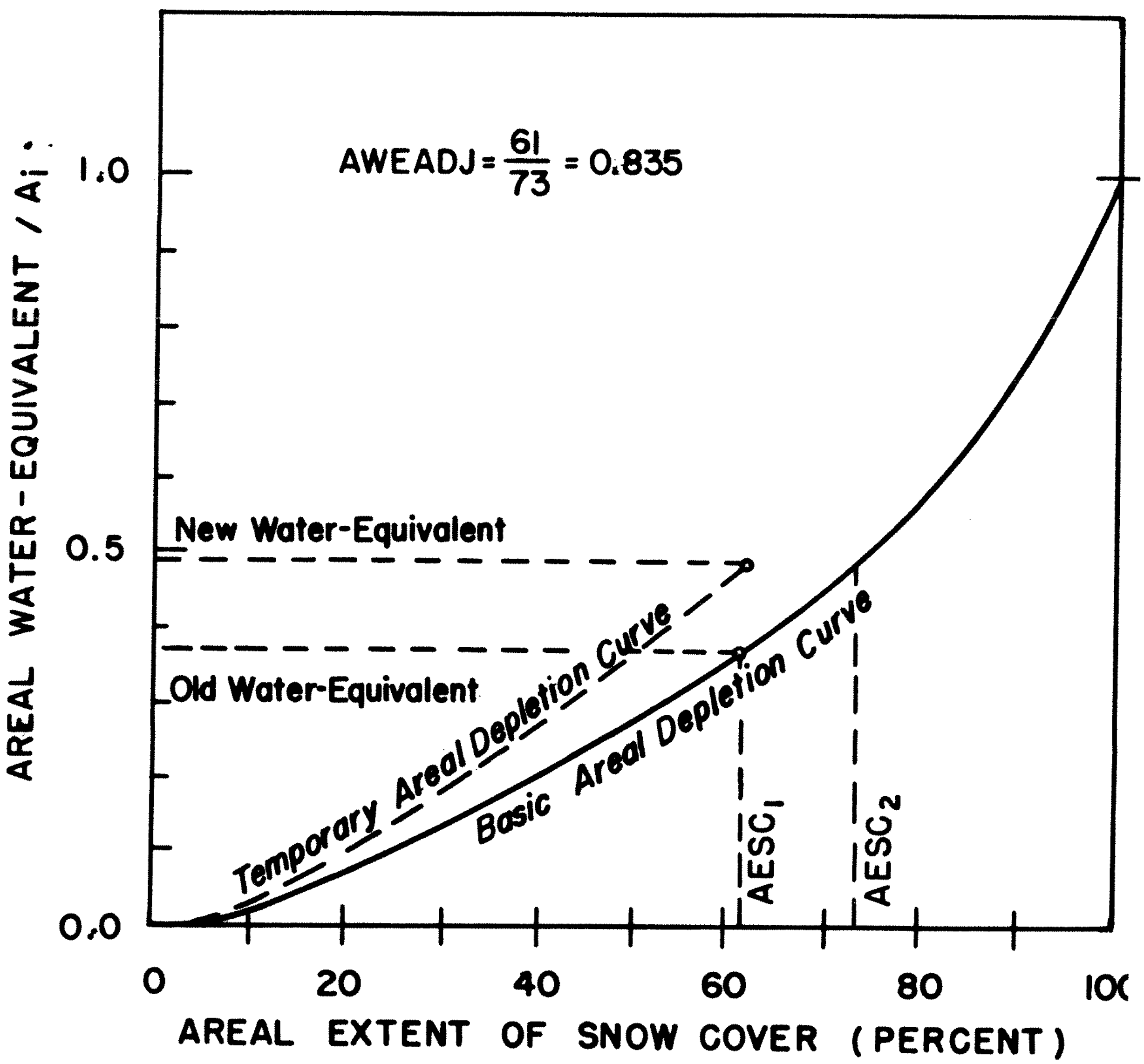


Figure 4-1. Effect of areal water-equivalent adjustment on the areal depletion curve.

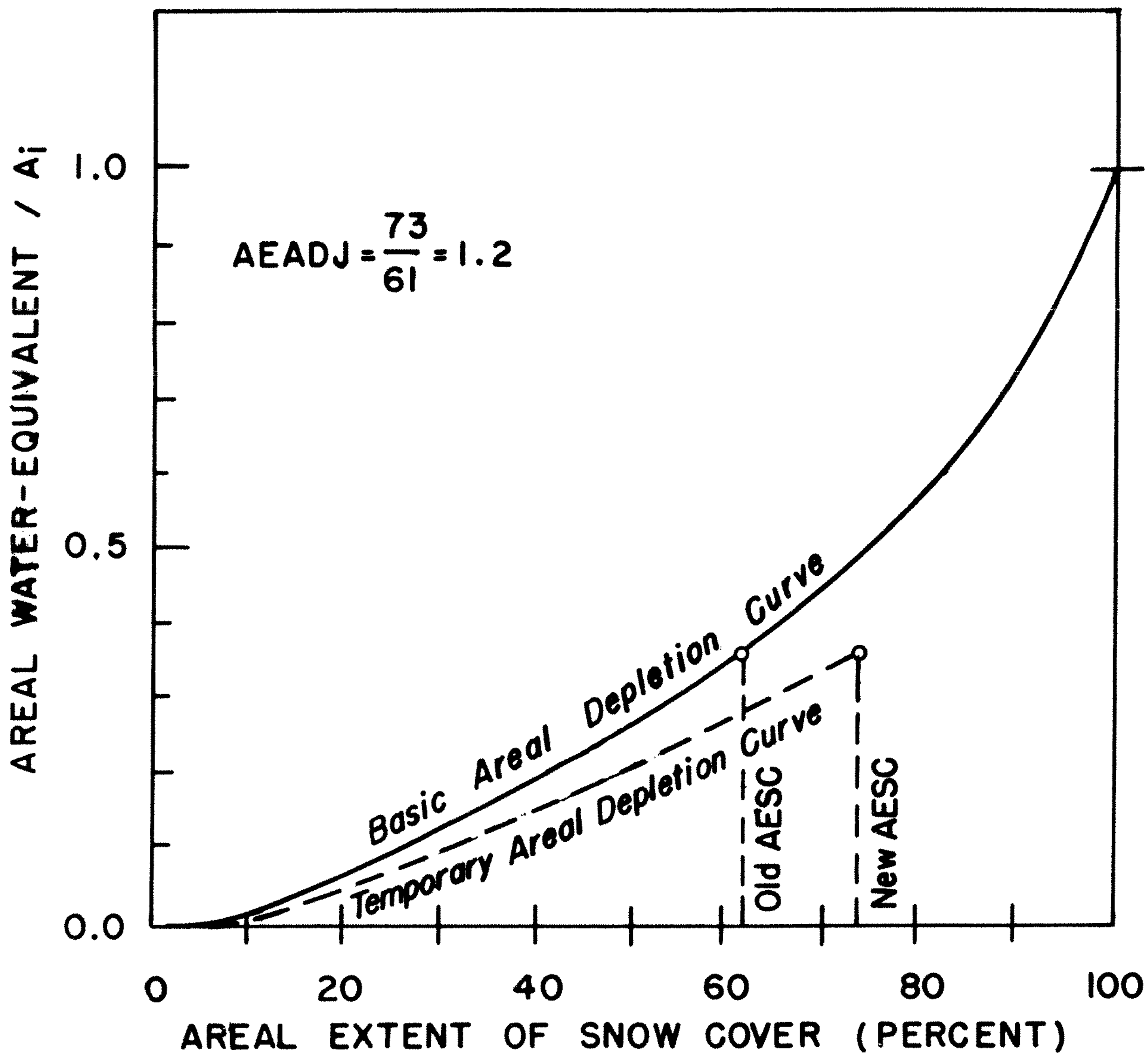


Figure 4-2. Effect of areal extent of snow cover adjustment on the areal depletion curve.

CHAPTER 5. CALIBRATION OF THE SNOW ACCUMULATION AND ABLATION MODEL

5.1 INTRODUCTION

In the application of a conceptual hydrologic model for river forecasting, the calibration process is extremely important. The calibration procedure used must not only result in realistic parameter values which produce reasonable simulation results, but also must be efficient so that a large number of river basins can be calibrated in a reasonable time. The procedure recommended is a combination of trial-and-error calibration and automatic parameter optimization. Trial-and-error calibration involves subjective manual adjustments to parameters based on an analysis of previous simulation results. In automatic parameter optimization, the computer adjusts parameters in a semi-random manner based on changes in the value of a single numerical evaluation criterion. The automatic technique used in the NWSRFS is the direct-search optimization technique, Pattern Search. A complete description of the Pattern Search algorithm is given by Monro (1971). The evaluation criterion which has been adopted is the sum of the squares of the errors between simulated and observed mean daily streamflow. Chapter 7 of HYDRO-14 describes the computational features and basic options of the computer program (NWSRFS3) which performs Pattern Search optimization.

This chapter outlines and discusses a recommended calibration procedure for river basins where the snow accumulation and ablation model is used. Only the snow model parameters are discussed in detail. The user should refer to chapter 7 of HYDRO-14 for suggestions regarding the determination of initial soil-moisture accounting and channel routing parameters and the optimization of those parameters.

In addition to calibrating the snow, soil-moisture accounting, and channel routing models on the basis of hydrograph simulation, the snow model can be calibrated by comparing the computed and observed water-equivalent of the snowpack. However, it is generally not feasible to calibrate the snow model using water-equivalent data because frequent representative water-equivalent measurements are not available for the large majority of watersheds.

5.2 OUTLINE OF STEPS IN THE RECOMMENDED CALIBRATION PROCEDURE

There are five basic steps in the recommended calibration procedure for the snow accumulation and ablation model. This section outlines the steps and the following sections discuss each step in detail.

a. Select initial values for each of the snow parameters (snow parameters are listed in section 3.4). Also select initial values for the soil-moisture accounting and channel routing parameters (see chapter 7 of HYDRO-14).

b. Simulate the entire calibration data period using the verification program. Check for periods when the form of the precipitation is in error, i.e., snow when rain actually occurred and vice versa. Adjust those periods that are determined to be in error. Also check for and correct any large data errors that can be substantiated.

Large errors should not be present if the data were properly checked for consistency at each stage of data preparation.

c. Perform trial-and-error calibration of the model parameters using the verification program (NWSRFS4).

d. Perform Pattern Search optimization on those parameters for which satisfactory values were not determined by trial-and-error calibra tion. The optimization program (NWSRFS3) is used for Pattern Search optimization.

e. Analyze calibration results. Repeat steps c and d if necessary.

