MIT

SIMULATION OF THE CONTINUOUS SNOWMELT PROCESS

by

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and

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for
WATER RESOURCES AND HYDRODYNAMICS

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ABSTRACT

The efficient design of many water management projects requires the ability to predict the time distribution of runoff from a melting snowfield. A continuous model of the snow accumation and melting processes is presented for this purpose. The empirical and theoretical equations that have been used to represent these processes are integrated into a model developed to have a wide range of applicability owing to its flexible data requirements.

The snowmelt model is tested using various combinations of recorded data thought likely to be available in practical design problems. A comparison of the generated values of certain important snowpack variables with those actually observed shows good agreement. Application of the model to an experimental catchment is made to estimate streamflows resulting from the computed snowmelt. Although the results were favorable, suggestions are made as to how they may be improved.

ACKNOWLEDGEMENTS

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The work was performed by Richard L. Laramie, Research Assistant in Civil Engineering, and, essentially as given here, constitutes his thesis presented in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering. The work was supervised by Dr. John C. Schaake, Jr., Associate Professor of Civil Engineering.

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A = Area of flow (ft^2)

AESC = Areal extent of snow cover

ALB = Albedo

ALH = Latent heat of evaporization/sublimation (cal/g/°C)

ALR = Ambient atmospheric lapse rate (°F/1000 ft)

BDHF = Basic degree-hour factor (langleys/°F/hr)

CC = Cold content of the snowpack (in)

CC' = Cold content of the snowpack before new snowfall (in)

CCNS = Cold content of new snow (in)

CKL = Cloud constant for longwave radiation

CKS = Cloud constant for shortwave radiation

CN = Cloud cover

c_a = Specific heat of air (cal/g/°C)

c_p = Specific heat of water (cal/g/°C)

c_s = Specific heat of snow (cal/g/°C)

DHF = Degree-hour factor (langleys/°F/hr)

DN = Density of snowpack (%)

DNS = Density of newly fallen snow (%)

DP = Depth of snowpack (in)

DPNS = Depth of new snowfall (in)

DP' = Depth of snowpack before new snowfall (in)

d = Depth of snowpack (in)

EFC = Effective forest cover (%)

e = Atmospheric vapor pressure (millibars)

F = Forest canopy density (%)

FADJ = Degree-hour seasonal adjustment factor

FTC = Forest transmission coefficient

FCV = Convective heat transfer constant (langleys/°F/hr)

FCN = Condensation heat transfer constant (langleys/°F/hr)

f = Degree-day factor (in/°F/day)

GH = Ground heat transfer constant (langleys/hr)

g = Atmospheric gradient of an air property

g = Fitting constant for albedo curves

H = Heat excess after eliminating cold content (langleys/hr)

HCN = Heat transfer from the condensate (langleys/hr)

HCV = Heat transfer due to convection (langleys/hr)

HG = Heat transfer from the ground (langleys/hr)

HP = Heat content of the precipitation (langleys/hr)

HRL = Net heat exchange between the snowpack and its environment (langleys/hr)

HRS = Heat transfer of shortwave radiation (langleys/hr)

HRS' = Incident shortwave radiation (langleys/hr)

HT = Total heat flux (langleys/hr)

H_a = Heat transfer with the air (langleys/hr)

H_{cn} = Heat transfer from the condensate (langleys/hr)

H_{cv} = Heat transfer due to convection (langleys/hr)

H_e = Heat transfer to evaporation/sublimation (langleys/hr)

H_g = Heat transfer from the ground (langleys/hr)

H_m = Heat transfer to melt water (langleys/hr)

H_p = Heat content of the precipitation (langleys/hr)

H_q = Change in heat storage of the snow (langleys/hr)

H_{rl} = Net longwave heat exchange between the snowpack and its environment (langleys/hr)

$H_{rl'}$ = Incoming longwave radiation (langleys/hr)

$H_{rl''}$ = Back (outgoing) longwave radiation (langleys/hr)

H_{rs} = Heat transfer of shortwave radiation (langleys/hr)

H_s = Heat transfer of shortwave radiation (langleys/hr)

H_t = Total heat flux (langleys/hr)

I = Average insolation received at the earth's surface (langleys/hr)

I = Precipitation loss due to interception by vegetation (in)

I_c = Average insolation received at the earth's surface under cloudless skies (langleys/hr)

K = Thermal conductivity of the soil (langleys/°C/cm)

K' = Interception constant

k = Turbulent exchange constant of proportionality

k = Coefficient of permeability of a porous media (ft/sec)

k_1 = Cloud constant for longwave radiation

k_s = Cloud constant for shortwave radiation

k_1 = Constant of proportionality for convection

k_2 = Constant of proportionality for condensation

L_f = Latent heat of fusion of ice (cal/g)

L_{fs} = Latent heat of fusion of snow (cal/g)

M = Quantity of snowmelt (in)

m = Quantity of snowmelt (in)

m = Fitting constant for albedo curves

m = Exponential constant relating Q and A

N = Cloud cover

n = Exponent of the power law distribution

n = Fitting constant for albedo curves

P = Amount of precipitation (in)

PC = Amount of melt reaching the ground per hour (%)

PF = Precipitation gage correction factor

PPT = Amount of precipitation (in)

p = Atmospheric pressure (millibars)

Q = Thermal Quality of the snow (%)

Q = Flow rate (cfs)

QCN = Vapor transfer due to condensation or evaporation (in)

QT = Thermal quality of the snow (%)

q = Vapor transfer due to condensation or evaporation (in)

q = Equivalent water frozen or melted by heat transfer (in)

q = Rate of lateral inflow (ft^2/sec)

RC = Net longwave radiation exchange for clouded skies (langleys/hr)

REDUCT = Reduction in snowpack depth due to compaction (in)

RF = Net longwave radiation exchange between a solid forest cover and the snowpack (langleys/hr)

R_a = Longwave radiation emitted by the atmosphere under cloudless skies (langleys/hr)

R_c = Net longwave radiation exchange for clouded skies (langleys/hr)

R_f = Net longwave radiation exchange between a solid forest cover and the snowpack (langleys/hr)

R_{net} = Net longwave radiation exchange between the snowpack and its environment (langleys/hr)

R_s = Longwave radiation emitted by a snow surface (langleys/hr)

S = Water equivalent of new snowfall (in)

SCI = Minimum basin snowpack water equivalent for complete areal cover (in)

SIG = Stephan-Boltzmann constant ($cal/cm^2/min/°K$)

SRO = Insolation of outer limits of earth's atmosphere (langleys/hr)

s = Slope of an area

T = Average snowpack temperature (°F)

TA = Surface air temperature (°F)

TAK = Surface air temperature (°K)

TD = Dew point temperature of the air (°F)

TNS = Temperature of newly fallen snow (°F)

TP = Average temperature of the snowpack (°F)

TS = Temperature of the snowpack surface (°F)
TSK = Temperature of the snowpack surface (°K)
TW = Wet-bulb temperature of the air (°F)
TX = Age of the snow surface (days)
T_a = Surface air temperature (°F or °K)
T_c = Temperature of the cloud base (°F)
T_d = Dew point temperature of the air (°F)
T_i = Index temperature for estimating heat transfer (°F)
T_p = Average temperature of the snowpack (°F)
T_r = Temperature of the rain (°F)
T_s = Temperature of the snowpack surface (°F)
t = Time
t = Temperature (°F)
V = Average wind velocity (mi/hr)
WEQ = Water equivalent of the snowpack (in)
WEQ' = Water equivalent of the snowpack before new snowfall (in)
WHC = Liquid water holding capacity of the snow (%)
W_B = Solar constant (langleys/hr)
W_o = Initial water equivalent of the snowpack (in)
x = Non-specified snowpack parameter
x = Distance downstream (ft)
Z = Height above ground surface (ft)
ZFCN = Condensation power-law factor
ZFCV = Convection power-law factor

z = Depth below ground surface (ft)

α = Solar altitude (degrees)

α = Velocity of flow (ft/sec)

Δt = Computation time interval (hr)

δ = Solar declination (degrees)

ε = RMS error criterion

ρ = Snow density (%)

σ = Stephan-Boltzmann constant (cal/cm^2/min/°K)

τ = Solar hour angle (degrees)

ϕ = Local latitude (degrees)

Chapter 1

INTRODUCTION

1.1 Motivation

The rapid growth of a technical society over the past century has lead to ever increasing demands on the water resources of this country. While it has long been known that an adequate supply of water is instrumental in this development and essential to its support, only over the last few decades has demand begun to approach the supply on a large scale. This has resulted in the construction of a variety of types of projects to control the distribution of water and provide for its efficient use. Thus, a need developed for the better understanding of the natural processes involved in the hydrologic cycle both for the economical design and for the efficient operation of the engineering works used in the management plans. This need has lead to a corresponding growth in the field of hydrology.

Because of the relative inaccessibility of important active catchment areas and the difficulty in maintaining adequate monitoring due to adverse weather conditions and long system response time, developments in snow hydrology have been slower than in other aspects of hydrology. Early investigations, lacking detailed knowledge of the physics of snow, were limited to the problem of forecasting the volume of spring runoff. Only recently has sufficient understanding of the behavior of snow come about to allow for the representation of snow accumulation and melting on a reasonably continuous basis.

1.2 Objective

The first models of the continuous snowmelt process represented a great advance in the snow hydrology field in that they made important steps in the synthesis of the time distribution of runoff, which provides the necessary basis for the design and management of water regulation facilities. These models were primarily concerned with defining which physical processes are hydrologically significant, and how these processes could best be represented in light of practical modelling considerations.

Each of these early models were developed primarily on the basis of data availability at a given location. Because of this, their application to other locations with different hydrologic conditions and data availability require time consuming changes to be made. Since the available data base varies from place to place, it seemed desirable to have a model that could readily be applied to a variety of practical engineering situations. To this end, the purpose of this study is to integrate and extend the existing models of the snowmelt process and to develop a more general model that would give the best possible snowmelt estimates using whatever data that may be available.

1.3 Scope of Study

The model developed here is intended to be applicable to a variety of commonly encountered situations where detailed information about the melting of snow is needed. This requires the capability to accept all of the significant meteorological variables in the various forms in which they are commonly recorded. Also, once the input at a particular site has been read in, the model must have the mechanism to select the appropriate procedures for modelling the physical processes based on the information supplied. The range of procedures utilized by the model varies from simple temperature index methods to detailed energy balance considerations. The accuracy of the results obviously can be expected to vary with the quality of data supplied.

In addition to the water excess reaching the soil surface, the model computes on a continuous basis various other parameters that are dependent on the time history of the pack. Several of the more important parameters such as snowpack depth, water equivalent and temperature are included in the output for comparison with actual recorded values of those variables where they are available. The water excess reaching the soil is input into an existing runoff model for computation of the resulting streamflow.

Comparisons of the computed quantities indicated above with the actual measured values are made for several sets of data representing a wide range of data availability. These comparisons are used as measures of the adequacy of the procedures used to model the physical processes and as indications of the relative importance of various input parameters. Also investigated is the effect of changes in the time step over which the computations are performed.

1.4 Approach

The background necessary for this study will be developed in the next two chapters. First, the history of snow hydrology from the beginning of the century is traced through a discussion of previous investigations that have been conducted in the field. Then the fundamentals of the physical processes involved, as they are presently understood, are presented in Chapter 3.

In Chapter 4 the model developed in this study is presented and its input and output specifications are discussed. Chapter 5 deals with the application of the model to various kinds of data. The results obtained and a discussion of them is included. The final chapter summarizes the results and suggests topics for further investigations.

Chapter 2

REVIEW OF PREVIOUS WORKS

2.1 Progress of Snow Hydrology

The first extensive investigations in the United States into the behavior of snow and the nature of the flows resulting from the melting of snow were conducted by the Forest Service from 1909-1926. This study dealt with the effect of forest cover on seasonal and annual water yield forecasts and was reported by Bates and Henry (1923). These seasonal water yield forecasts were concerned with the prediction of the total volume of flow for a given period, often April-July, and did not take into account rates of melt or the distribution in time within the forecast period of the rates of flow. Forecasting techniques were improved in later studies such as those by Croft[8], who investigated the influence of other topographic factors on the water yield, and by Strauss[15] in the development of better methods of measuring the water content of a snow field.

Early attempts to relate snowmelt runoff directly to its causes were largely based on empirical relationships derived from very limited data. In order to make valid estimates of the progressive melting process as required for the design and operation of engineering control works, a fundamental understanding of snow and the processes by which snow melts and is converted into streamflow is required. In response to this need, there have been a great many investigations into the physics of snow in the last few decades. The most intensive studies have been conducted by the Corps of Engineers' Cold Regions Research Laboratory and a cooperative venture by the Corps of Engineers and the Weather Bureau conducted from 1944-1956. Its report entitled "Snow Hydrology"[5] describes the investigations and results obtained. In revealing the details of the mechanisms by which snow accumulates, matures, and melts, it set the basis for the continuous analysis of snowmelt processes.

2.2 Recent Snowmelt Models

As mentioned earlier, in order for a snowmelt model to be useful for project design and management, it must be representative of the continuous melt process. Several models have been developed in the past few years to accomplish this. The primary ones reviewed during this study are by: Anderson and Crawford (1964), Winston (1965), Amorocho and Espildora (1966), and Anderson (1968). This study utilizes many of the concepts, formulations, and modeling techniques developed in these models. Therefore, it is appropriate to discuss them individually in a general way in the remaining sections of this chapter, and again in more detail where it is necessary in the following chapters.

The Stanford Model

The Stanford Watershed Model [Crawford and Linsley (1962)] contains a subroutine to compute snowmelt as an element in the hydrologic cycle. This snowmelt routine [Anderson and Crawford (1964)] employs a temperature index method in the determination of melt quantities; that is, air temperature is the primary meteorological input. Having read in the initial values of the snowpack parameters, the model updates them continuously and outputs their values in periods when the melt is a significant portion of the runoff. Excess water reaching the ground is returned to the main model where infiltration, runoff, and routing computations are performed.

The Ohio River Forecast Center Model

This model, as developed by Winston (1965), computes snowmelt and the related snowpack parameters on the basis of hourly meteorological observations taken by the U.S. Weather Bureau and transmitted via teletype to all major weather stations across the country. The data used by the model are cloud conditions (as an index of radiation) air temperature, dew point temperature, and wind velocity. These variables are used in a simple representation of an energy budget which includes heat transfers due to radiation, convection, and condensation/sublimation. The model output is excess water reaching the ground every six hours and daily values of the computed snowpack parameters.

The University of California (Davis) Model

This model, written by Amorocho and Espildora (1966), utilizes a comprehensive representation of the snowpack heat budget to simulate the snow melting processes. The input requirements for the component energy fluxes in this case restrict the range of applicability because these data normally would not be available for a large-scale engineering project. Observations are necessary on an hourly basis of: Incident solar radiation, air temperature, dew point temperature, wind velocity, and precipitation. Also needed are daily observations of cloud type and cloud cover. Computations are performed on an hourly basis resulting in the synthesis of the important melt parameters and the excess water reaching the soil surface.

The Anderson Model

This work by Anderson (1968) was performed to give the Stanford Watershed Model a more physical rational representation of the melt processes actually taking place than was available from the Stanford Model discussed earlier. Using a snowpack energy balance approach, this model achieved good results using 12-hour mean estimates of radiation components, air temperature, dew point temperature, wind velocity, and precipitation. It divides the day into two 12-hour periods and during the daylight hours it computes the melt, while at night it computes the snowpack surface temperature. Again the results were verified by comparing discharge as computed by the Stanford Watershed Model with that observed.

Chapter 3

BASIC SNOW HYDROLOGY

3.1 Introduction

In order to be able to represent the behavior of a snowpack in a rational mathematical model from the time of accumulation to the time of melting and runoff, the actual physical processes involved must be understood. The intent of this chapter is to discuss these processes as they are presently understood and to present the common formulations and assumptions used to represent them. Before beginning a discussion of these details, however, it will put things in better perspective if the process by which a snowpack is created, ages, and melts is traced in very general terms.

Snowfall occurs when atmospheric meteorological conditions are favorable for the formation and growth of ice crystals. The properties of this new snow is dependent upon the conditions under which it was formed and the properties of the air through which it falls. With the accumulation of more snow the density of the existing pack increases due to compaction and settling. As time passes, the surface of the snowpack weathers under the influence of radiation, rain, and thermal exchange processes. During most of the season when accumulation occurs, the temperature of the snowpack can be expected to be below the freezing point ($32^{\circ}F$). But when warm weather occurs, and heat is added to the pack, melting at the surface may occur. Due to the porous structure of snow, a certain amount of liquid water can be held against gravity after the snow temperature reaches 32°F. The surface melting may soon exceed this liquid water holding capacity, allowing the water to percolate downward. Initially this water will only penetrate a small distance before it is refrozen by the subfreezing snow below, releasing its heat of fusion in the process and thus warming the inner pack. During periods of prolonged warm weather the entire pack may be warmed to its melting point in this way. As warming continues, the liquid water holding capacity becomes satisfied; and the pack is termed ripe. Further addition of heat does not change the properties of the pack appreciably so the melt water percolates freely through the pack to begin the runoff process.

3.2 Snow Accumulation

A fundamental problem studied by snow hydrologists is to determinate the amount and distribution of precipitation and snowpack water equivalent at a given location and time. These quantities must be reliably known if he is to determine the resulting water yield due to melt over a specified period of time. The factors that influence these characteristics and the effects of new snow falling on an existing pack are discussed in this section.

Meteorological Factors

An important aspect in determining the depth of snow accumulation is the form in which precipitation occurs. Because precipitation is commonly measured in terms of water equivalent, it is important that proper differentiation as to the type of precipitation that falls be made in areas where direct observation is not feasible. Attempts to relate the form of precipitation to existing air mass conditions have shown that surface air temperature is as reliable as any other index for differentiating between rain and snow. As with the other variables tested, surface air temperature showed a range over which either rain or snow could occur. Figure 3.1 shows the percentage occurrances of both forms for various surface air temperatures.[5] This shows that an index temperature in the range of 32°F to 35°F should be valid to determine the form of precipitation. Thus if the index temperature is selected to be 34°F, it is assumed that precipitation occurs in the form of snow whenever the surface air temperature is less than 34°F.

If the precipitation is in the form of snow, its properties will depend on the meteorological conditions existing in the air mass through which it falls. The properties of importance for newly fallen snow are its density, liquid water holding capacity and thermal quality. Based on data taken at the Central Sierra Snow Laboratory (CSSL), the density of newly fallen snow has been related to the surface air temperature. This new snow density in turn, is

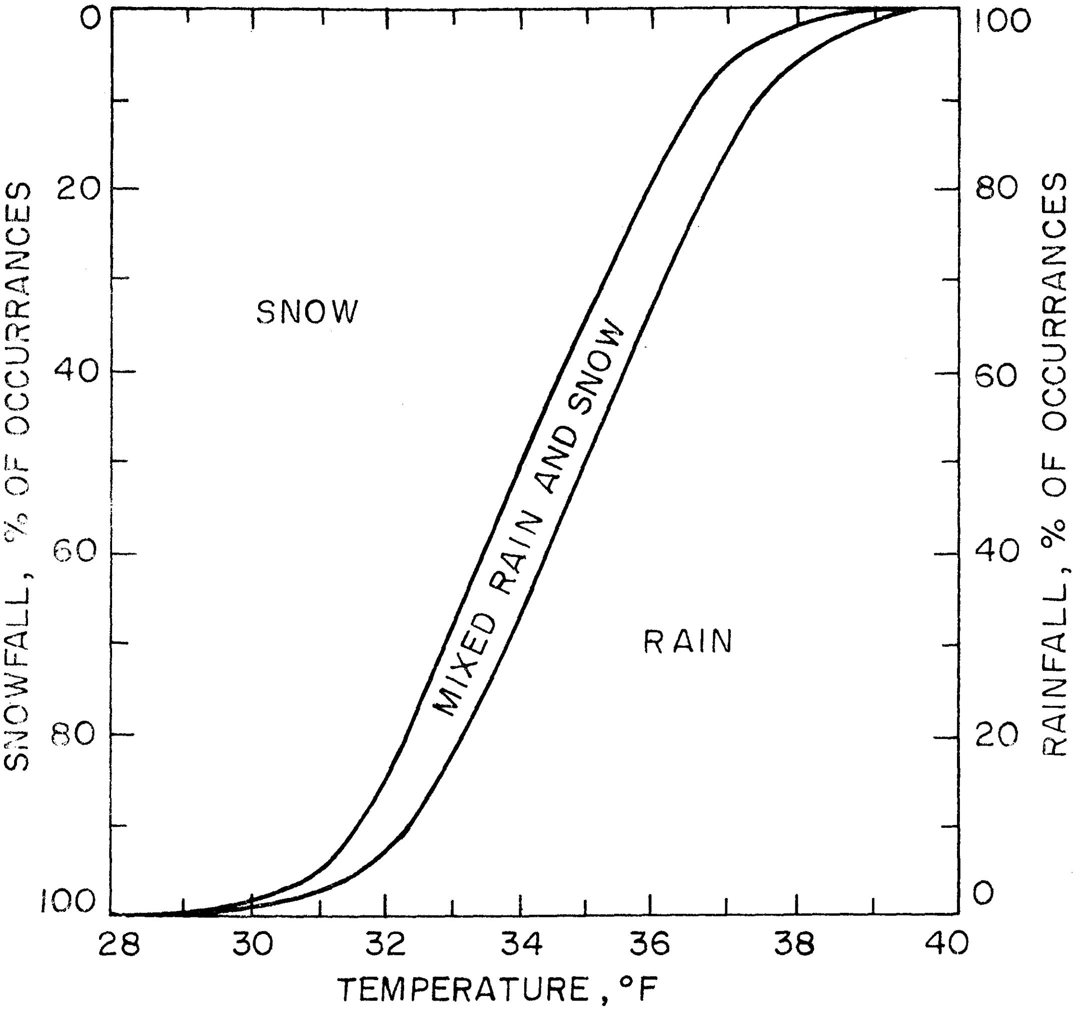

Figure 3.1 Frequency of Occurrence of Rain and Snow at Various Temperatures (U.S. Army Corps of Engineers, 1956)

often taken as an index to its liquid water holding capacity. The nature of these relationships as they are modelled is discussed in Chapter 4.

Topographic Factors

The topographic factors that may play a role in snow accumulation include elevation, slope, aspect, exposure, and vegetation. Perhaps the most important of these is elevation. Elevation has significant effects on the amount and distribution of precipitation and variation in surface temperature, and hence the form of precipitation. Studies[13] have shown that snow water equivalent generally increases with elevation due to the greater amounts of precipitation falling at higher altitudes and the more likely event that precipitation occurs as snow due to the lower temperatures normally associated with higher elevations.

In general, it is believed that snow water equivalent decreases with slope and exposure and increases with increased deviation of aspect from the south (for the Northern Hemisphere). Due to the complex terrain characteristics of each site, however, no general relationships have been developed to relate snow accumulation to these quantities.

The effect of vegetation on snow accumulation is primarily caused by forest cover acting to intercept part of the precipitation. The amount of precipitation reaching the ground or snowpack surface is the difference between the precipitation that would occur in an open unforested location and the amount intercepted by the forest canopy. This interception loss will eventually be returned to the atmosphere through evaporation without ever reaching the ground level. Interception loss, which is generally expressed as a fraction of the total precipitation occurring, varies from site to site depending on type and density of the forest cover.

Effects of New Snow on an Existing Pack

The process of snow accumulation is one in which the existing pack is intermittently exposed to the effects of snowfall, rainfall, and thermal exchange processes which, over the course of an accumulation season, cause the underlying snow to undergo marked changes. This entire process is termed snow metamorphosis or ripening and is discussed in more detail in a later section.

Of concern here is the effect that a new snowfall has on the existing pack. Perhaps the most obvious effect is to add to the depth and increase the water content of the snow. Also under the weight of the added snow the underlying snow will be compressed over a period of time, resulting in an increase in the snow density. Empirical formulas have been developed[1] which estimate the amount of the compaction of the underlying snow due to addition of new snow, so that the resulting total snow depth, and hence its density, can be determined.

3.3 The Heat Budget

Snow, having accumulated on the ground, will be exposed to the weathering process which may result in heat being added to the pack. In fact, a number of heat transfers can occur, some of which add heat to the pack and some of which result in heat being lost from the pack. This section will consider the different ways by which the pack gains or loses heat.