5.3 INITIAL VALUES OF THE PARAMETERS FOR THE SNOW ACCUMULATION AND ABLATION MODEL

This section presents guidelines for determining initial values for each the parameters included in the snow accumulation and ablation model. The definition of each parameter is listed in section 3.4. If other nearby watersheds have been calibrated, the parameter values from these watersheds should also be helpful in determining initial values. However, as mentione in the following guidelines, certain snow parameters are influenced significantly by geographical conditions. Thus, values of these parameters from nearby watersheds should only be used to determine initial values if geographical conditions between the watershed being calibrated and the nearby watersheds are similar.

a. PXTEMP. Model calibration studies to date indicate that 33°F provides for the best delineation of rain from snow, i.e., 33°F and below, precipitation is snow - above 33°F, precipitation is rain. Some other investigators have found that 34°F or even 35°F gave the best results.

b. SCF. The gage catch deficiency correction factor during snowfall varies considerably depending on gage exposure, especially the effects of exposure on the wind velocity at the gage. Another important consideration is whether the gage has a windshield. Figure 5-1 shows typical gage catch deficiency correction factors during snowfall for shielded and unshielded gages as a function of wind speed. Although wind speed data at each precipitation gage are generally not available, Fig. 5-1 should be helpful in determining the initial value of SCF if some information on wind speeds over the area and on gage exposures is available.

c. MBASE. It is recommended that 32°F be used as the base temperature for melt computations during non-rain periods. In some studies other base temperatures have been used in an attempt to get a better linear relationship between snowmelt and air temperature. Results from the watersheds calibrated using this snow model indicate that 32°F is a completely adequate base temperature.

d. UADJ. Sublimation - condensation measurements during the Snow Investigations (1955) at the Central Sierra Snow Laboratory, and at the NOAA-ARS cooperative snow research station near Danville, Vermont resulted in nearly identical wind functions. The wind function computed from these measurements is:

$$f(u) = 0.006 \cdot u, \qquad (5.1)$$

where: u is wind movement at 1/2 meter above the snow surface in miles, and
f(u) has units of inches/(in. Hg · miles).

Thus, the initial value of UADJ would be 0.006 multiplied by the average six-hour wind movement in miles at the 1/2 meter level during rain on snow events.

e. MFMAX and MFMIN. As noted in Chapter 3, melt factors change as the relationship varies between air temperature and the meteorological variables affecting heat exchange. Therefore, climatological differences and differences in physiographic variables such as forest cover, slope, and aspect which affect radiation exchange and wind movement will cause one area to have a different melt factor than another area. With all other variables held constant, the following statements are generally true:

1. South facing slopes would have a higher melt factor than north facing slopes.

2. Areas where windy conditions prevail generally have a higher melt factor than areas where calm conditions prevail (however, under conditions of low humidity, sensible heat gain could be balanced or exceeded by latent heat loss).

3. The melt factor increases as forest cover decreases.

Most of the other variables are so interrelated that it is impossible to change one and hold all the others constant (e.g., solar radiation cannot be increased significantly without a decrease in atmospheric longwave radiation). Thus, it is difficult to make general statements about the effect of these variables on the melt factor.

A good initial value of MFMAX and MFMIN can be computed for a few areas based on snowpack water-equivalent and temperature data. When there is no snowfall during a snowmelt period, the amount of snowmelt can be approximated by the difference in water-equivalent measurements. The slope of a plot of the summation of snowmelt versus the summation of six-hourly air temperatures above MBASE is the melt factor for that snowmelt period. (It should be noted that when the area has less than 100 percent areal snow cover that the snowmelt values should be adjusted to represent the condition of 100 percent areal snow cover since the melt factor used in the model represents melt over the entire area.) A number of such plots from snowmelt periods occurring at different times during the year and from several snow seasons should define good initial values for

MFMAX and MFMIN. The main problem with using this method to estimate melt factors is that representative water-equivalent measurements, taken at frequent intervals, are made on only a very few areas.

Based on results from the areas tested on the model to date, forest cover seems to be the major factor affecting the variability of melt factors from one area to another area. Figures 5-2 and 5-3 show plots of maximum and minimum melt factors versus forest cover for the areas on which the model has been tested. These plots should be helpful in providing a reasonable initial value for parameters MFMAX and MFMIN when representative water-equivalent data are not available.

f. TIPM. The antecedent temperature index (ATI) is an index to the temperature of the surface layer of the snowpack, as discussed in section 3.3.2.2. The parameter TIPM indicates the thickness of the layer being considered. Values of TIPM less than 0.1 would give significant weight to temperatures over the past week or more and would thus indicate a deeper layer than TIPM values greater than 0.5 which would essentially only give weight to temperatures during the past day. A brief examination of snowpack temperature and air temperature data from the NOAA-ARS cooperative snow research site indicates that TIPM = 0.5 would correspond to a three- to six-inch surface layer while TIPM = 0.2 would correspond to approximately the top 12 inches of the snowpack.

It is felt that eventually the value of TIPM can be standardized. However, a complete analysis of the effect of different values of TIPM has not been completed. TIPM = 0.5 has given reasonable results on the watersheds tested though there is some indication that a lower value may be more appropriate.

g. NMF. The value of the negative melt factor is a function of the climatic conditions that occur over the snowpack when the air temperature is below 32°F. The value of NMF is also influenced by the density of the surface layer of the snowpack since the thermal conductivity of snow is a function of density. In addition, the value of the negative melt factor is dependent on the value of TIPM since TIPM controls the magnitude of ATI (ATI is an important quantity in Eq. 3.15 for calculating the change in heat storage during periods when the air temperature is below 32°F). Because of the interrelationship between NMF and TIPM it is recommended that a reasonable value of TIPM be established based on the guidelines suggested previously for parameter TIPM. Then, during model calibration only NMF would be allowed to vary. It should be noted that the optimization program does not allow TIPM to vary. Only parameter NMF can be included in automatic optimization.

The value of the maximum negative melt factor (NMF) has varied from 0.003 to 0.007 for the watersheds tested to date. An initial value of 0.005 should be satisfactory.

h. Areal depletion curve. There are a number of ways to determine the areal depletion curve for a given area. Several methods are listed below in order of the accuracy of the final product.

1. Determine the areal extent of snow cover over a number of years from aerial photographs and the areal water-equivalent from ground surveys on a number of days during the snowmelt period. An analysis of such measurements will result in the areal depletion curve Except for a few watersheds, such information is not available nor is it generally practicable to obtain such measurements.

2. Measure the ablation of the snowpack by periodically making water-equivalent measurements at a representative site within each reasonably homogeneous geographical subarea. The subareas would be selected on the basis of elevation, vegetal cover, and aspect. As each subarea becomes bare, a point on the areal depletion curve could be established since the number of bare areas would be known and also the water-equivalent of those areas, where snow remains, would be known. Five to ten subareas should be adequate to obtain a reasonable estimate of the areal depletion curve.

3. In many areas the data necessary to use method number 2 for computing the areal depletion curve are not available and it would not be practicable to obtain water-equivalent data for each homogeneous subarea. However, in many areas some water-equivalent data are available. An approach similar to method 2 could be used in such areas by using the available water-equivalent data and by subjectively estimating accumulation and melt rates for the other subareas.

If data are not available to compute the shape of the areal depletion curve, then the shape of the curve must be arbitrarily selected. The same shaped areal depletion curve has been used for all of the watersheds tested to date. This curve (shown in Fig. 3-3) was originally computed for the Central Sierra Snow Laboratory using water-equivalent data from snow courses and areal snow cover determined from aerial photographs. Analysis of similar data indicates that the shape of the areal depletion curve for the Upper Columbia Snow Laboratory is essentially the same as that for Central Sierra. The same curve was also used for the Sleepers River watersheds and the Passumpsic River areas for which similar data were not available. Model calibration did not indicate that the shape of the areal depletion curve should be altered All of these watersheds are similar with respect to elevation range and cover. In addition, the same curve was used successfully for the Rock River above Rock Rapids, Iowa. This watershed is an open agricultural area with little variation in elevation where during spring melt the period from complete snow cover to bare ground is normally only a few days. In this case, it was difficult to determine the shape of the areal depletion curve accurately by hydrograph simulation. While the same shaped curve gave good results on these watersheds, different shaped curves would probably be required on areas with different elevation ranges and cover configurations.

i. SI. The previously mentioned methods of determining the areal depletion curve would also indicate the areal water-equivalent above which 100 percent snow cover always exists. If one of these methods is not used, the following guidelines can be used to select an initial value for parameter SI.

1. If the area is very heterogeneous in regard to slope, aspect, and vegetal cover, then the initial value of SI should be about the same as the maximum water-equivalent that occurs. This is due to the fact that in very heterogeneous areas there are usually places where very little snow accumulates. Thus, these places will become bare soon after snowmelt begins.

2. If the area is more homogeneous, then the area would remain at 100 percent cover during the early portion of the snowmelt season, thus SI would be lower than the maximum water-equivalent that occurs. In the extreme case of a perfectly homogeneous area, such as a point study area, SI would be equal to zero.

j. PLWHC. Most measurements on "ripe" snow have indicated liquid-water retention capacities of less than 10 percent and in most cases on the order of two to five percent. Slush layers may be formed at the snow-soil interface or in conjunction with ice layers within the snowpack. These slush layers can hold a considerable amount of liquid-water. While slush layers form in deep snowpacks, their relative effect on the total liquid-water retained is usually small. However, in shallow snowpacks slush layers will increase the percent liquid-water holding capacity significantly. It is recommended that the initial value of PLWHC should be in the range 0.02 to 0.05 for areas which normally have deep snowpacks (approximately greater than 10 inches water-equivalent). The initial value of PLWHC should be greater for areas with normally shallow snowpacks, with a value of 0.25 not being unreasonable for an area such as the northcentral region of the United States.

k. DAYGM. The following guidelines, based on model testing to date, should be sufficient to obtain a reasonable estimate of the daily amount of melt at the snow-soil interface.

TABLE 5-1.--Guidelines for determining parameter DAYGM.