According to Wilson (1941), the inflow of heat to the snowpack and the losses from it can be categorized as follows:

Heat inflows:

H_{rs} = Solar (shortwave) radiation
H_{rl}' = Incoming longwave radiation
H_{cv} = Turbulent exchange (Convection)
H_{cn} = Condensation
H_{p} = Precipitation
H_{g}' = Conduction from soil
H_{a}' = Conduction from the air

Heat losses due to:

H_{rl}'' = Outgoing longwave radiation
H_{e} = Evaporation and/or Sublimation
H_{m} = Loss with melt water
H_{g}'' = Conduction to the ground
H_{a}'' = Conduction to the air

These heat exchange components are shown schematically in Figure 3.2.

Of these components, the conductive heat exchange between the snow and the overlying air is relatively small and can be neglected. Also, if 32°F is taken as the zero point for computations of heat storage, water leaving the pack (usually at 32°F) has no heat associated with it and can be neglected. Thus the total effect of remaining components can be represented in the form of the following heat budget equation:

$$H_{rs} + H_{rl} + H_{cv} + H_{cn} + H_p + H_g + H_q + H_s = 0 \qquad (3.1)$$

where

H_{rs} = Absorbed shortwave radiation

H_{rl} = Net longwave radiation exchange between the pack and its environment

H_{cv} = Convective heat transfer from the air above

H_{cn} = Heat supplied by condensate

H_p = Heat content of precipitation

H_g = Conductive heat from the ground

H_q = change in stored heat of the snowpack

H_s = Heat involved in changes of state.

If the quantity H_q+H_s is represented by H_t it can be seen that the total heat flux applied to the snowpack to produce changes in its energy content as well as its state can be expressed as follows:

$$H_t = H_{rs} + H_{rl} + H_{cv} + H_{cn} + H_p + H_g \qquad (3.2)$$

The remainder of this section deals with the individual components of

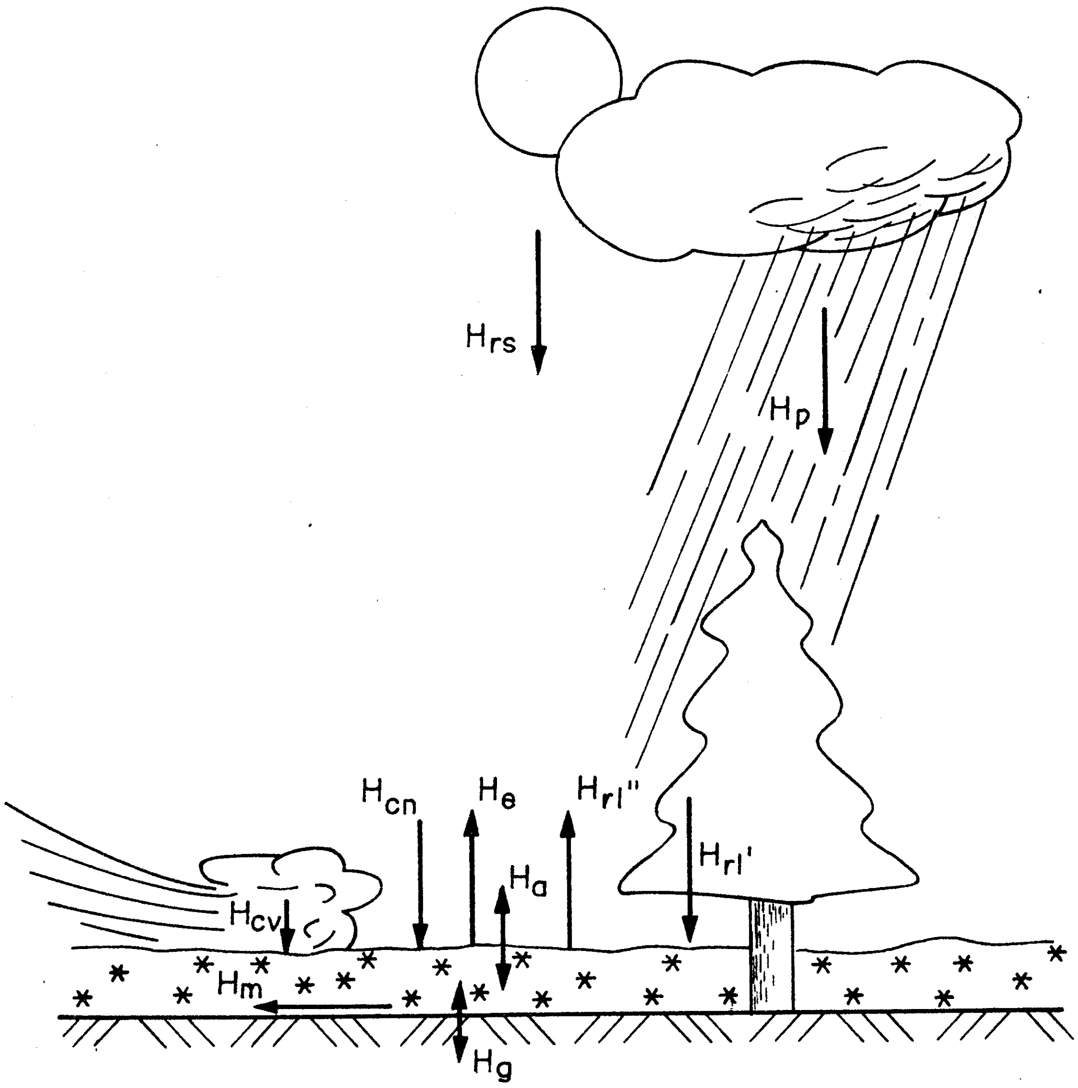

Figure 3.2 Schematic Representation of the Heat Transfer Components

this equation and how they are evaluated.

Absorbed Solar (Shortwave) Radiation, H_{rs}

The amount of heat transferred to the snowpack by solar radiation is the difference between the amount incident on the surface of the pack and the amount reflected by it. Thus it can be seen that the absorbed radiation is a function of the amount of radiation penetrating the earth's atmosphere to reach the surface and the snow's albedo, a factor indicating the reflectivity of the snow surface.

The amount of solar radiation incident on a horizontal plane is known as *insolation*. The insolation at the outer limits of the earth's atmosphere may be calculated for a given time and location from the solar constant (1.94 cal/cm^2/min), the time of year, the local latitude, and the sun's hour angle. The amount of this radiation to reach the snow surface, however, depends on a variety of factors including the transparency of the earth's atmosphere. The type of clouds and cloud cover, the slope and aspect of the terrain, and the effects of vegetal cover. The complex way in which these factors interact to influence the insolation over a snowpack make its theoretical computation somewhat uncertain, so direct measurement with pyrheliometers is desirable where possible.

The effect of the transparency of the earth's atmosphere can be taken into account by the use of an atmospheric *transmission coefficient* which is defined as the ratio of the insolation at the earth's surface under cloudless skies to the insolation received at the outer limits of the atmosphere. The value of this coefficient will vary slightly with time and location, but it has been estimated[1] to generally be in the range of 0.80 to 0.90.

The largest source of variation in the portion of solar radiation transmitted through the atmosphere is the result of the absorbtion and scattering due to clouds. This effect is dependent on the type, height, density, and amount of cloud cover. The following relationship has been used to account for the effect of clouds[5]:

$$\frac{I}{I_c} = 1 - (1-k_s)N \tag{3.3}$$

where:

I = average insolation received at earth's surface

I_c = average insolation received at earth's surface under cloudless skies

k_s = solar radiation cloud constant

N = cloud cover in tenths

The value of the parameter k_s is shown in Table 3.1 for various types of clouds.

The effect of forest cover is another important but complex factor influencing the insolation received by the pack. Such variables as tree type, density, and spacing will vary widely with location, but for fairly uniform coniferous cover as is typical in many important catchment areas, correlations with forest canopy density have been developed.[5] Such a relationship is shown in Figure 3.3.

Although the effects of slope and aspect can be theoretically computed on the basis of the geometry of the surface, the problem

Table 3.1

Variation of Radiation Constants with Cloud Type

Cloud Type	Index	k_s	k_l
Clear Sky	0	1.0	0.0
Thin Cirrus Veils			
Cirrus (C_i)	1	0.80-0.85	0.25
High Thin Clouds			
Cirro-stratus (C_s)	2	0.65-0.85	0.50
Alto-cumulus (A_c)	3	0.45-0.50	
Alto-stratus (A_s)	4	0.40	
Low Thick Clouds			
Strato-cumulus (S_c)	5	0.30-0.35	0.75
Stratus (S_t)	6	0.25	
Nimbo-stratus (N_s)	7	0.15-0.25	

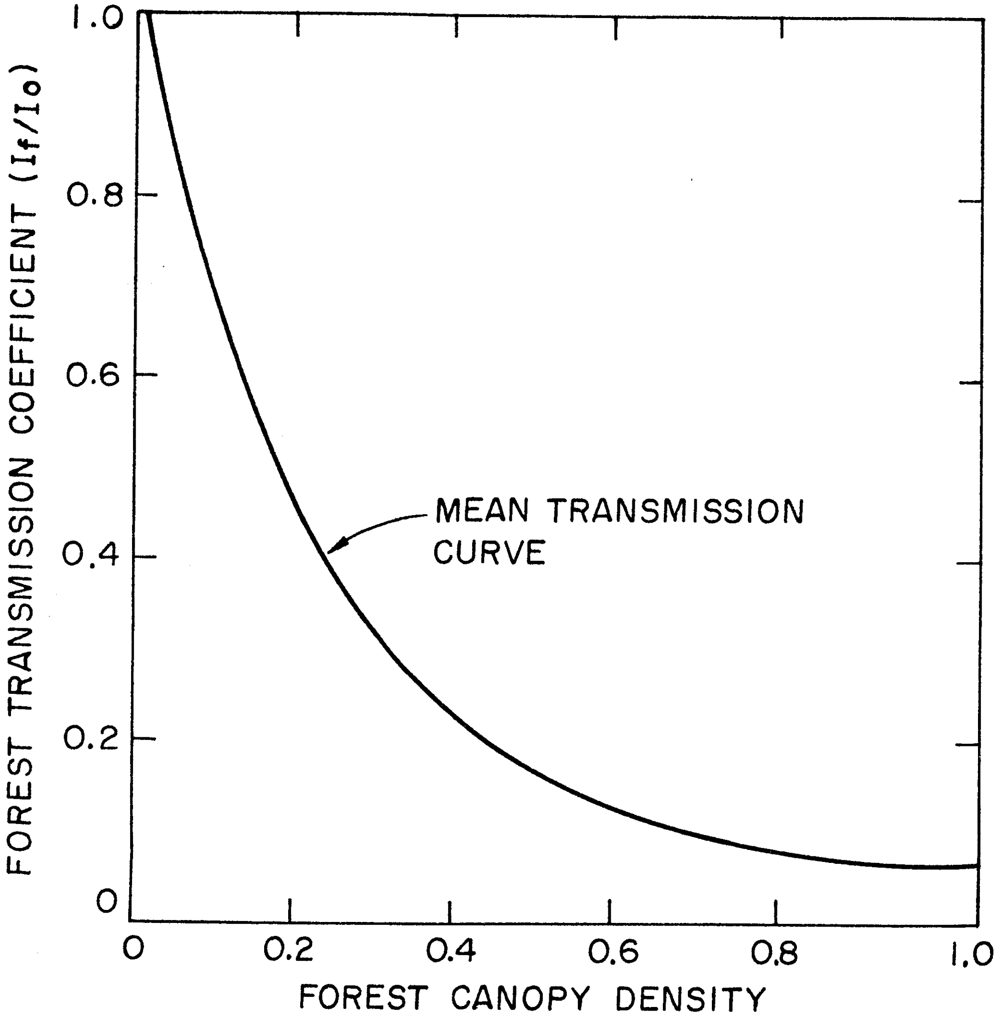

Figure 3.3 Transmission of Insolation by a Coniferous Forest Canopy (U.S. Army Corps of Engineers, 1956)

becomes very complex for the irregular configurations of most basins so no general relationships have been developed to take these effects into account.

Once the incident solar radiation that reaches the snow surface has been estimated, it becomes necessary to determine the amount of it that is actually absorbed by the pack. The *albedo* of the snow is defined as the ratio of the reflected solar radiation to the incident solar radiation. This quantity varies between a maximum of about 0.85 for a new snow surface to a minimum of about 0.40 for an old, weathered surface. Figure 3.4 illustrates this variation with the age of the snow surface.

Net Longwave Radiation, H_{rl}

The net longwave radiation exchange between the snowpack and its environment is the difference between the longwave radiation emitted by the snowpack surface and the longwave radiation emitted by the earth's atmosphere, the clouds, and the vegetal cover that is absorbed by the snowpack. The methods for evaluating these effects will be discussed in the following paragraphs.

With respect to longwave radiation, snow behaves very nearly as a black body, absorbing all such radiation and emitting in accordance with Stephan's law. The reason for this is the large surface area due to the crystalline nature of the exposed snow. The longwave radiation emitted by the snow is therefore,

$$R_s = \sigma T_s^4 \qquad (3.4)$$

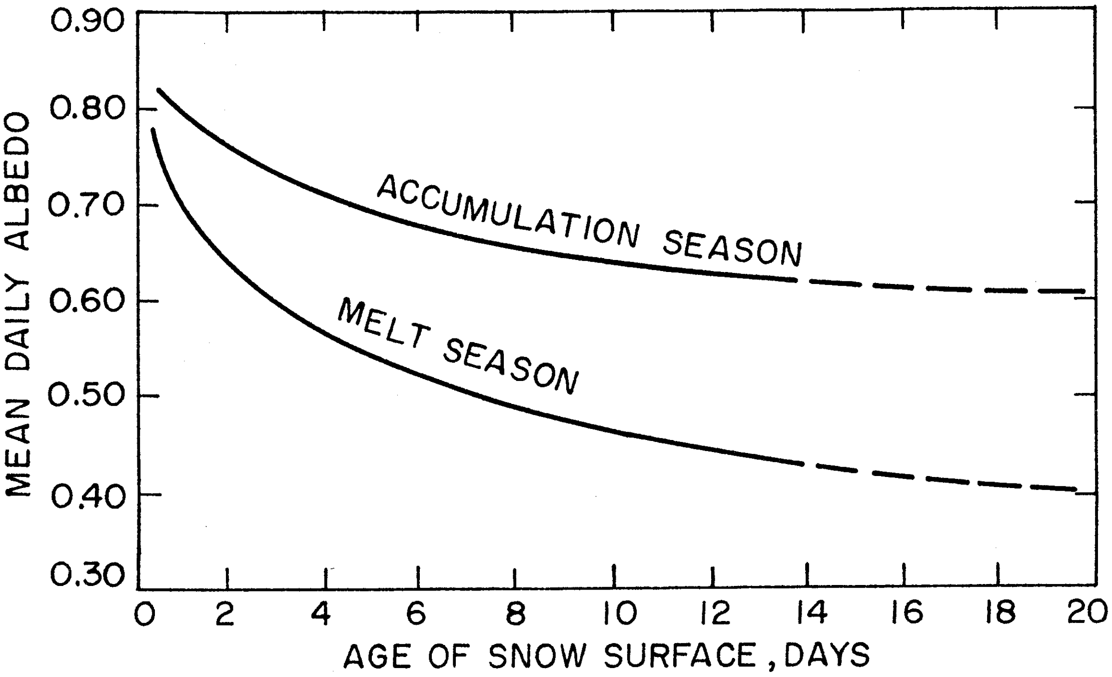

Figure 3.4 Time Variation in Albedo of a Snow Surface (U.S. Army Corps of Engineers, 1956)

where T_s is the surface temperature of the snow in degrees Kelvin and σ is the Stephan-Boltzmann constant (0.826×10^{-10} cal/cm^2/min/°K^4).

The earth's atmosphere does not behave as a black body with respect to longwave radiation due to the variable absorption and emission that are dependent mainly on the amount of water vapor in the atmosphere. Investigations[5] have shown, however, that the longwave radiation from the atmosphere under cloudless skies is related to its theoretical black body radiation (computed on the basis of the surface air temperature) by a factor of 0.757 which is almost constant over the usual range of vapor pressure over a snowpack. Therefore, the longwave radiation emitted by the atmosphere under cloudless skies is given by:

$$R_a = 0.757\ \sigma\ T_a^{\ 4} \qquad (3.5)$$

where T_a is the surface air temperature in degrees Kelvin.

Due to the dominant effect of clouds on longwave radiation the above relation does not hold for cloudy conditions. Clouds, like snow, are considered as black bodies with respect to longwave radiation, so if the skies are overcast and the effects of forest cover are not considered, the net longwave radiation exchange between the snowpack and its environment can be expressed according to Stephan's law as:

$$R_{net} = \sigma\ (T_c^{\ 4} - T_s^{\ 4}) \qquad (3.6)$$

where T_c is the cloud base temperature in degrees Kelvin. If the skies are partially covered the net longwave radiation exchange can be approximated[5] by the expression:

$$R_c = (0.757\ \sigma T_a^{\ 4} - \sigma T_s^{\ 4}) \cdot (1 - k_1 N) \qquad (3.7)$$

where k_1 is the constant given in Table 3.1 for various types of clouds and N is the cloud cover in tenths.

A solid forest canopy also approximates a black body with respect to the emission of longwave radiation, so again from Stephan's Law, the net longwave radiation exchange between a solid forest cover and the snowpack can be represented by the equation;

$$R_f = \sigma(T_a{}^4 - T_s{}^4) \tag{3.8}$$

For partial forest cover an approximate representation of the total net longwave radiation can be made by dividing the forested area into canopy free surfaces and forest covered areas. Thus the general expression is

$$H_{rl} = F \cdot R_f + (1-F)R_c \tag{3.9}$$

where F is the forest canopy density and R_f and R_c are given by Equations 3.8 and 3.9 respectively.

Convective Heat Transfer from the Air, H_{cv}

By applying the basic equation of turbulent exchange, together with a power-law distribution for the variation of a given air property with height, and assuming a linear variation of the air exchange coefficient with wind velocity, the following equation for turbulent exchange was derived[5];

$$q = k/n \ (Z_a Z_b)^{-\frac{1}{n}} g_a V_b \tag{3.10}$$

where q is the rate exchange of the air property through a unit horizontal area, g_a is the gradient of a related property, V_b is the wind velocity, Z_a and Z_b are the heights of measurement of g_a and V_b respectively, k is a coefficient of proportionality and n is the exponent of the power-law distribution.

If the heat of convection is considered as a turbulent exchange process, the related air property, g_a, that is introduced into Equation 3.10 is the air temperature gradient. Therefore, introducing the specific heat of air, c_a, to convert to heat units, the heat of convection is:

$$H_{cv} = \frac{k_1}{n} c_a (Z_a Z_b)^{-\frac{1}{n}} (T_a - T_s) V_b \tag{3.11}$$

where T_a is the air temperature measured at height Z_a and T_s is the snow surface temperature.

Heat of Condensation, H_{cn}

Heat of condensation is transferred to the snowpack when moist air condenses on it. This is also a turbulent exchange process where the proper air property to be used in Equation 3.10 is the specific humidity gradient which is given by the expression:

$$g_a = \frac{0.622}{p} e \tag{3.12}$$

where e is the vapor pressure difference and p is the ambient air pressure. From this it can be said that the moisture transfer will be given by:

$$q = \frac{k_2}{n} \left(\frac{0.622}{p}\right) (Z_a Z_b)^{-\frac{1}{n}} (e_a - e_s) V_b \tag{3.13}$$

where e_a is the vapor pressure measured at height Z_a and e_s is the vapor pressure at the snow surface. Since for every gram of water condensed, 597 cal of heat are released, the following gives the heat of condensation:

$$H_{cn} = 597 \frac{k_2}{n} \left[\frac{.622}{p}\right] (Z_a Z_b)^{-\frac{1}{n}} (e_a - e_s) V_b \qquad (3.14)$$

If the vapor pressure gradient is reversed (i.e., $e_s > e_a$) evaporation and/or sublimation of the snow will occur and the snowpack will lose heat.

Heat Content of Precipitation, H_p

If the precipitation falls as rain, it must be cooled to the snow temperature. If the amount of rain, P, is measured in inches; if its temperature is T_r while the snowpack is at T_p; and if c_p is the specific heat of water (1.0 cal/g/°C): then the heat given off by the rain is given by

$$H_p = 2.54\ c_p \cdot \frac{5}{9} \cdot (T_r - T_p)P$$

$$= 1.41\ (T_r - T_p)P \qquad (3.15)$$

Similarly if the precipitation falls as snow its temperature must be changed to equal the pack temperature. In this case the heat gained or lost by the pack will be:

$$H_p = 2.54\ c_s \cdot \frac{5}{9} \cdot (T_s - T_p)P$$

$$= 0.715\ (T_s - T_p)P \qquad (3.16)$$

where c_s is the specific heat of snow (0.5 cal/g/°C), T_s is the snow temperature, and P is its water equivalent.

Heat of Conduction from the Soil, H_g

The heat given off by the soil to the snow is proportional to the product of the thermal conductivity, K, of the soil and the temperature gradient across the interface, as expressed in the following equation,

$$H_g = K \frac{dt}{dz} \tag{3.17}$$

Neither K nor $\frac{dt}{dz}$ remain constant over the snow season and both are difficult to determine, so generally a constant value of ground melt over a season is assumed.

3.4 Snow Metamorphasis

As mentioned earlier, all of the heat components discussed in the previous section contribute to the weathering of the snowpack. But this aging is a highly complex process in which the heat exchange at the surface is only a part. Other factors that contribute are the weight of the new snow compressing that underneath, the percolation of rain or melt water through the pack, the transfer of water vapor within the pack, and the constantly varying influence of the wind. All of these effects combine over a period of time to produce significant changes in the properties of the snowpack. Changes in density, liquid water holding capacity, water permeability, and internal temperature are the most important hydrologically.

As the season progresses the combined influence of these weathering effects is to produce a snowpack which becomes increasingly uniform throughout its depth. Its density and liquid water content increase and its temperature approaches the melting point. The result of these changes is what is termed a *ripe* pack - one which has a uniform granular structure, high density, its liquid water holding capacity satisfied, and a uniform temperature of 32°F.

Even having once reached a state of ripeness, the surface of the pack will at times be sufficiently cooled to produce freezing of the liquid water held near the surface. This comes about particularly with the formation of what is commonly known as *nocturnal snow crusts*. Because the clear cold nights of spring allow ideal conditions for the rapid loss of heat, these crusts occur frequently, even following warm days. Although the penetration is usually only a few inches below the surface, they do represent a heat deficit that must be restored before melting can resume. Also, the alternate freezing and thawing cycles tend to enhance the aging process by gradually changing the crystal structure of the snow.

The significance of the aging process is that a ripe pack is more responsive to heat input, and as a result melting of the snow can occur rapidly.

3.5 Calculation of the Melt

The above discussion demonstrates the intricate processes that are continuously occurring from the time the snow is deposited on the ground until it melts, percolates to the bottom of the pack, and enters the runoff phase of the cycle.

But as noted, in order for melt to occur the snow must be at its melting point of 32°F. Throughout much of the accumulation season, and during periods of crusts, the pack or at least its surface may be at sub-freezing temperatures. This represents a heat deficit that must be made up by a net heat input before melting can occur. The whole process by which a sub-freezing pack is elevated to its melting point causes many internal heat transfers to be set up as the surface snow melts, percolates, refreezes, etc. The details of these processes would be very difficult to analyze individually due to the frequent change of state and physical properties of the snow. Therefore, the common procedure is to consider heat deficits explicitly by employing the concept of the *cold content* of the pack, which can be evaluated in terms of the temperature of the pack and its density.

Cold Content

The cold content of a sub-freezing snowpack is defined as the amount of heat required to raise the temperature of the pack to 32°F. It is a common practice to express this heat requirement as inches of liquid water at 32°F which upon freezing will release this quantity of heat through its heat of fusion. The cold content, CC, expressed in this way is given by the equation

$$CC = .0003476\rho d(32-T) \tag{3.18}$$

where ρ is the snow density, d is the snow depth in inches and T is the average snow temperature in °F.

The General Melt Equation

A final property of snow that plays a role in the melting of snow is that of its *thermal quality*. This quantity is an indication of the amount of free liquid water (not included in the definition of free water is water which is held by adsorption and capillary forces, is in the process of percolating, or is impounded) that is being held by the pack. Thus a pack at 32°F may have free water in the range of zero to its liquid water holding capacity, depending on its past history. The thermal quality of snow is defined as the ratio of the amount of heat required to produce a given amount of water from the snow to that required to produce the same amount of water from pure ice at 32°F. It can be shown[9] that this ratio may be represented by the equation:

$$Q = \frac{L_{fs}}{L_f} + \frac{c_s T_p}{L_f} \tag{3.19}$$

where Q is the thermal quality of the snow, L_{fs} is the latent heat of fusion of the snow, L_f is the latent heat of fusion of pure ice, c_s is the specific heat of the snow, and T_p is the snow temperature in °C. Since L_f equals 80 cal/g and c_s is equal to 0.5 cal/g/°C, this can be written as:

$$Q = \frac{L_{fs}}{L_f} + 0.00347*(32-T_p) \tag{3.20}$$

where T_p is now in °F.