DAYGM (inches)	Climatic Conditions
0.0	Long cold winters (many days with air temperatures below 0°F), and shallow snowpacks
0.01	Long cold winters, and deep snowpacks
0.02	Moderate winters (temperatures above 0°F during most of the snow season), and deep snowpacks

1. EFC. A reasonable value for EFC can be obtained from a knowledge of the percent of the area covered by forests (usually available from topographic maps with a woodland overprint) and the type of forests. EFC is not an important parameter in most areas, but does influence the volume of snowmelt runoff from forested watersheds. The influence is greatest on forest watersheds where snowmelt occurs in late spring when evapotranspiration demand is increasing.

5.4 ADJUSTMENT OF AIR TEMPERATURE DATA WHEN FORM OF PRECIPITATION IS IN ERROR

The determination of model parameters can be severely affected when there are large errors in the data used for calibration. Errors in determining the form of precipitation can be classified under data errors. Ideally, the basic input data to the model would include the form of the precipitation. However, information on the form of precipitation for each six-hour period is not available. Therefore, since such input data are not available, it is necessary for the model to estimate the form of precipitation. As discussed in Chapter 3, the estimation of the form of precipitation is based on air temperature. The form of precipitation can be correctly estimated in most cases using air temperatures measured near the ground surface. However, ground level air temperatures are obviously not a perfect index to the form of precipitation, thus there will be times when the model estimation of the form of precipitation is in error. These cases should be corrected after the initial run of the verification program so that further parameter calibration is not affected.

An examination of the simulated versus observed discharge plot will indicate those periods during which an error in determining the form of precipitation might have a significant effect on model results (e.g., if the observed hydrograph shows a sizable response and the simulated hydrograph shows no response, this could be a case of rain occurring when the model determined that it was snowing). The next step is to examine the daily snow summary printout to determine if precipitation did occur, since the discrepancy could have been the result of an error in estimating the amount of snowmelt. In many cases, a significant deviation between model response and observed response is sufficient to verify that the form of the precipitation is in error. However, especially when the deviation is not great enough to make the cause obvious, it becomes necessary to examine other available data to determine if the form of precipitation is actually in error. Two types of data which are helpful in determining whether the form of precipitation is in error and which are usually readily available are:

a. Hourly or three hourly air temperature data from NWS first order stations or other recording temperature stations. Experience has shown that in most cases when the form of precipitation was in error, it was because maximum-minimum air temperature data were not sufficient to describe the daily variation in air temperature. The assumption of the maximum air temperature occurring in the afternoon and the minimum occurring near sunrise is more likely to be in error on days with precipitation than on days with no precipitation. For example, most of the periods when the form of precipitation was in error for the Passumpsic basin were nighttim periods when the model estimated that it was snowing when actuall rain was occurring. An examination of hourly temperature records revealed that in almost all cases the nighttime temperatures had remained well above 33°F. Minimum temperatures below 33°F had occurred during daylight hours on the previous day and/or the fol lowing day.

b. Snowfall and snow on the ground data from daily observation stati Program PRELIM2 (see section 2.4.2) will list snowfall and snow o the ground data for all daily observation stations that are selec for use in the basin analysis. This information is helpful in determining the actual form of the precipitation.

After determining which periods the form of precipitation is in error, t next step is to correct those periods. In some cases, it may be possible to correct most of the periods by changing the parameter PXTEMP. To corre the remaining periods it is necessary to change the six-hourly mean areal air temperature. On the watersheds tested to date, the number of periods which air temperature was changed varied from zero on the Rock River at Rock Rapids, Iowa to 39 over an eight-year period on the Passumpsic River. Appendix G lists a computer program which will transfer data in NWSRFS standard tape format from one tape to another tape and change air temperat data for selected periods in the process.

5.5 TRIAL-AND-ERROR CALIBRATION

Trial-and-error calibration involves subjective manual adjustments to mo parameters based on specific characteristics of previous simulation result To perform trial-and-error calibration in an effective manner it is necess to know: 1) which displays of simulation results should be examined and what to look for, 2) how different types of deviations between simulated observed conditions indicate which parameters need to be changed, and 3) large an adjustment should be made to a parameter to correct an observe deficiency in simulation results. Obviously, experience with using the mo is very helpful in trial-and-error calibration. Even though there is no r substitute for experience, hopefully the following suggestions will improv the effectiveness of trial-and-error calibration for those who are using t model for the first time.

a. <u>Which displays of simulation results to examine and what to look</u> The most all inclusive display of simulation results is the plot the simulated and observed mean daily discharge. This is the primary display to be analyzed. Displays such as the daily summary snowpack conditions and the monthly summary of soil-moisture accounting volumes and variables are helpful in interpreting deviations between simulated and observed mean daily discharge. Portions of the statistical summary table should also be examined during trial-and-error calibration. The monthly, annual, and flo interval percent bias columns are the most important statistics t examine in terms of determining simulation errors. In addition, RMS error, correlation coefficient, and the intercept and slope o the best fit linear regression line between simulated and observed daily discharge, give an indication as to whether a trial-and-error run was an improvement over previous runs.

The important thing to look for in examining these displays is consistent errors. Examples of consistent errors are:

1. The volume of flow during spring melt is always low.

2. Discharge is normally too low during the early portion of the spring melt period and too high during the later portion.

3. Mid-winter snowmelt rises are too high.

4. Low flows are simulated too high and high flows are too low.

5. Monthly flow volume is low in the spring, slightly high in the summer and winter, and quite high during the autumn.

6. Runoff volume is over-estimated during periods when soil-moisture is relatively low and under-estimated during periods when soil-moisture is high.

7. Peak discharge is low, but the recession limb of the storm hydrograph is high.

When the deviations between simulated and observed discharge are reasonably random, then parameter calibration is complete.

b. How to identify consistent deviations with model parameters. Once consistent model errors are identified, the next step is to determine which model parameter or parameters need to be changed to correct the error. Two suggestions which may be helpful in this regard are:

   1. Try to relate the deviation in the hydrograph to the most likely physical cause. Then look at the structure of the model to determine which parameter or parameters control the physical process that is in error. For example, if the volume of spring runoff is low, it may be because the water-equivalent of the snowpack prior to melt is too low. An examination of the model structure reveals that the water-equivalent of the snowpack prior to spring melt is primarily a function of the gage catch deficiency correction factor and melt during the accumulation season. If there are no significant melt periods during the winter or if winter melt periods are simulated with reasonable accuracy, then parameter SCF is probably in error. On the other hand, if there are a number of mid-winter melt periods, the majority of which are simulated much too high, then MFMIN and MFMAX may be all or partly to blame for the error in the volume of spring snowmelt runoff.

2. Experiment with the model by varying the value of a single parameter and noting the effect on model response. Such experi ments will indicate under what conditions each parameter affect model response and also the characteristics of the change in response. Figures 5-4, 5-5, and 5-6 show the effect of three o the most important snow parameters on model response. It shoul be noted that each of these parameters has a unique effect.

The complicating factor in determining which parameter values shoul be changed is that in most cases not one, but a number of parameter are in error simultaneously. In these situations, it is usually no possible to identify all the parameters that should be changed. It is recommended that the parameter which is felt to have the largest effect on the simulation error be changed first. A hydrologist wit experience in using a model may change a large number of parameters on a single trial-and-error run. However, it is recommended for the beginner that the number of changes be kept small. Only the value of one parameter should be changed for each major simulation error that is identified (e.g., spring volume is too high or melt occurs too early in the spring).

In addition to experimenting with model parameters to determine their effect on hydrograph response, the sensitivity mode of the optimization program can be used to study the magnitude of the effect a given parameter has on simulation results. The sensitivit mode of the optimization program shows the effect that various values of different model parameters have on the evaluation criteri (sum of squares of the difference between simulated and observed mean daily discharge). This effect can be illustrated by a sensitivity plot. A sensitivity plot is made by establishing a paramete set and varying a single parameter holding all other parameters constant. Figures 5-7, 5-8, and 5-9 show sensitivity plots for the six major snow parameters on the Passumpsic River. Two different data periods were analyzed to show that the effect of parameter variation and the "optimum" magnitude of parameters can be differen for different data periods. Several points should be noted regardi these plots:

1. The value of one parameter, especially an important parameter, can affect the sensitivity plot of other parameters. For example, the water-equivalent of the snowpack was underestimated for the earlier period (12/64 - 5/68). To compensate for this volume deficiency, the evaluation criterion could be improved by retarding melt during the winter, thus holding the water in the snowpack until spring. This is why low values of parameter MFMIN and high values of parameter NMF caused an improvement in the evaluation criterion. This helps show why a examination of the plots of mean daily discharge is essential i trial-and-error calibration. The output of the 12/64 - 5/68 sensitivity run might suggest that SCF, MFMIN, and NMF should b changed when in reality the values of MFMIN and NMF are quite reasonable and only SCF is in error.

2. The snow correction factor, SCF, and the non-rain melt factor are the most sensitive and the most important snow parameters SCF is the only snow parameter which has a significant effect on the volume of runoff from the snowpack (EFC affects volume to a small degree). All the other snow parameters affect the timing of the snowpack runoff. Of these, the non-rain melt factor is the most important. MFMAX is generally more import than MFMIN since most of the snowpack runoff occurs after March 21 in areas where there is a significant snowmelt contr bution to runoff.

3. Some parameters are more sensitive to changes in one directio than to changes in the other direction. This can be noted in the sensitivity plot for parameter SI.

c. How to determine the magnitude by which to change parameter value There are two basic methods of determining how the magnitude of a change in the value of a parameter will affect simulation results These have been mentioned previously since the methods also aid i determining which parameters should be changed. The two methods are: 1) experimentation with the model parameters to determine their effect on hydrograph response, and 2) evaluation of sensiti plots. Experience has shown that in the early stages of trial-an error calibration reasonably large changes in parameter values ar better than small changes. The determination of the optimum valu of a parameter seems easier if the optimum value is bracketed tha if the optimum value is approached from one direction.

Trial-and-error calibration should be applied to the entire data period used for the calibration analysis. Initially, one or two water years may be sufficient to determine parameter changes. However, as the simulation results begin to look reasonable, the entire data period should be included in the analysis. Trial-and error calibration should be continued until the purpose for which trial-and-error calibration is being used is accomplished. This purpose may be to obtain reasonable initial parameter values for Pattern Search optimization or the purpose may be the complete calibration of the watershed. Sections 5.6 and 5.7 include a discussion of the uses of trial-and-error calibration in conjunct with Pattern Search optimization for determining model parameter values for a given watershed.