Having determined this quantity it can be reasoned that for an amount of heat, H, added per unit time to a snowpack at 32°F (since 80 cal/cm^2 are required to produce one centimeter of water from pure ice at 32°F), a general expression for the melting of snow is,

$$M = \frac{H}{80 \cdot Q} \quad \text{(cm)}$$

or

$$M = \frac{H}{80 \cdot 2.54 \cdot Q} \quad \text{(inches)} \qquad (3.21)$$

For a snowpack at sub-freezing temperatures, the heat given by Equation 3.2 must be first applied to eliminate the heat deficit (cold content). Any remaining heat after satisfying this requirement will produce melt in accordance to Equation 3.21.

3.6 Liquid Water Content and Time Delay to Runoff

A quantity that is closely related to the runoff that will result from the application of an amount of heat to a pack, as indicated in the above discussion, is the liquid water content of the snow. For a subfreezing pack the liquid water content is zero and for a melting pack it is limited by the *liquid water holding capacity*, which is defined as the maximum amount of free water the pack can hold against gravity. This liquid water holding capacity is determined by a number of complex factors, such as the nature of the crystal structure and degree of ripeness, and as such can not be expressed theoretically in terms of readily observed quantities. A large part of its variability can be accounted for, however, by empirical correlation with snowpack density.

The water content and water holding capacity of a snowpack are of great practical importance in that they are influential not only in determining the amount of runoff that will result from melt or rainfall, but also in the time delay between the beginning of melt (or rainfall) and the beginning of runoff. When water occurs at the surface of a pack as in the case of melt or rainfall it will begin to percolate through the pack to become runoff only when the liquid water content exceeds the holding capacity of the snow. Anderson[2] has studied the time required for water to percolate through a ripe pack of a given depth. Figure 3.5 illustrates the results of his findings.

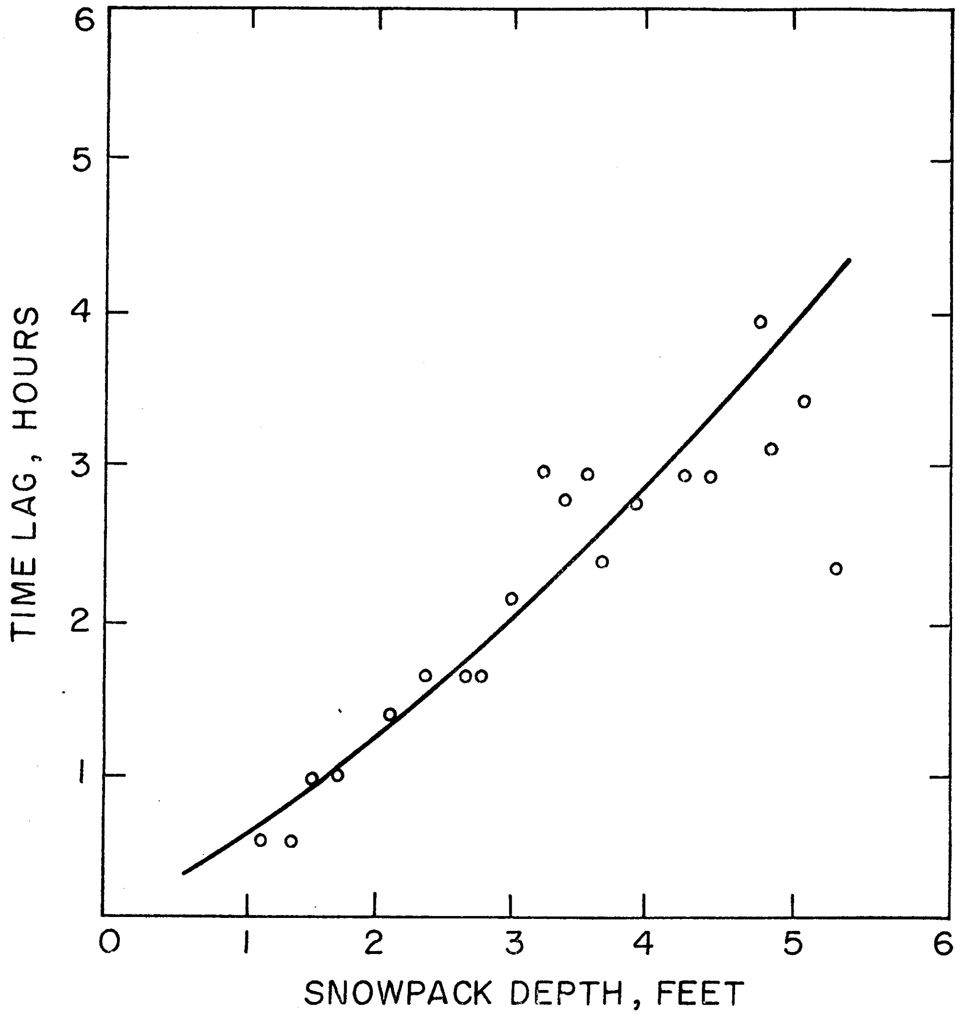

Figure 3.5 Time Lag for Routing Melt Water Through a Ripe Snowpack (Anderson, 1968)

Chapter 4

DEVELOPMENT OF THE SNOWMELT MODEL

4.1 Introduction

This chapter will discuss how the ideas and formulations presented in Chapter 3 were used in the development of a mathematical model to simulate snow accumulation and melting processes. These concepts will serve as a theoretical basis for the proper representation of the processes in model form and allow for an understanding and evaluation of any assumptions or modification that are necessary.

It is important to emphasize from the outset that the formulations discussed in Chapter 3 that represent the various processes are in general strictly applicable only to areas where there is no significant spacial variation in the important parameters. It has been adequately demonstrated in previous studies[1,3] using techniques similar to those used here, that these concepts represent small, uniform snowfields surrounding the measuring stations. Hence, the model assumes a lumped-parameter, equivalent system in which the model inputs (air temperature, precipitation, etc.) and snowpack parameters (depth, water equivalent, temperature, etc.) are assumed to be uniform over the area they represent. If an area is chosen for which this is not reasonably true, the accuracy of the results can be expected to be reduced. Thus, when it is desired to model an entire watershed in which the terrain features vary significantly, and the meterological conditions would not be expected to be uniform, it may be necessary to divide the basin into smaller units and perform the simulation on each segment, separately.

The objective of this chapter is then, to describe the model that was developed in this study and discuss how it relates to previous work. This will involve discussing how the concepts of Chapter 3 have been modified in light of practical hydrologic considerations, data availability, and efficiency of computation.

The approach taken to accomplish this will be first to discuss the general model of operation of the model. Attention is then narrowed to the snowmelt subroutine, the operation of which is represented in a basic block diagram illustrating the logical sequence in which the various processes are considered. Each process is first discussed in general terms, and then in detail, to establish how it fits into the model as a whole, how it interacts with other processes, and any assumptions that have been made.

The final sections of the chapter describe how the input is specified and prepared for use in the model and the output options that are available.

Before proceeding further, it is desirable to explain some of the terminology to be used throughout this chapter. The model developed in this study will be referred to simply as *the model*, or the snowmelt model, while the various subroutines composing it will always be referred to by name (e.g., the snowmelt subroutine, or

SUBROUTINE SNOW) where such a distinction is necessary. The model was designed to have considerable flexibility in both the *sampling interval* of the meteorological inputs, and the time step represented by the snowmelt computations. The latter will be referred to frequently herein as the *computation interval*. This computation interval may either be greater than, equal to, or less than the input data sampling interval.

4.2 Mode of Operation of the Model

Most of the discussion that follows in this chapter will deal with the detailed nature of SUBROUTINE SNOW, the subroutine that actually models the snow accumulation and melt processes. But before continuing with this, it is desirable to examine how this subroutine relates to others thay may be used in conjunction with it.

In most practical engineering problems requiring detailed estimates of snowmelt quantities, it is expected that the snowmelt subroutine will be used with several other subroutines that model other hydrologic occurrences of interest. In a situation where the estimation of streamflow hydrographs for a watershed is desired, for example, the other processes to be modelled might include; precipitation, infiltration, surface runoff, and channel flow. In a model involving all of these inter-related processes, it is likely that the subroutines would be linked together by an executive program with a data bank common to all the subroutines so that each routine, including the snowmelt subroutine would have ready access to all of its required input variables, and would store its output variables back in the data bank for easy access by other subroutines using these results.

For the purposes of this study the snowmelt subroutine was developed to be used as a part of a hydrologic systems model, but was actually used independently of other hydrologic processes for convenience in testing. Here, the input variables are read in directly, modified as required for use in the subroutine, and may be included in the output for future reference.

A general schematic diagram showing the component subroutines included in the model developed for this study is given in Figure 4.1. The main program, MAPR, controls the calling sequence of the various subroutines shown. Subroutines CONST, SDAT, and MDAT are used to input data and make any needed adjustments to the variables used by SUBROUTINE SNOW, as discussed in Section 4.5. SUBROUTINE PRMV may be called to output the adjusted meteorological variables as they are stored for use in the snowmelt subroutine. Several other output options may be called through SUBROUTINE OTPT as is discussed in Section 4.6. SUBROUTINE SNOW will be discussed in detail in the next two sections.

4.3 General Sequence of Operation of the Snowmelt Subroutine

Perhaps the best means of illustrating the major components of the snowmelt subroutine and how they interact is through the use of a block diagram as is shown in Figure 4.2. Here blocks representing inputs, decisions, calculations, or results are numbered for reference in the discussion which follows.

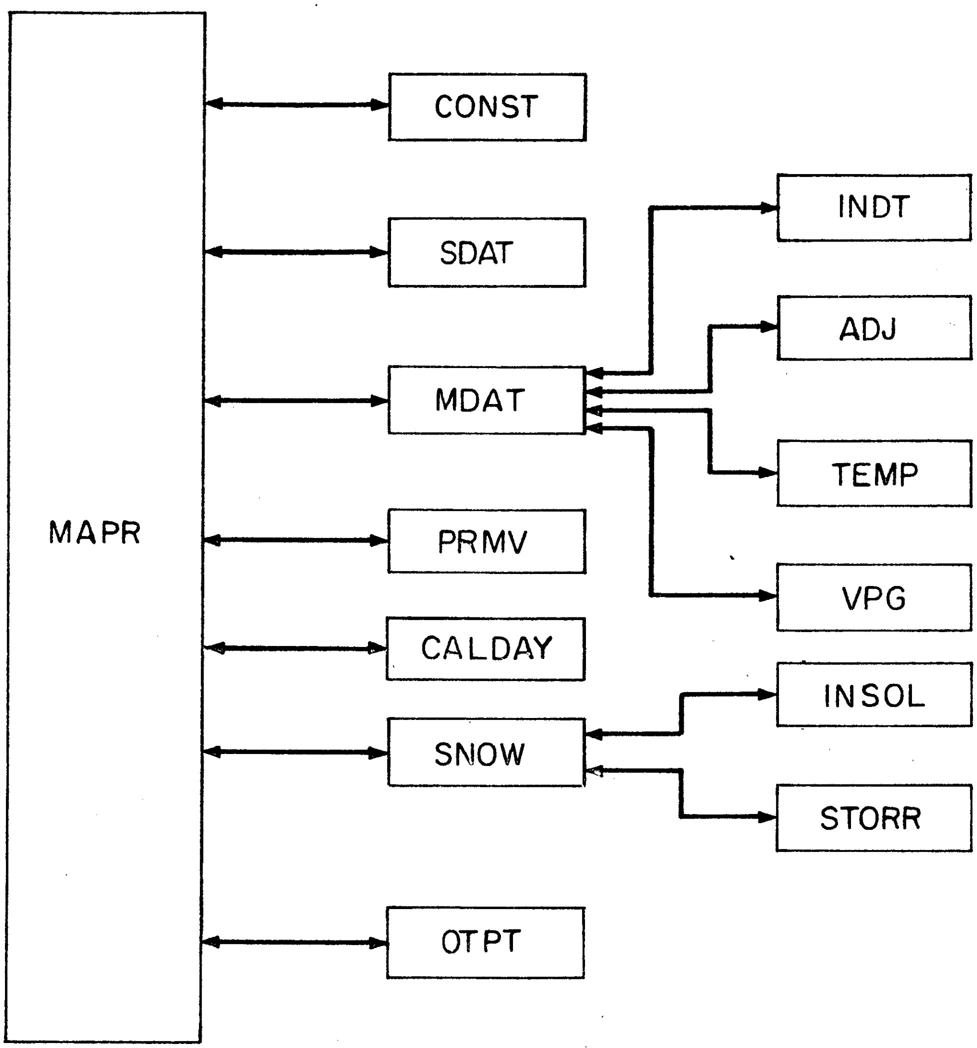

Figure 4.1 Component Subroutines of the Snowmelt Model

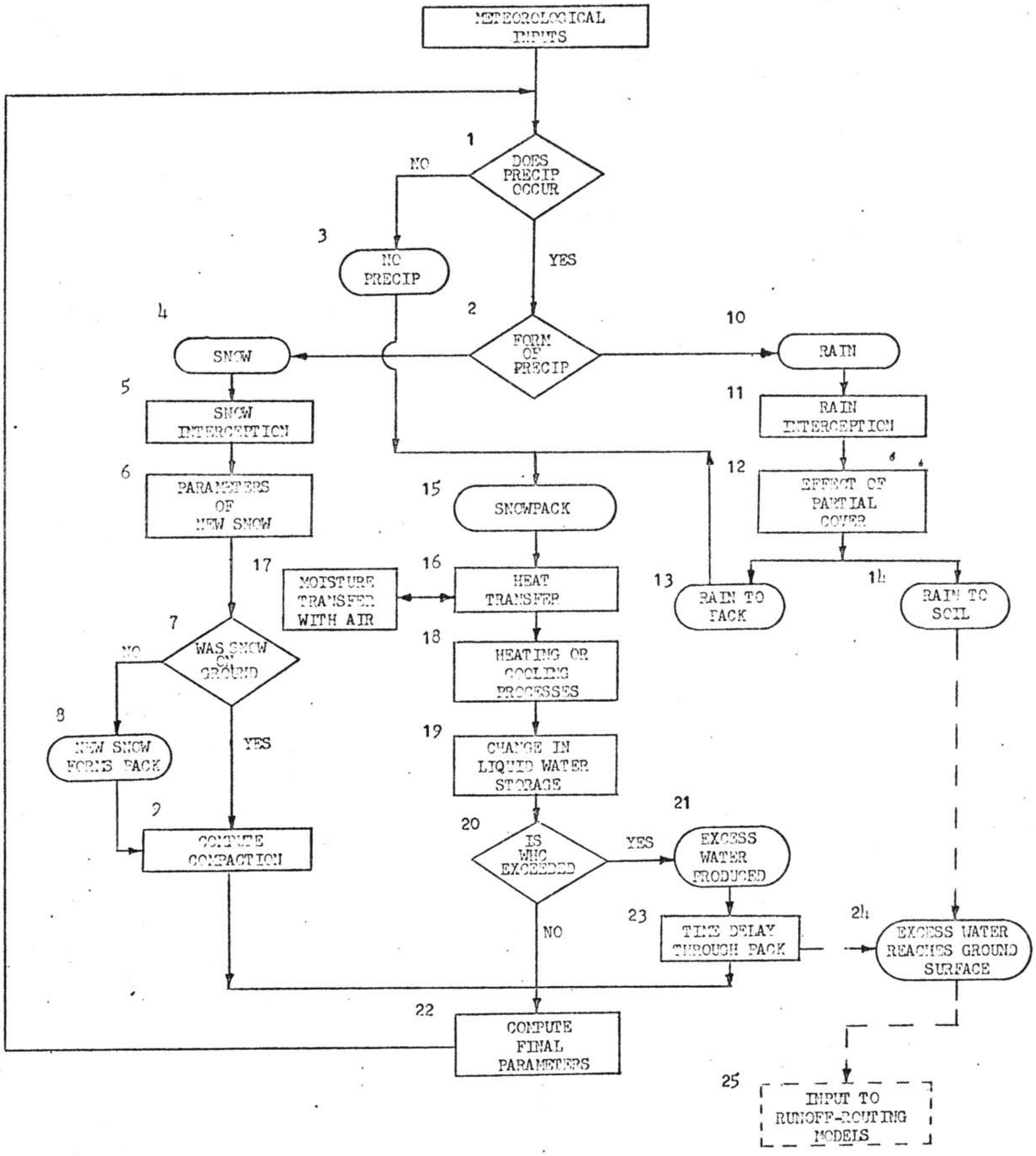

Figure 4.2 Block Diagram of the Snowmelt Model

In SUBROUTINE SNOW, the first operation required is to determine if precipitation has occurred during the present computation interval (Block 1). If not (Block 3), control passes to Block 15 where the effect of the atmospheric conditions on the snowpack may be determined immediately. Otherwise, if precipitation did occur, it is necessary to establish whether the precipitation was rain or snow (Block 2). This decision is made on the basis of the current air temperature as discussed in Chapter 3. In either case a certain portion of the precipitation is lost as the result of interception by vegetation (Blocks 5 and 11) and will eventually be returned to the atmosphere through evaporation.

For the situation where precipitation has occurred in the form of snow (Block 4) the subroutine first determines the parameters of the new snow (Block 6) such as its density, temperature, and heat content. If it is determined (Block 7) that there was no snow on the ground previously, then the new snow forms a new snowpack (Block 8) whose properties are those of the new snow. If on the other hand, there was snow on the ground previously, the existing snow will be compacted by the weight of the new snow. This compaction must be computed (Block 9) in order to determine the properties of the composite pack. Since conditions that accompany snowfall inhibit significant heat transfer between the pack and its environment, these properties of the composite pack represent the properties to be used at the start of the next time interval (Block 22).

When precipitation occurs as rain (Block 10), the effect of the extent of the snow cover must be considered (Block 12) to determine the distribution of rain to the snowpack and to bare ground (Blocks 13 and 14). Rain falling directly on bare ground immediately begins to runoff. That falling on the snowcovered portion of the catchment is added to the snowpack (Block 15), and its effect must be considered in the melt portion of the model.

The only place where the model uses significantly different procedures depending on the different alternative input data forms is in the computation of the net heat transfer to the pack (Block 16) and the net moisture transfer with the air (Block 17). One approach utilizes a temperature index to determine the effective heat transfer and evaporation potential for moisture transfer. When detailed meteorological data are given, for more detailed data these quantities are computed directly from the energy transfer relationships.

Once the net heat transfer has been computed, the effect of this heat on the pack depends on its deficit (Block 18). A positive heat transfer (heat added to the pack) will reduce this deficit or be applied to produce melting, while a negative heat transfer (heat removed) will be used to freeze any liquid water present and increase the heat deficit. Depending on the heat transfer, the appropriate change in liquid water storage of the pack may be determined (Block 19). If this change results in the liquid water holding capacity being reached (Block 20), any additional water produced (Block 21) will begin to percolate through the pack to become runoff. The time required for the penetration of this water is computed (Block 23) in order to determine the excess water reaching the ground surface (Block 24) during this computation interval. This water is then used as input in existing runoff and routing models (Block 25) to determine the resulting streamflow. The final step in each interval is to compute new snowpack parameters (Block 22), based on the changes that have occurred.

4.4 Snow Accumulation and Melt Processes as Represented in the Snowmelt Subroutine

The mathematical expressions incorporated in the snowmelt subroutine are discussed in this section. Since one of the principle reasons for building this particular model was to permit snowmelt computations to be made for a wide range of input data availability, particular attention is given here to the approach taken to accomplish this objective.

Mathematical representations of the snowmelt process are typically classified as either heat budget methods or temperature index methods. The distinctions involve, primarily, the way in which the available meteorological data is utilized to estimate the heat flux across the air-snow interface. In general, the heat budget approach is used where possible, because this theory is believed to represent reality more closely, and gives more reliable results. Data limitations, however, may necessitate the use of temperature index methods, which have been demonstrated, to give acceptable results also.

The other processes occurring, such as snow accumulation, heat effects on the snow, and liquid water storage, are not affected by the method used to determine the heat transfer; so the techniques used to model these processes do not need to vary for different data inputs.

4.4.1 Elevation Effects

As noted in Section 3.2, elevation plays a very significant role in the spatial variability of several important aspects of the snow accumulation process. It has been established that, in general, the relationships developed in Chapter 3 are valid only for areas that may be considered uniform. Practical modelling considerations for most watersheds, however, require the extension of these concepts to large areas that are not quite uniform. Recorded meteorological conditions may not be representative of the entire area, a fact which may account for differences between actual and computed melt rates. Thus it is necessary to be able to define average snowpack parameters and average meteorological conditions that adequately represent an area as a whole. Spatial variation, due to elevation effects, of variables such as air temperature, precipitation, and snow water equivalent may be accounted for in the following way.

The temperature of the air over the snowpack varies with elevation according to its *ambient lapse rate*. In the model this lapse rate, ALR, is assumed to vary between a dry-adiabatic lapse rate and a saturated-adiabatic lapse depending on the time since the last precipitation occurrence. The further assumption is that of a dry-adiabatic lapse rate varying from -4°F per 1000 feet during the day to 0°F per 1000 feet at night, and a saturated-adiabatic lapse rate of

-3.3°F per 1000 feet. These values have been used by Anderson and Crawford (1964) to adjust both the surface air temperature and the dew point temperature of the air for elevation effects.

The precipitation is generally greater at higher elevations due to orographic cooling effects. This variation is subject to a great number of variables and is difficult to evalute theoretically. It has been proposed[3] that this effect can be estimated adequately by determining the ratio of the average precipitation over the area to the average precipitation at the measuring gage. This factor, PF, applied to each occurrence of precipitation as measured at the gage, will account for the variation of precipitation with elevation in an approximate way.

The water equivalent of a snowpack generally increases with elevation due to the effects of lower temperatures and greater depths of precipitation at higher elevations. This can lead to a condition, especially late in the melt season, where part of the area is not snow covered. Rain falling on the ground immediately becomes available as surface runoff and need not be considered in the snowmelt calculations. On the other hand, it is important to note that any heat transfer within the area must be accounted for only on the snow covered portion. Thus it is necessary to be able to estimate the areal extent of snow cover. For this purpose an areal depletion curve, which relates the extent of snow cover to average snowpack water equivalent, has been used.[2] It has a shape, for most watersheds, similar to that shown in Figure 4.3. When the area's snowpack water equivalent is greater than

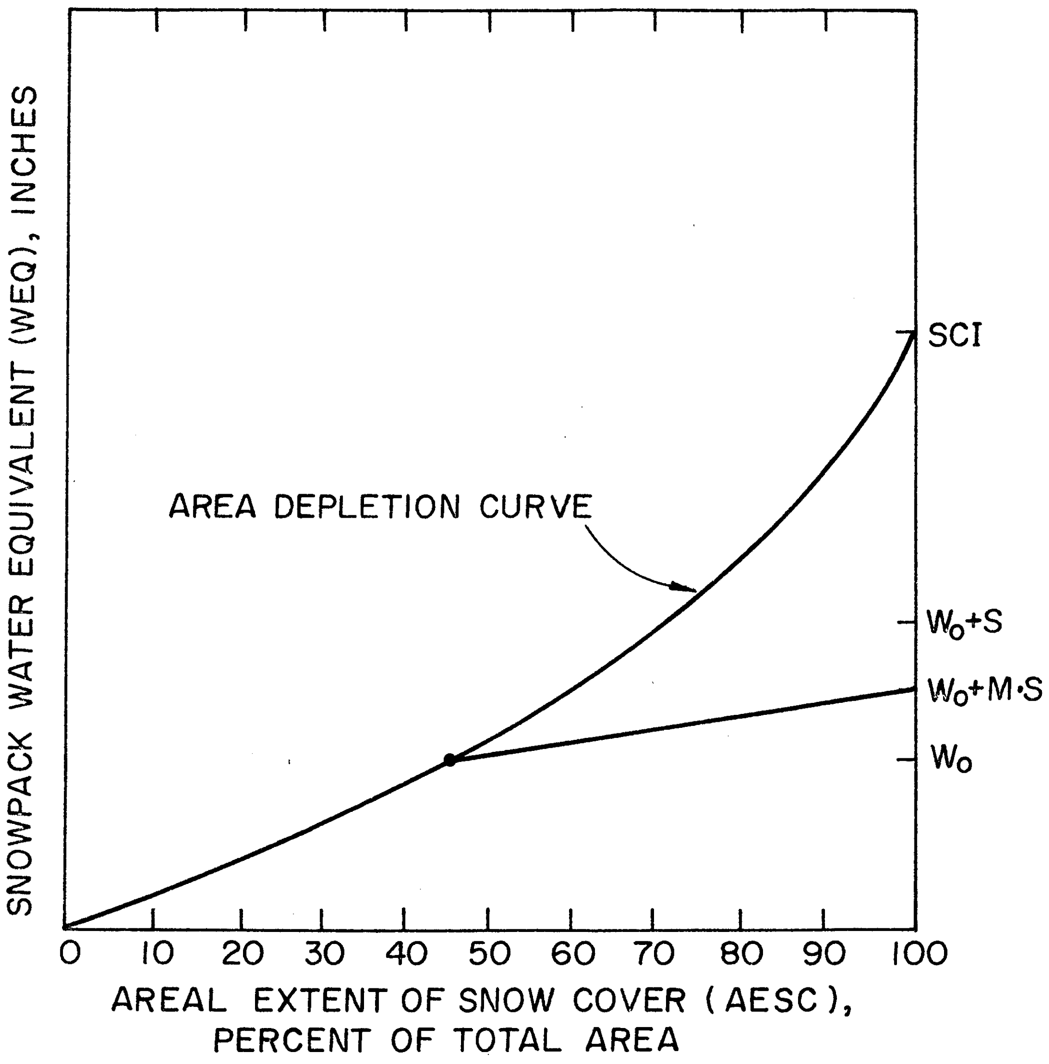

Figure 4.3 Areal Depletion Curve for Watershed Snow Cover (Anderson, 1968)