5.6 PATTERN SEARCH OPTIMIZATION

5.6.1 INTRODUCTION

It is obvious that a conceptual hydrologic model can be calibrated solel by a trial-and-error procedure. However, there are two disadvantages of trial-and-error calibration: 1) the effectiveness of the procedure is largely determined by the amount of experience that the person who is performing the calibration has with the model, and 2) the number of man-hours needed to analyze simulation results to determine parameter changes is generally large. An automatic optimization technique would overcome these disadvantages. However, besides requiring relatively large amounts of computer time as compared to trial-and-error calibration, automatic optimization techniques have disadvantages of their own. These include:

a. Parameter adjustments are based on a single criterion of model performance.

b. A sub-optimum set of parameter values can be calculated as a result of poorly selected starting values.

c. Interrelationships between model parameters can cause: 1) the solution to converge slowly to the optimum, 2) parameter values to be distorted, and 3) optimum parameter combinations, but unrealisti values of individual parameters to be calculated.

In addition, because of the computer time necessary, there is usually a practical limit on the period that can be analyzed by automatic optimization techniques. The procedure recommended for use with the NWSRFS uses trial-and-error in the initial stages of calibration to minimize most of the disadvantages of automatic optimization. Automatic optimization using the direct search technique, Pattern Search, is then used to minimize the disadvantages of trial-and-error calibration.

5.6.2 MINIMIZING THE DISADVANTAGES OF PATTERN SEARCH

The following disadvantages of Pattern Search optimization can be minimize by the proper use of trial-and-error calibration.

a. Poor selection of starting values. The main reason for using trial-and-error calibration prior to Pattern Search optimization is to insure a reasonable set of starting parameter values. Trial-and-error calibration should always be continued until a set of parameter values is obtained which will produce a simulated mean daily discharge plot which resembles the actual mean daily discharge plot.

b. Effect of interrelationships between parameters. There are several difficulties that can arise during Pattern Search optimization because of interrelationships between parameters. These difficultie include:

   1. When one parameter is not at its optimum value, other parameter values can be distorted. This is especially true when the parameter, which is not at the optimum, is a very important paramete Table 5-2 illustrates how Pattern Search optimization can distor parameter values. The final parameter values based on eight yea of data are: SCF = 1.1, MFMAX = 0.022, and NMF = 0.003. When S is set to 1.4 and not included in the optimization, the values o MFMAX and NMF are distorted. When all three parameters are optimized, the value of NMF is still distorted because NMF has only a minor effect on the evaluation criterion compared to SCF and MFMAX.

2. The solution may converge slowly to the optimum. This effect is also illustrated by Table 5-2. The value of SCF converges slowly to the optimum when all three parameters are included, partly because of the interrelationship between SCF and MFMAX. The value of MFMAX increases at first to compensate for the high starting value of SCF. As SCF approaches its optimum value, the value of MFMAX reverses direction and returns to its optimum. The value of SCF converges more rapidly to the optimum when only SCF is included in the optimization.

3. If several parameters have much the same effect upon the transformation of the input data into the output hydrograph; Pattern Search will seek the optimum parameter combination. This can lead to satisfactory model performance, but physically unrealistic parameter values. Examples of this case are the parameters CC and LIRC6, which control the volume and timing of interflow, and the time-delay histogram and the parameter KS1, which determine the channel response function in the NWSRFS (these parameters are defined in chapter 4 and chapter 5 of HYDRO-14). A large volume of interflow and significant attenuation within the channel system have a similar effect on the output hydrograph.

Table 5-2.--Effect of including different parameter combinations in Pattern Search optimization. Passumpsic River, 12/69 - 6/71.

Case	Run No.	Parameter Value			Evaluation Criterion x 10^8
		SCF	MFMAX	NMF	
All three parameters included	1	1.40	0.022	0.0030	2.20
	15	1.27	0.028	0.0017	.87
	30	1.02	0.027	0.0004	.63
	47	1.11	0.022	0.0009	.34
MFMAX and NMF optimized	1	1.40	0.022	0.0030	2.20
	31		0.026	0.0003	1.54
Only SCF optimized	1	1.40	0.022	0.0030	2.20
	13	1.11			.38

To avoid some of the difficulties caused by interrelationships between parameters, the number of parameters which are included in Pattern Search optimization should be kept to a minimum. Especially those parameters which have only a minor effect on the evaluation criterion should not be included in Pattern Search optimization. To keep the number of parameters which are included in Pattern Search optimization to a minimum, the value of as many parameters as possible should be determined in advance. Parameter values can be determined by:

1. An analysis of the observed discharge hydrograph. Soil-moisture accounting parameters LKK6, A, EPXM, LIRC6, and KGS, plus the

channel response function can generally be determined by hydrograph analysis.

2. The value of a number of parameters can be determined adequately by physical considerations. This includes snow parameters PXTEMP, MBASE, TIPM, EFC, and the shape of the areal depletion curve plus soil-moisture accounting parameters K1, GAGEPE, K24EL, and SRC1.

3. The value of parameters which have a minor effect on the evaluation criterion can be determined through trial-and-error calibration by examining only those periods when the parameter is important. The evaluation criteria used in Pattern Search optimization is affected mainly by parameters which control high flow periods and parameters which control the majority of the events.

A number of snow model parameters have been purposely excluded from Pattern Search optimization because of the difficulties caused by interrelationships between parameters. The parameters PXTEMP, MBASE, TIPM, EFC, and the shape of the areal depletion curve must be determined prior to Pattern Search optimization. In addition, adequate final values for parameters NMF, PLWHC, and DAYGM should be able to be obtained from trial-and-error calibration. This leaves five snow model parameters which could be included in Pattern Search optimization. These parameters are SCF, MFMAX, MFMIN, UADJ, and SI.

c. Analysis of a limited data period. In order to get realistic and stable parameter values, the data period being analyzed by Pattern Search optimization should contain a variety of typical hydrologic conditions which can occur over the watershed (e.g., periods of high soil-moisture and periods of low soil-moisture, high flows and low flows, relatively large snowpacks and relatively small snowpacks mid-winter melt events and rain on snow events, as well as spring snowmelt). In addition, there should be a reasonably large number of events so that plus-and-minus data errors would tend to balance each other. Also in regard to the snow model, it is important to include many days of snowmelt so that the melt factors will not be based on a limited number of climatic conditions. The optimization computer program (NWSRFS) limits the period that can be analyzed by Pattern Search optimization to 50 months. A 50-month period can generally be found which contains sufficient hydrologic variety plus reasonably unbiased data errors and climatic conditions. Trial-and-error calibration should be quite helpful in the selection of a data period for Pattern Search optimization. This is true, since many of the factors which determine period selection are examined closely when analyzing the hydrograph to determine parameter changes during trial-and-error calibration.

It should be noted that in some watersheds it is impossible to find a 50-month period which has enough hydrologic variety plus unbiased data errors and climatic conditions. An example of such a watershed is the Rock River at Rock Rapids, Iowa. There were four significant snowmelt rises, each of short duration, in the ten-year period being analyzed. In addition, there were two significant rises caused by rain. Only three of the significant rises in the hydrograph occurred in any 50-month period. In this case, Pattern Search optimization was not an effective tool for parameter calibration, thus the calibration was performed solely by trial-and-error.

5.6.3 ADDITIONAL COMMENTS OF THE USE OF PATTERN SEARCH OPTIMIZATION

The previous section discussed several things that could be done to improve the effectiveness of Pattern Search optimization for use in the calibration of a conceptual hydrologic model. The three major recommendations were:

a. Reasonable starting values should be determined for all model parameters that are to be included in Pattern Search optimization.

b. The number of parameters included in Pattern Search optimization should be kept to a minimum. Parameters which have a small effect on the evaluation criterion should not be included. As many parameters as possible should be determined by physical consideration by hydrograph analysis, and by trial-and-error calibration before using Pattern Search optimization.

c. The data period selected for analysis with Pattern Search optimization should contain as much hydrologic variety as possible. The period should also contain reasonably unbiased data errors and climatic conditions.

Several other comments regarding the use of Pattern Search optimization and the optimization computer program (NWSRFS3) which may be helpful are:

a. The optimization program contains a provision that selected periods can be removed from the calculation of the evaluation criterion. Thus, the parameter values will be based only on the remaining periods. This provision can be used to an advantage in some watersheds where snow is included. Soil-moisture accounting and channel routing parameters could first be optimized by removing all periods when snow is a factor. Then the snow parameters could be optimized by using only those periods when snow influenced the hydrograph. Obviously, this procedure is of no value in areas where snow is a factor in almost all significant rises of the hydrograph. The procedure of optimizing soil-moisture accounting and channel routing parameters on one run and snow parameters on the next run is ideally suited to the transitional zones where snowmelt is not the major source of runoff.

b. The input for the optimization program specifies that upper and lower constraints be provided for each parameter. The purpose of having constraints is to insure that physically unrealistic parameter values are not calculated by Pattern Search optimization.

c. The purpose of Pattern Search optimization is to assist in the determination of realistic parameter values which produce reasonable simulation results. These parameter values will then be used to predict hydrographs in the future. It is not the purpose of Pattern Search optimization to make slight adjustments to parameter values in order to get the best possible RMS error. The future is not going to be exactly like the past. Figs. 5-7, 5-8, and 5-9 indicate that the analysis of different periods will give different parameter values. Therefore, there is no reason to expect that aft reasonable simulation results have been obtained that further sligh adjustments to parameter values will improve future streamflow fore

d. It is suggested that the maximum number of runs (MAXN, see card 21 of input summary - appendix E) of the optimization program be set equal to approximately ten times the number of parameters that are included in Pattern Search optimization.

e. The "best" parameter values as determined by Pattern Search optimization are not necessarily those which give the lowest value of the evaluation criterion. The mean discharge column also should be examined. In some cases, a large flow bias can exist when the evaluation criterion is at its lowest value. A large bias is not desirable.

5.7 ANALYSIS OF THE CALIBRATION RESULTS

After finishing the initial trial-and-error calibration and the first use of Pattern Search optimization, the results need to be analyzed to determine if parameter calibration is complete or if further trial-and-error calibratic and possibly further Pattern Search optimization are necessary. The first step is to run the entire data period, using the verification program, with the parameter changes determined by Pattern Search optimization. If an analysis of the estimated and observed mean daily flow plots and an examination of the statistical summary indicates that the errors seem to be reasonably random, then the calibration is complete. If consistent errors still remain, then further trial-and-error calibration and possibly further Pattern Search optimization are needed to try to eliminate or reduce these errors.

Listed below are some possible reasons for consistent errors still remainir after the initial trial-and-error calibration and the first use of Pattern Search optimization:

a. Important model parameter or parameters may not have been corrected properly during trial-and-error calibration nor included in Pattern Search optimization.

b. The period used for Pattern Search optimization may not be representative of the entire data period.

c. The channel response function may not be adequate to describe properly the response of the channel over the entire range of discharge. Variable Lag and/or variable K may need to be includeč

d. There may be deficiencies in the conceptual model. For example, the effect of frozen ground and other temperature related phénomer which affect the movement and retention of water in soil are not included in the soil-moisture accounting model. Consistent errors will result when phenomena occur which are not included in the conceptual model or which are not modeled satisfactorily. Further calibration will not correct these deficiencies.

5.8 OTHER CALIBRATION CONSIDERATIONS

5.8.1 USE OF ELEVATION ZONES

The computation of snowmelt and the form of precipitation is based on mea areal temperature in the snow accumulation and ablation model. Snowmelt is either assumed to be occurring over the entire area or no snowmelt is assum to be occurring anywhere in the area. Also, either all the precipitation i assumed to be rain or it is all assumed to be snow. In addition, as the areal extent of the snowpack is depleted in a mountainous area, the mean areal temperature is no longer the same as the mean temperature over the sn covered area. The use of mean areal temperature to estimate snowmelt and t form of precipitation can result in errors. Simulation errors in the computation of snowmelt will occur primarily during the early portion of th snowmelt season when melt occurs only at low elevations and late in the snc melt season when only the high elevations are covered with snow. The estin tion of the form of precipitation will cause simulation errors during peric when rain is occurring at low elevations and snow is occurring at high elevations. Such simulation errors will be unimportant when the elevation range of the area is small, but increase in importance as the elevation rar increases. To reduce these simulation errors, the elevation range needs tc be reduced. The elevation range can be reduced by dividing the watershed into subareas based on elevation (elevation zones). Based on the watershec tested to date with the snow model, it is not possible to give specific guidelines as to when elevation zones should be used. For the Passumpsic River, the RMS error was improved by about six percent and the correlation coefficient by about one percent when two elevation zones were used. The Passumpsic River has an elevation range of 1500 feet over 90 percent of the area (discounting the lower and upper five percent of the area - elevation range is 2900 feet for the entire area). The same parameter values that we used for the total area were used for each subarea except for SI (SI variec between areas since the amount of water equivalent varies). None of the other watersheds were modeled using elevation zones.

In addition to improving simulation results because of more representati air temperature data, improvements also may be possible through the use of different parameter values for each elevation zone. Since physiographic ar climatic conditions vary with elevation, it would seem logical that model parameters also should vary. Simulation results can be improved by varying parameter values between elevation zones. However, unless care is exercise the improvements may be at the expense of unrealistic parameter values. As mentioned previously, a slight improvement in simulation results does not insure that the future can be predicted with greater accuracy. Several suggestions which may be helpful if parameter values are varied between elevation zones are:

a. In a large watershed with several elevation zones, it may be poss: that there are some small gaged areas which lie within a single elevation zone. Calibration of these small areas will provide a good estimate of the parameter values for the elevation zone, as long as physiographic conditions are similar between the small gaged area and the rest of the elevation zone.

b. The simulated snowpack water-equivalent for each elevation zone should be compared with available water-equivalent measurements t(insure that the simulation of the snowpack is reasonable.

c. Differences in parameter values between elevation zones should be physically realistic.

5.8.2 EFFECT OF THE PRECIPITATION NETWORK ON THE SNOW CORRECTION FACTOR

In many cases, the precipitation network used in model calibration is different from the network used for operational river forecasting. Many stations are included in the published climatological network which do not report to a River Forecast Center. On the other hand, stations report to a River Forecast Center, but their precipitation data are not published as pa of the climatological network. Results to date indicate that the most stab and realistic parameter values can be obtained when as much data as possibl are included in the parameter calibration analysis. Because of data retrie problems, it is generally not feasible to include stations which are not pa of the published climatological network in the calibration analysis. Parameter values obtained during the calibration analysis are applicable to the operational data network as long as there is no bias between the data values obtained from the two networks. If there is no bias, the difference in simulation results from the two networks will be random.

The snow correction factor is an indication of the catch deficiencies dur snowfall of the individual gages which makeup the precipitation data networ Thus, the snow correction factor for one precipitation data network probabl will be different than that for another. Two possible methods for determin the snow correction factor for the operational precipitation network are:

a. The snow correction factor, SCF, could be determined for the opera tional precipitation network by trial-and-error calibration and Pattern Search optimization if all the stations included in the operational network are also part of the climatological network. this case, mean areal precipitation would be recomputed using only those stations which are in the operational network.

b. The snow correction factor for the operational precipitation netwo: (SCF_H) could be computed as

$$SCF_H = R_{C/H} \cdot SCF_C \quad , \tag{5.2}$$

where: $R_{C/H}$ is the ratio of mean areal precipitation during snowfall of the climatological network compared to the operationa network, and
SCF_C is the snow correction factor for the climatological precipitation network.

In this case, all the stations in the operational hydrologic network do not have to be part of the climatological network.

The number of stations actually reporting during any time period would not affect the value of the snow correction factor. Missing precipitation data would be estimated from those stations which do report based on predetermined inter-station relationships. These relationships might include storm type, form of precipitation, and wind speed.

It should be noted that in addition to adjusting the snow correction factor, network effects on rainfall amounts and air temperature also must be considere so that the operational data network will not bias the simulation results.

References:

Monro, John C., "Direct Search Optimization in Mathematical Modeling and a Watershed Model Application," NOAA Technical Memorandum NWS HYDRO-12, U. S. Department of Commerce, Washington, D.C., April 1971, 52 pp.

Larson, Lee W., "An Application of the Dual-Gage Approach for Calculating "True" Solid Precipitation," National Weather Service, NOAA, Silver Spring, Md., presented at the 53rd Annual Meeting of the American Geophysical Union, Washington, D.C., April 17-21, 1972, 18 pp.

"Lysimeter Studies of Snow Melt," Snow Investigations Research Note No. 25, U. S. Army Corps of Engineers, North Pacific Division, Portland, Oregon, 1955, 41 pp.

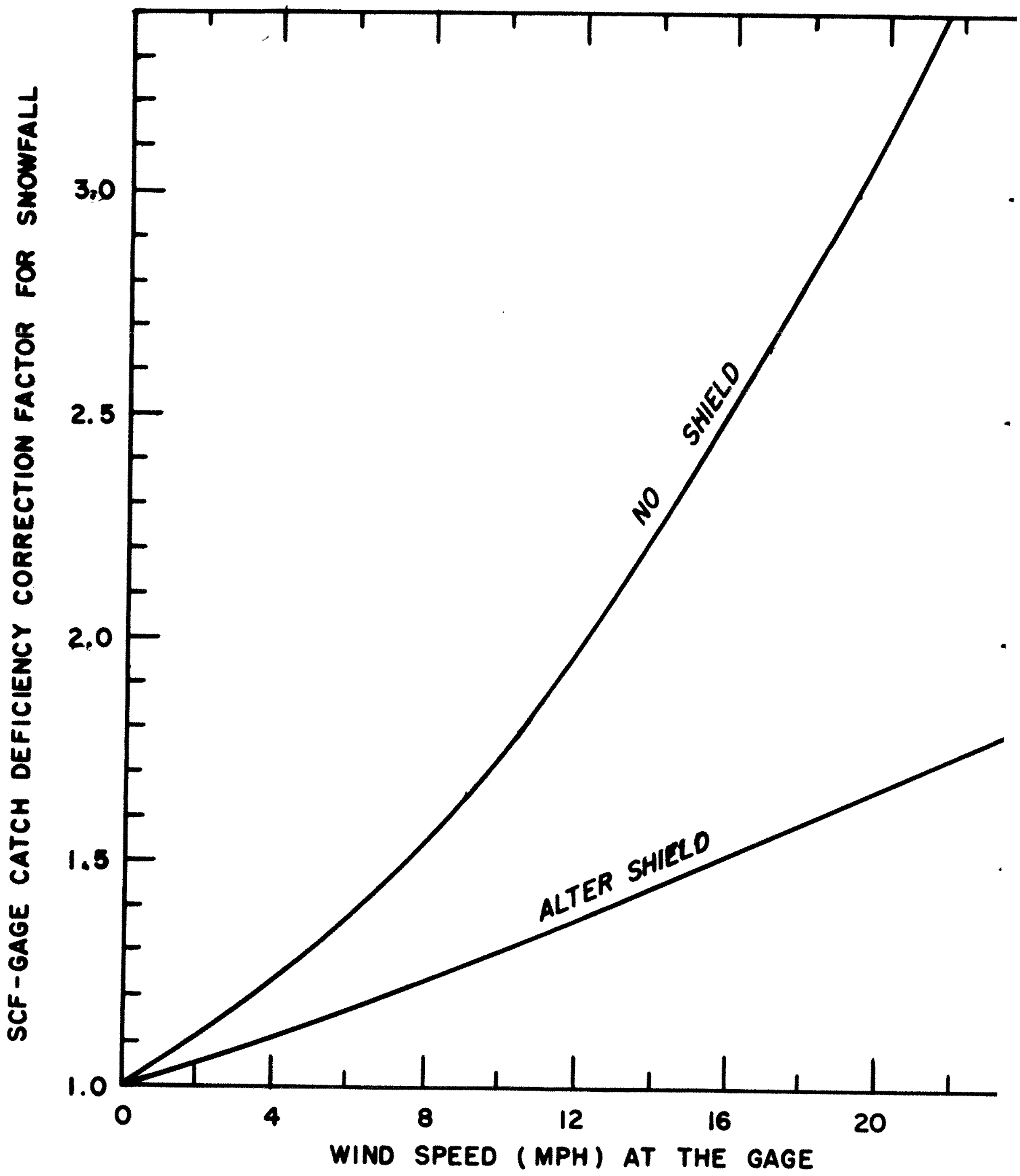


Figure 5-1. Typical gage catch deficiency correction factors during snowfall f shielded and unshielded gages (Larson 1972).