an index value, SCI, total cover is assumed. When the water equivalent is less than, SCI, the areal extent of snow cover, AESC, may be determined from the following expression for the curve of Figure 4.3:

$$\text{AESC} = \frac{\log(\text{WEQ}+1.0)}{\log(\text{SCI}+1.0)} \tag{4.1}$$

If snowfall occurs during a period of partial cover, the area reverts back to complete cover, at least for a short time. In this case the area is assumed to have complete cover while the water equivalent is greater than $W_0 + M \cdot S$, where W_0 is the water equivalent before the new snow (S) occurred and M is the portion of S that must melt before partial cover again exists. When the water equivalent is between W_0 and $W_0 + M \cdot S$, the areal cover is assumed to vary linearly between 100% and its value before the new snowfall.

4.4.2 Snow Accumulation

In order to keep proper account of changes in snow depth and the related snowpack parameters, it is important to have a reliable means of determining the form of precipitation when it occurs. Direct observation would satisfy this requirement best, but this kind of data is not likely to be kept over an entire watershed. Therefore, it is more practical to employ an index temperature, as discussed in Section 3.2, to differentiate rain from snow. In the model, PTI, the selected precipitation temperature index is an input variable, as it may vary from place to place. A suggested range for this value is 32°F to 35°F.

In areas where there is forest cover, some precipitation is intercepted by the trees as it falls and never reaches the ground. This portion of the precipitation will eventually be lost to evaporation and does not enter into snowmelt considerations. Studies[5] have shown that this loss is directly proportional to the forest canopy density and decreases as the storm progresses.

Due to lack of data on interception losses the model assumes that the interception loss is equal to a constant portion of the precipitation that occurs and that this interception constant is the same throughout the storm. Further, it is assumed that the interception loss for an area as a whole may be determined from the *effective forest cover*, which is the net forest cover (percent of total area) times the forest canopy density. Thus interception is given by,

$$I = K' * EFC * PPT \tag{4.2}$$

where K' is the interception constant for the given form of precipitation, EFC is the effective forest cover, and PPT is the amount of precipitation in inches.

To determine the effect of an accumulation of new snow on the parameters of an existing snowpack, it is necessary to estimate the *density*, *liquid water content*, and *temperature* of the newly fallen snow.

The *density* of the new snow has been expressed[3] in terms of the surface air temperature by the following relationships:

$$\begin{aligned} DNS &= 0.05 + (TA/100)^2 \quad , \text{ for } TA > 0°F \\ DNS &= 0.05 \quad , \text{ for } TA \leq 0°F \end{aligned} \tag{4.3}$$

where DNS is the density of the new snow in percent of that of pure ice and TA is the surface air temperature in °F. This relationship is shown in Figure 4.4. The *temperature* of the new snow, TNS, is also estimated using the surface air temperature by assuming that they are equal,

$$\mathrm{TNS} = \mathrm{TA} \tag{4.4}$$

The *liquid water content* of the new snow was assumed to be zero, thus neglecting the situation of mixture of snow and water known to occur frequently (Figure 3.1). This simplification was necessary due to the wide range of temperatures over which a mixture can occur and the lack of another suitable index for this purpose.

Having estimated these quantities it is then possible to determine the depth of the new snow and its cold content by means of the following relationships:

$$\mathrm{DPNS} = \mathrm{PPT}/\mathrm{DNS} \tag{4.5}$$

where DPNS is the depth of the new snow and PPT is the water equivalent of the snowfall, and

$$\begin{aligned} \mathrm{CCNS} &= 0.00347 * \mathrm{DPNS} * \mathrm{DNS} * (32-\mathrm{TNS}), \\ &\qquad \text{for TNS} < 32°\mathrm{F} \\ \mathrm{CCNS} &= 0.0 \quad , \quad \text{for TNS} \geq 32°\mathrm{F} \end{aligned} \tag{4.6}$$

where CCNS is the cold content of the new snow.

The effect of the new snow on that beneath will be to compact it, as discussed in Section 3.2. An empirical formula that

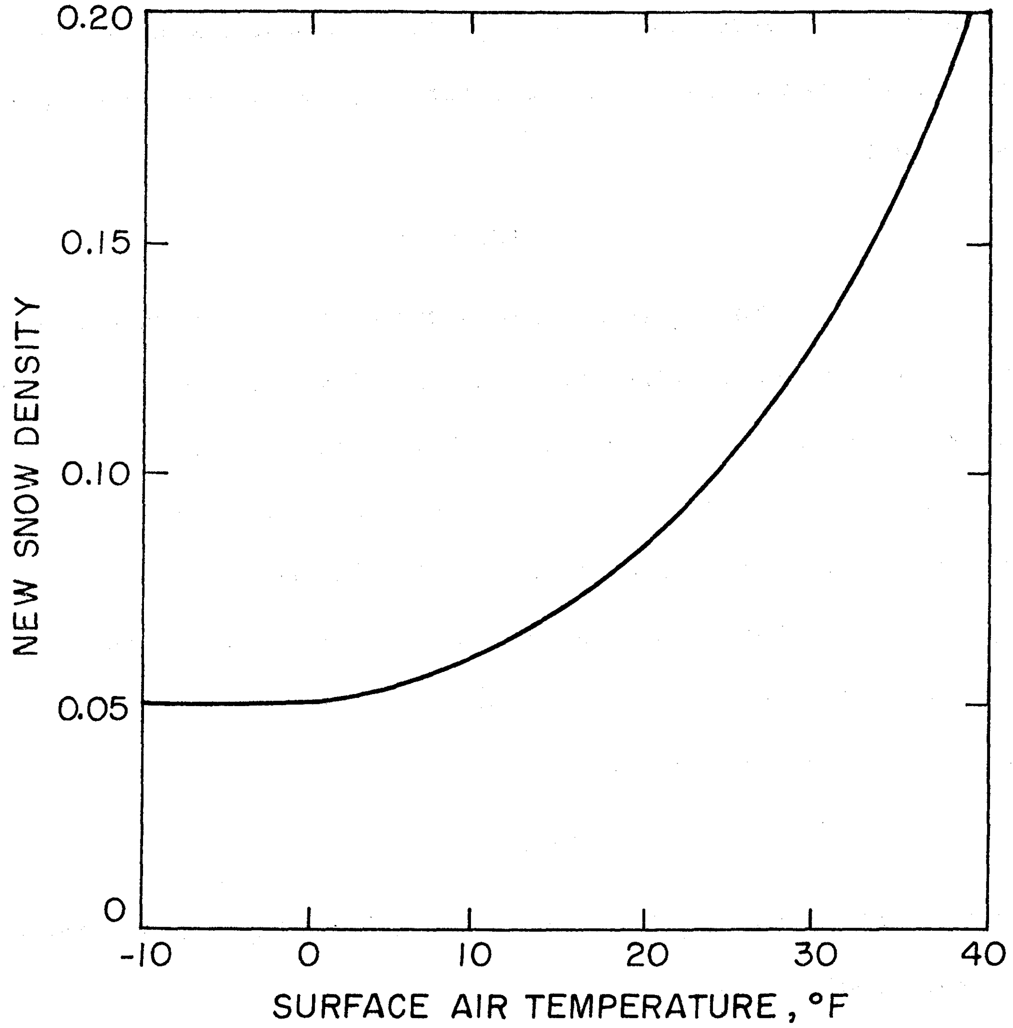

Figure 4.4 Correlation of New Snow Density with Surface Air Temperature (Anderson and Crawford, 1964)

has been used to determine this effect is the following[3]:

$$\text{REDUCT} = \frac{\text{PPT} * \text{DP}}{\text{WEQ}} \left(\frac{\text{DP}}{10}\right)^{.35} \tag{4.7}$$

where REDUCT is the reduction in depth of the old pack due to compaction, DP was its depth, and WEQ was its water equivalent.

From this and the new snow parameters, the parameters of the resulting snowpack can be computed from the following:

$$\text{DP} = \text{DP}' - \text{REDUCT} + \text{DPNS} \tag{4.8}$$

$$\text{WEQ} = \text{WEQ}' + \text{PPT} \tag{4.9}$$

$$\text{DN} = \text{WEQ}/\text{DP} \tag{4.10}$$

$$\text{CC} = \text{CC}' + \text{CCNS} \tag{4.11}$$

DN is the density of the snow. The primed quantities represent values before the addition of the new snow, and those unprimed are for the resultant snowpack.

4.4.3 Heat Budget Processes

It was noted in Section 4.3 that the major procedural differences utilized in the model for different types of data occur in the computation of the net snowpack heat transfer and evaporation. This section will discuss the heat budget method for determining these quantities and the data requirements for its use. The theoretical basis for the computation of a heat budget was developed in Section 3.3. In the notation of the model, Equation 3.2 appears as

$$\text{HT} = \text{HRS} + \text{HRL} + \text{HCV} + \text{HCN} + \text{HP} + \text{HG} \tag{4.12}$$

The techniques for estimating each component of the heat budget as used in the model will be presented in the following paragraphs.

The most reliable means of determining the *incident shortwave radiation* for a given set of conditions is direct measurement of this value with a pyrheliometer. These measurements can be input directly into the model as the variable, HRS'. In the absence of such data, the incident solar radiation may be estimated for a given location and time from the *solar constant*, W_B(116.3 langleys/hr), the *solar attitude*, α, and the cloud conditions. The insolation received at the outer limits of the earth's atmosphere, SRO, in langleys/hr, is given by

$$SRO = W_B \sin \alpha = 116.3 \cdot \sin \alpha \qquad (4.13)$$

where α is given from spherical trigonometry[9] by

$$\sin \alpha = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \tau \qquad (4.14)$$

in which δ is the declination, τ the sun's hour angle, and ϕ is the local latitude. The model uses these relationships to compute SRO for each computation interval.

The effect of the transparency of the earth's atmosphere is accounted for by assuming an atmospheric transmission coefficient of 0.90. The effect of clouds, on the other hand, is found from Equation 3.3. Thus, having passed through the atmosphere, the insolation reaching the earth's surface, HRS', in langleys/hr, will be given by

$$HRS' = 0.9 * (1-(1-CKS) * CN) * SRO \tag{4.15}$$

where CKS is the value of k_s from Table 3.1 for the given cloud types and CN is the cloud cover in tenths.

The amount of solar radiation that will actually be absorbed by the snow is dependent on how much of it will be reflected and how much will be absorbed by forest cover. These effects are modelled using the snowpack albedo and forest transmission coefficient respectively, as defined earlier. The albedo of a snowpack is believed to vary with the age of its surface according to Figure 3.4. These curves have been represented in the following form[2]:

$$ALB = m(n)^{TX^g} \tag{4.16}$$

where ALB is the snowpack albedo, TX is the age of the snow surface in days and m, n, and g are fitting constants. It was found that the curves of Figure 3.4 may be well represented by

$$\begin{aligned} ALB &= 0.85(0.94)^{(TX)^{0.58}} &&\text{, for the accumulation season} \\ ALB &= 0.85(0.82)^{(TX)^{0.46}} &&\text{, for the melt season} \end{aligned} \tag{4.17}$$

The forest transmission coefficient varies with the forest canopy density according to Figure 3.3. If the effective forest canopy density is defined as in Equation 4.2, then the forest transmission coefficient is given by

$$FTC = (10. * EFC + 1.)^{-1} \tag{4.18}$$

The absorbed shortwave radiation is given by:

$$HRS = FTC * HRS' * (1-ALB) \qquad (4.19)$$

where HRS is the absorbed short wave radiation in langleys/hr, and HRS' is the incident short wave radiation.