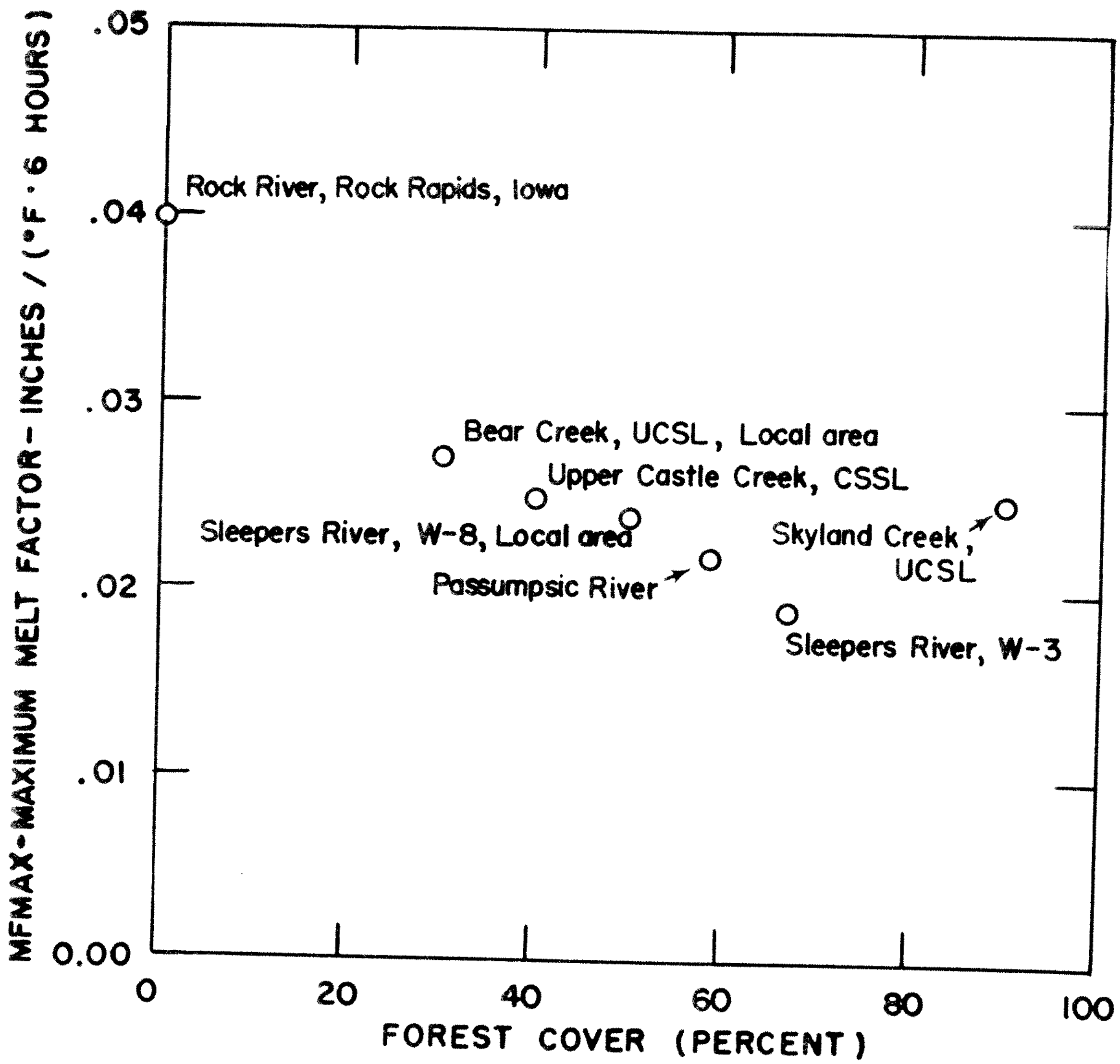


Figure 5-2. Maximum melt factor versus forest cover for areas tested on snow model.

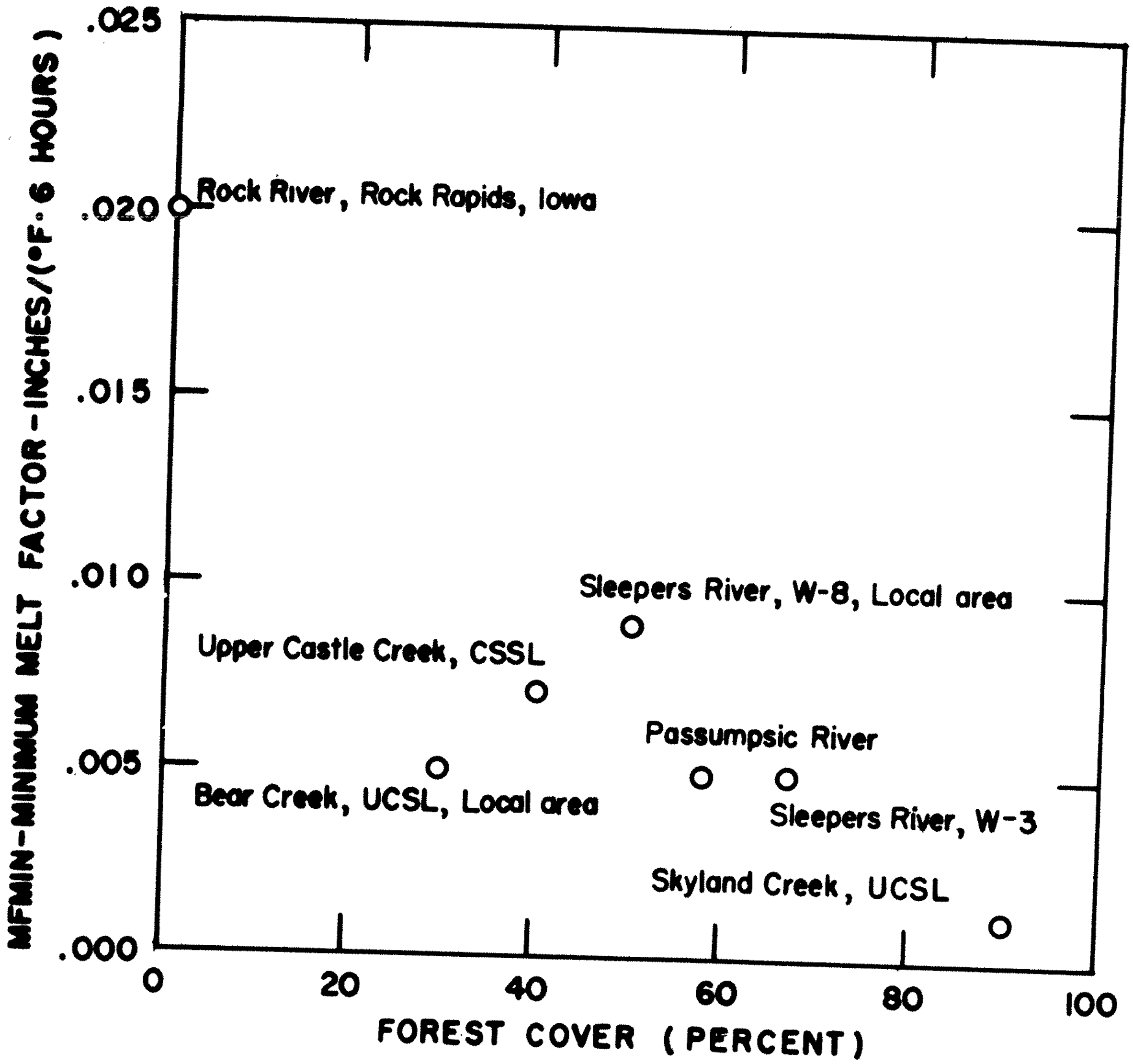


Figure 5-3. Minimum melt factor versus forest cover for areas tested on snow model.

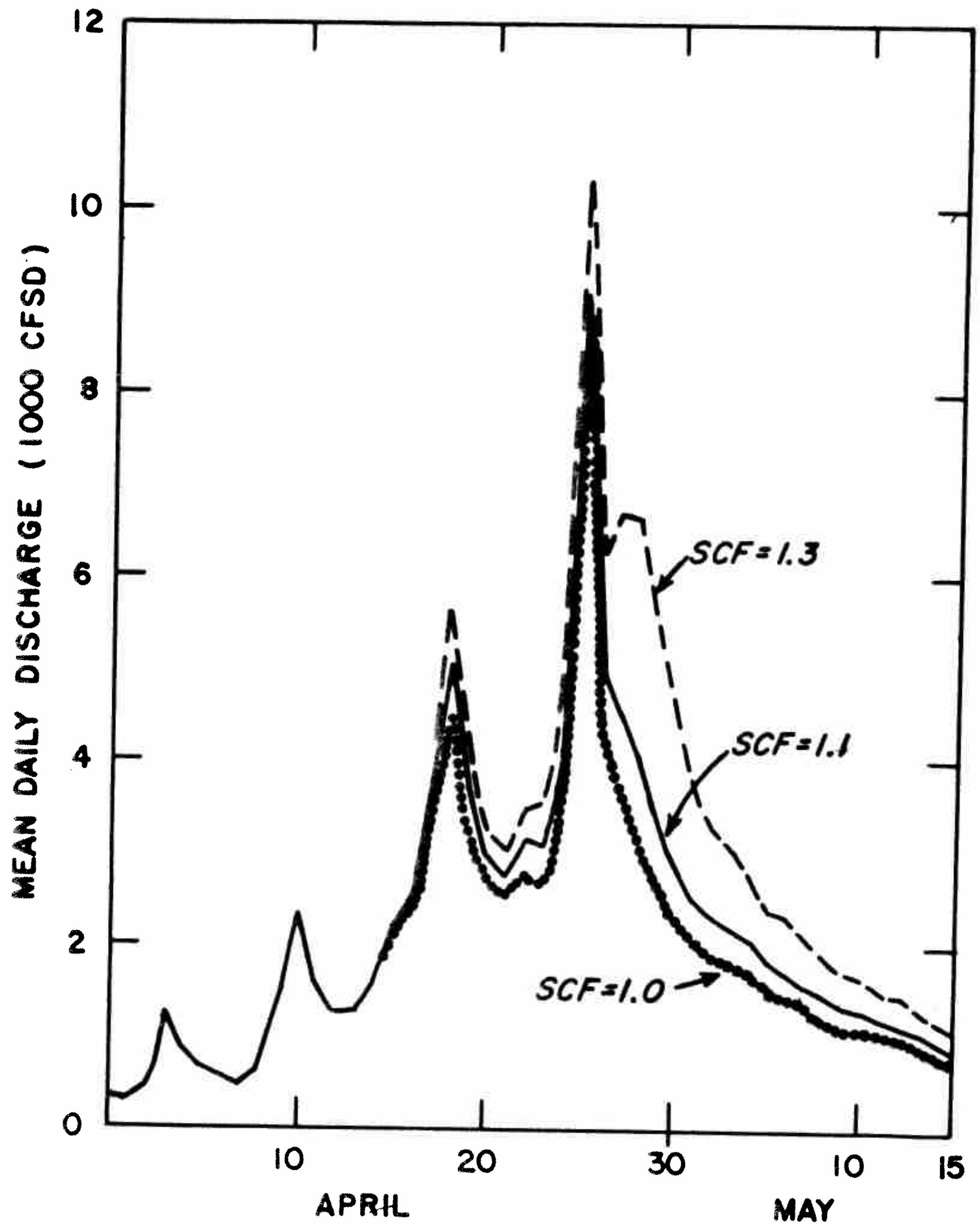


Figure 5-4. Effect of parameter SCF on spring snowmelt hydrograph. Passumpsic River at Passumpsic, Vermont, 1970.

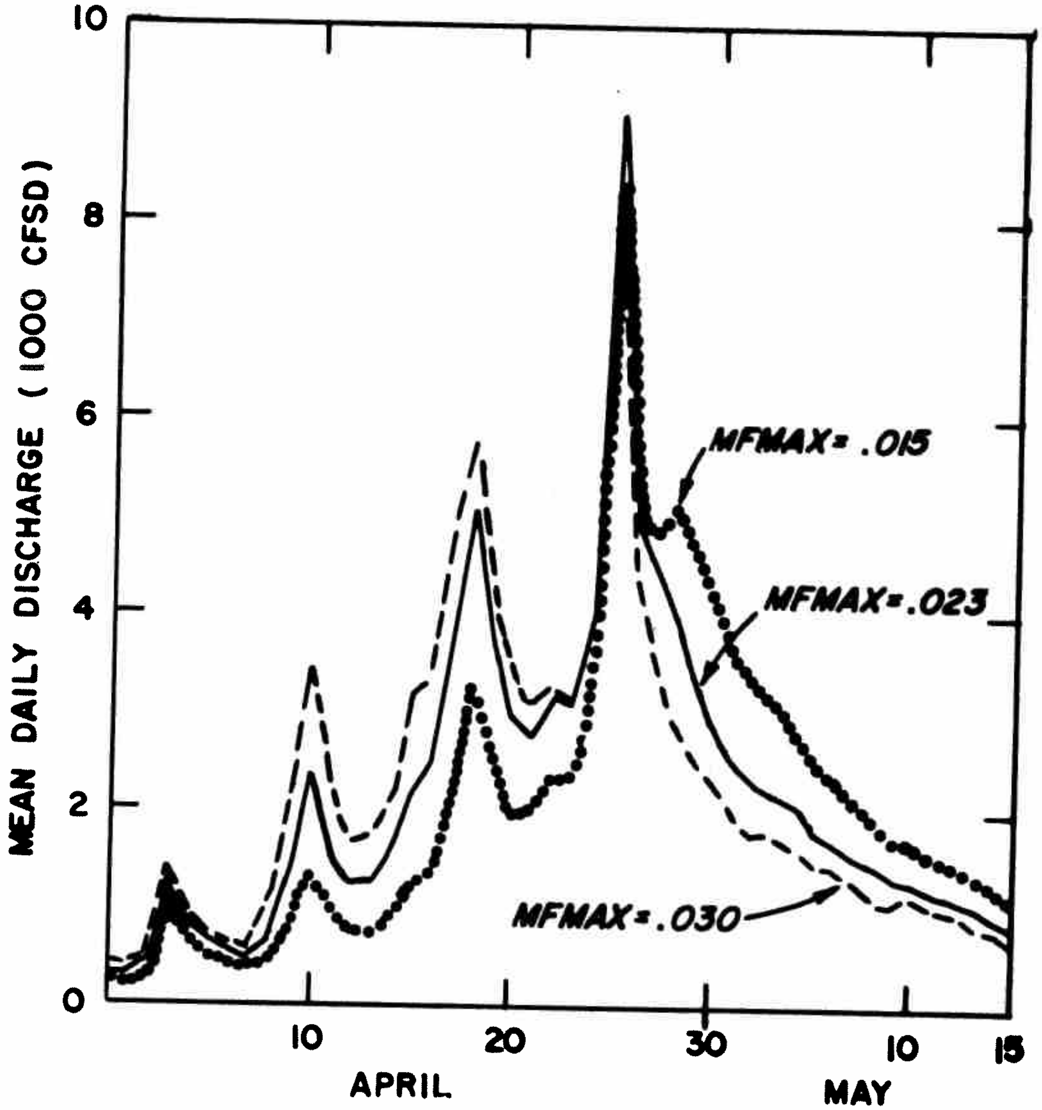


Figure 5-5. Effect of parameter MFMAX on spring snowmelt hydrograph. Passumpsic River at Passumpsic, Vermont, 1970.

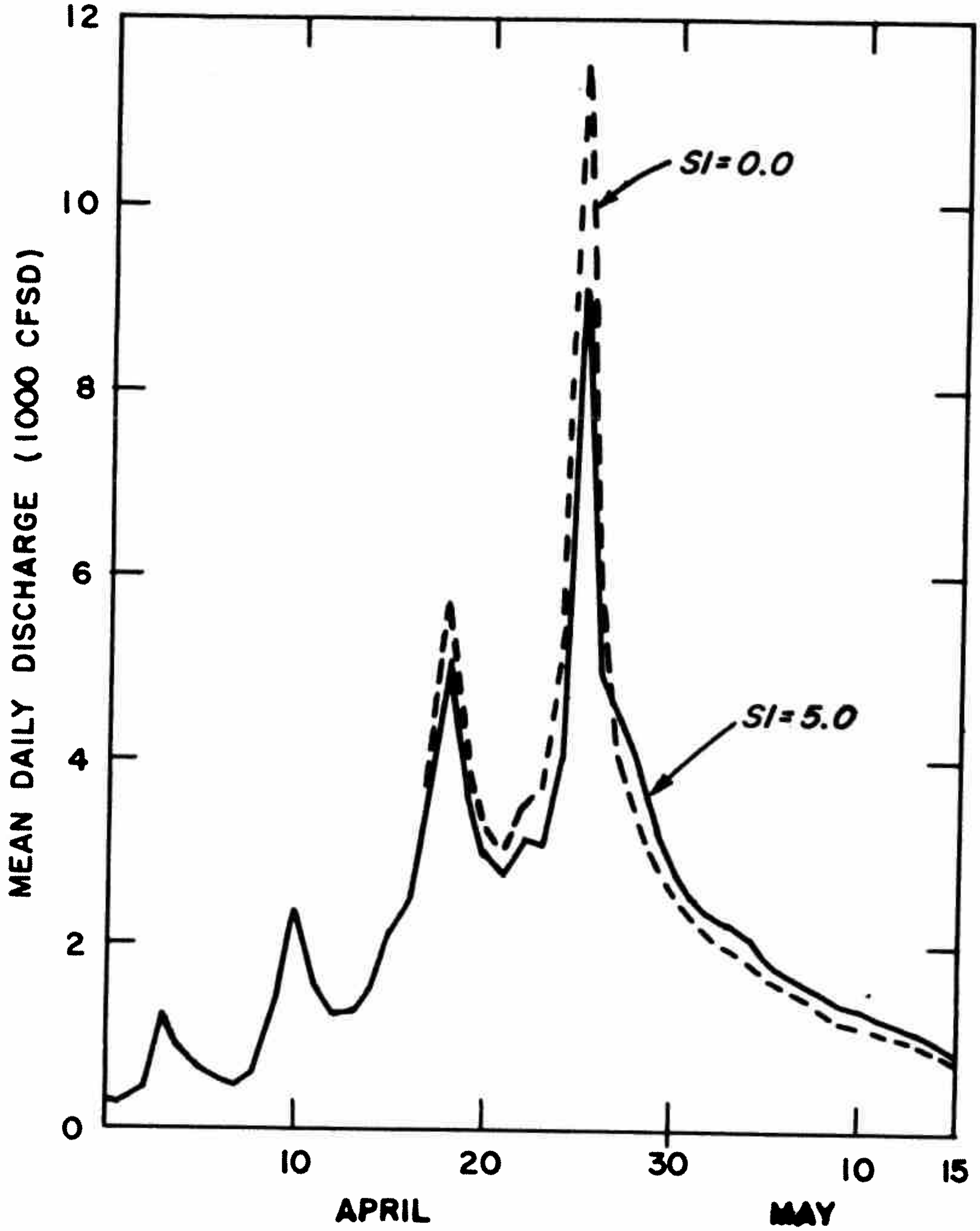


Figure 5-6. Effect of parameter SI on spring snowmelt hydrograph. Passumpsic River at Passumpsic, Vermont, 1970.

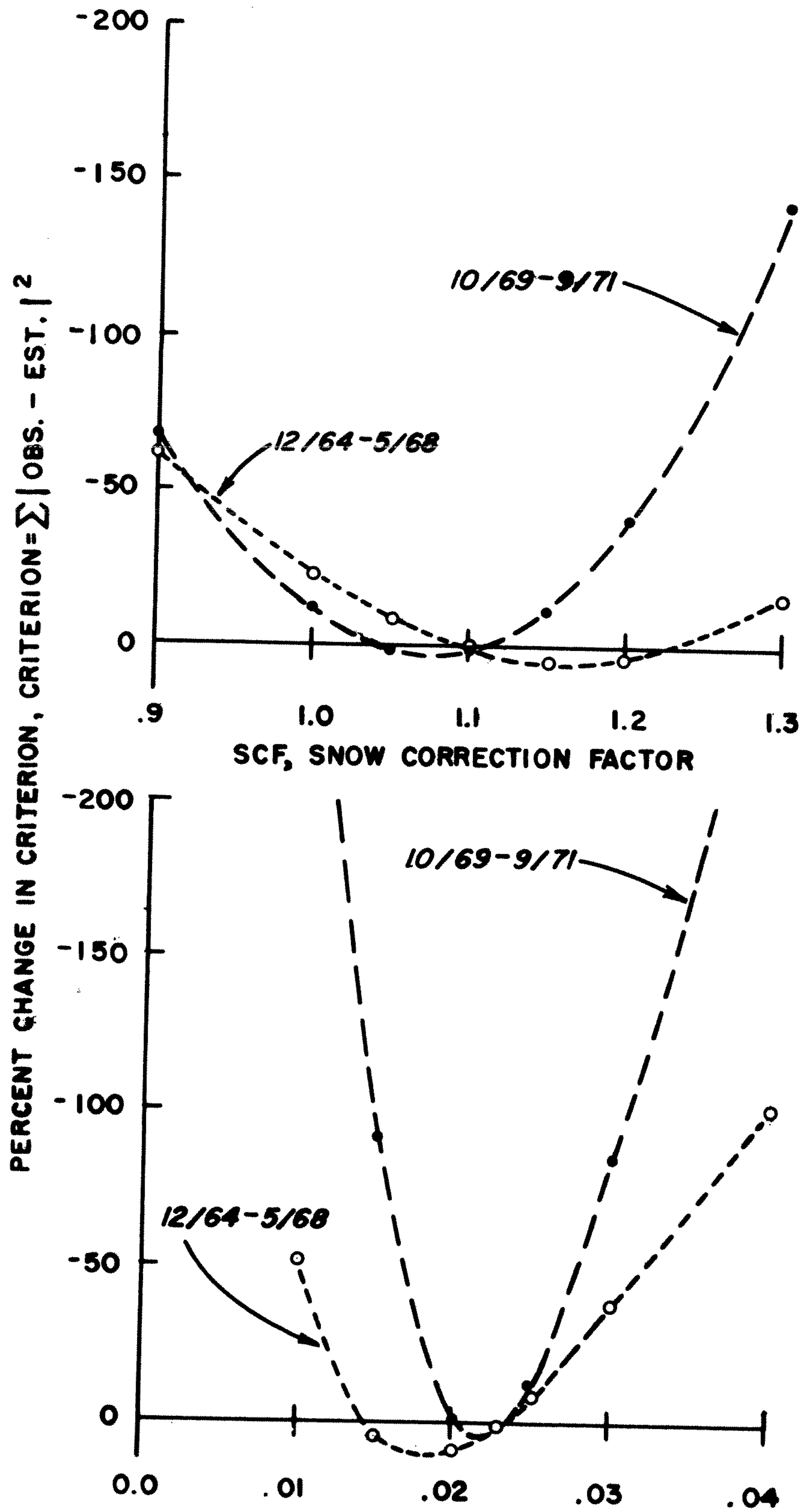


Figure 5-7. Sensitivity plots for parameters SCF and MFMAX. Passumpsic River at Passumpsic, Vermont, 1970.

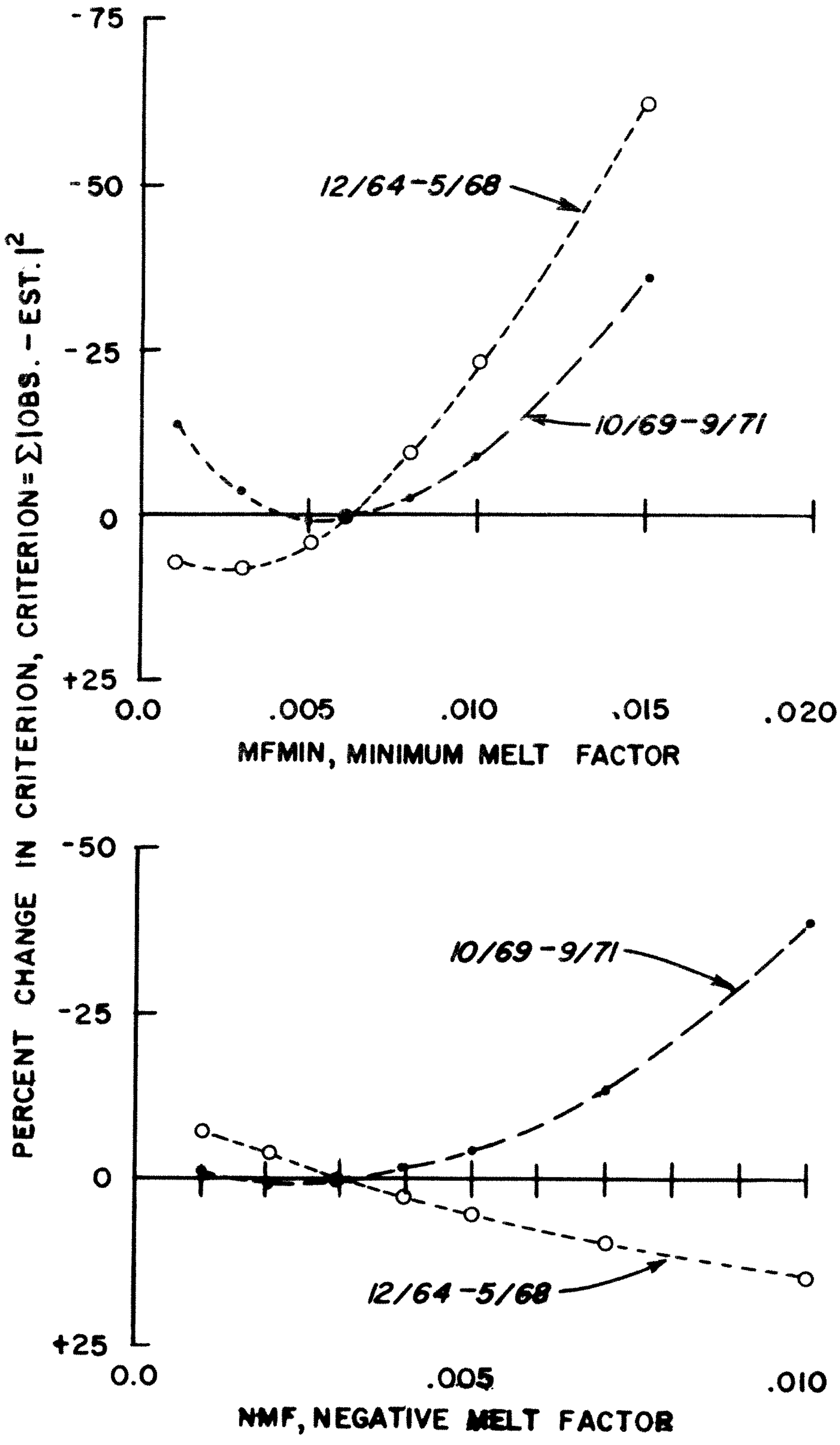


Figure 5-8. Sensitivity plots for parameters MFMIN and NMF. Passumpsic River at Passumpsic, Vermont, 1970.

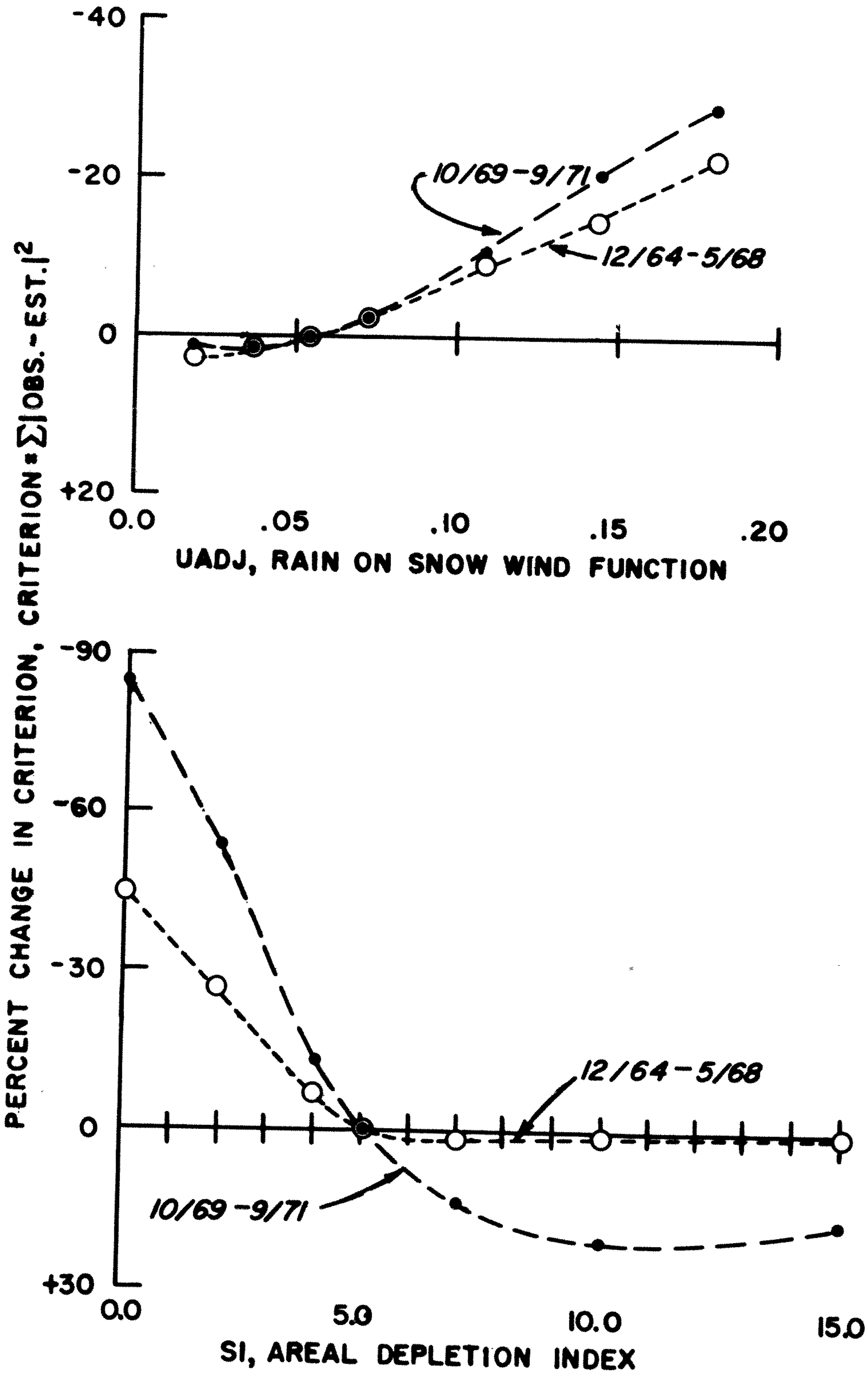


Figure 5-9. Sensitivity plots for parameters UADJ and SI. Passumpsic River at Passumpsic, Vermont, 1970.