To determine the *net longwave radiation* exchange between the snowpack and its environment, the estimations of Equations 3.7, 3.8, and 3.9 are used. In the notation of the model, these are:

$$RC = (0.757 * SIG * TAK^4 - SIG * TSK^4)(1-CKL * CN) \qquad (4.20)$$

$$RF = SIG(TAK^4 - TSK^4) \qquad (4.21)$$

$$HRL = EFC * RF + (1-EFC) * RC \qquad (4.22)$$

where HRL is the net longwave radiation exchange in langleys/hr, where TAK is the surface air temperature in °K, TSK is the surface temperature of the snow in °K, SIG is the Stephan-Boltzmann constant (0.496×10^{-8} langleys/hr/°K), CKL is the value of k_1 from Table 3.1 for the given cloud type, CN is the cloud cover in tenths, and EFC is the effective forest cover.

The equation developed in Chapter 3 for the *heat of convection* was:

$$H_{cv} = \frac{k_1}{n} c_a (Z_a Z_b)^{-\frac{1}{n}} (T_a - T_s) V_b \qquad (4.23)$$

A value of n equal to 6 is commonly assumed. This equation was included in the model as

$$HCV = FCV * ZFCV * (TA-TS) * V \qquad (4.24)$$

where HCV is the convective heat transfer in langleys/hr, FCV is an estimate (see Reference 5) of the value of the expression $\frac{k_1}{n} c_a$ for the watershed in question, ZFCV is equal to $(Z_a Z_b)^{-1/6}$, and V is the average wind speed in mi/hr over the computation interval. For the Central Sierra Snow Laboratory (CSSL) the value of FCV has been estimated to be 0.0426.[1]

The model expression for the *heat of condensation* is based on Equation 3.14 which requires information regarding the partial pressure of water vapor in the atmosphere. The vapor pressure over a snowpack, however, is not a value that is commonly measured; thus it is desirable to express the vapor pressure gradient in terms of variables that are more likely to be observed. For the usual range of temperatures occurring over a snowpack, the vapor pressure gradient can be related to the dew point temperature of the air by the expression[5]:

$$(e_a - e_s) = 0.339(T_d - T_s) \qquad (4.25)$$

The heat transfer due to condensation is given by:

$$HCN = FCN * ZFCN * (TD-TS) * V \qquad (4.25)$$

where HCN is the condensation heat transfer in langleys/hr, FCN is an estimate (See Reference 5) of the value of the expression $597 \left(\frac{k2}{n}\right) \frac{0.622}{p}$ for the watershed in question, ZFCN is equal to $(Z_a Z_b)^{-1/6}$, and TD is the dew point temperature of the air. Again, for the CSSL, the value of FCN has been estimated to be 0.137.[1]

From this heat it is possible to determine the amount vapor that is transferred in the process from Equation 3.21:

$$QCN = \frac{HCN}{ALH * 2.54 * QT} \qquad (4.27)$$

where QCN is the vapor transfer in inches, ALH is the latent heat of vaporization (597 cal/g) for TS $\geq$ 32°F or the latent heat of sublimation (677 cal/g) for TS $<$ 32°F, and QT is the thermal quality of the snow. QCN is the amount of condensation if TD $>$ TS and it is the amount of evaporization (or sublimation) if TD $\leq$ TS.

If the precipitation falls as rain, the *heat content of precipitation* is represented by Equation 3.15 and in the model is given by

$$HP = 1.41 * (TW-32) * PPT \qquad (4.28)$$

where HP is the heat transfer in langleys and TW is the wet-bulb temperature of the air. The heat transfer due to precipitation falling as snow is accounted for in Equation 4.6.

Heat Transfer from the Ground

As discussed in relation to Equation 3.17, the variation of the thermal gradient of the soil beneath the snowpack over the course of the winter, prevents the use of an explicit equation to estimate the heat transfer from the ground. In the model the *heat transfer from the ground* is assumed to be constant throughout the snow season and equal to the input variable, GH. This value has been estimated[1] to be about 0.17 langleys/hr based on actual measurements at the CSSL.

4.4.4 Temperature Index Method

In situations where there is not sufficient data to use the more rational heat budget procedures for estimating the *heat transfer*, the temperature of the air may be used as an index of this heat transfer.

This was the approach taken in the early attempts to forecast snowmelt, usually by estimating the melt occurring directly from the air temperature through a constant melt factor according to an expression such as:

$$m = (T_a - T_i) \cdot f \qquad (4.29)$$

where m is the estimate of the melt produced in the interval, T_a is the mean air temperature, T_i is the index temperature, usually selected as 32°F, and f is the factor indicating the melt produced per degree that T_a exceeds T_i. It is assumed that whenever T_a is greater than T_i melt is produced and for T_a less than T_i no melt is produced. It is known that this is not actually the case since intense shortwave radiation on a clear winter day may produce melt when the air temperature is less than 32°F, while in the spring the back longwave radiation on a clear night may result in a heat loss although the nightly low temperature remains well above freezing. However, in the absence of all the data required to compute the individual components of the melt, a temperature index relation of this kind gives a reasonable estimate of the melt over short term periods.

Over longer periods such as a snow season, however, it is not possible to assume a constant melt factor. The melt factor is known to vary with time of year and using a constant melt factor over the snow season will produce either too much melt in the winter or too little in the spring. An example of the variation of the melt factor is shown in Figure 4.5.

It has been suggested[3], on the basis of a correlation with the results given by computing the components of the melt, that the major reasons for this change in the melt factor over the snow season are the variations of the incident shortwave radiation and albedo of the snow surface. Therefore, by modifying the basic melt factor over the year according to changes in these values, it has been shown[3] that acceptable estimates of the actual melt produced can be obtained.

The procedure used by the model in this study is to use temperature as an index to the heat transferred according to the expression:

$$HT = (TA-32) * DHF \tag{4.30}$$

where HT is the net heat transferred in langleys/hr, TA is the surface air temperature in °F, and DHF is a degree-hour factor, indicating the heat transfer per hour for each degree that TA differs from 32°F.

In order to account for the two factors mentioned above as the primary causes of seasonal variation in the degree-hour factor, the following adjustments are made:

$$DHF = BDHF * FADJ * (1.0-ALB) \tag{4.31}$$

where BDHF is the degree-hour factor for the most intense spring

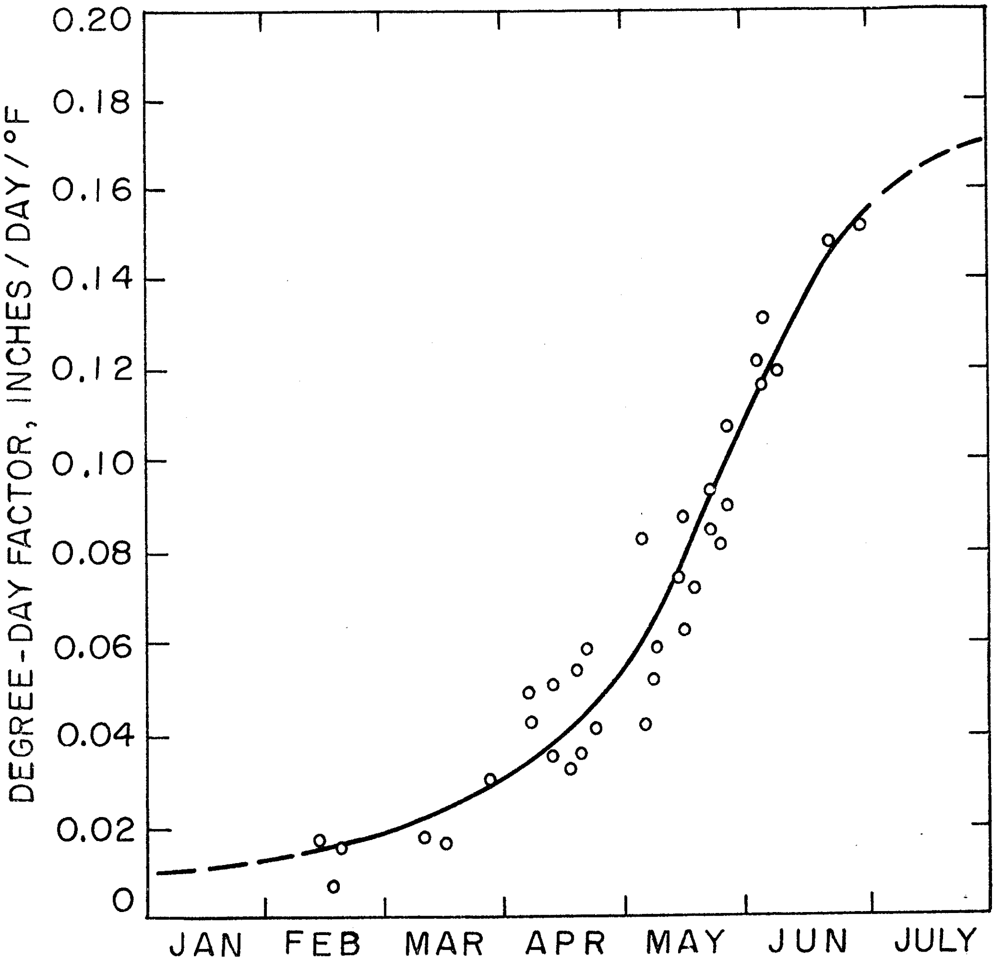

Figure 4.5 Degree Day Factor Curve for the Tuolumne River above Don Pedro Dam, California (Linsley, Kohler, and Paulhus, 1958)

insolation, FADJ is an adjustment for the variation of incident shortwave radiation over the season as given by the ratio of SRO, as computed from Equation 4.13, to SRO for the most intense springtime insolation (occurring on June 21 in the Northern Hemisphere), and ALB is the snowpack albedo as given by Equation 4.17.

In the absence of air moisture and wind data, it is not possible to use Equations 4.26 and 4.27 to estimate *snow evaporation*, so it is also necessary to have an empirical means of estimating the vapor transferred at the surface of the snow. Computations of the condensation and evaporation over snow using the heat budget have shown that the amount of water added to the snowpack through condensation is small and can be neglected.[3]

Evaporation on the other hand, is included in the model using average daily snow evaporation as a function of time of year. Experiments have shown that the shape of this relationship is approximately the same for most watersheds and that the magnitude of it may be determined from mean values of the meteorological variables.[17] The model assumes, as did Anderson and Crawford[3], that snow evaporation is equal to the estimated snow evaporation potential if snow is present and the minimum temperature is less than 32°F (hence the dew-point temperature was less than 32°F at least for part of the day). If the minimum temperature is greater than 32°F snow evaporation is assumed to be zero.

Using this method, the snow evaporation on a daily basis may be in error; but over a period of time it should be correct. Since losses from snow evaporation are relatively small, errors of this type will not significantly affect the water balance.

4.4.5 Melt Processes

Using either the energy budget or temperature index approach as described above, the net total heat transfer for the computation time interval may be estimated from either Equation 4.12 or 4.30. It is convenient to express the effect of this heat on the snowpack in terms of the number of inches of liquid water that may be frozen or melted by this amount of heat. This quantity is given by Equation 3.21 as,

$$q = \frac{H}{80.* \; 2.54 \; * \; QT} \qquad (4.32)$$

where q is the amount of water in inches that could be frozen for a negative H, or melted for a positive H. This conversion from heat to depth of water is convenient so that the effect of the heat can be added directly to the liquid water, cold content, and snow water equivalent of the pack to determine changes in these quantities. The effects of heat added or removed are now considered individually.

If it is determined from Equation 4.12 or 4.30 that heat is removed from the pack, it is desirable to consider two situations that may exist.

For a snowpack whose temperature is below 32°F it is known that there is no stored liquid water in the snow and that its cold content is given by Equation 3.18. The *heat removed* will first be applied to freeze any rain water that is present and the remainder will lower the snow temperature, hence, increase the heat deficit as measured by the cold content.

For a snowpack whose temperature is at 32°F the cold content will be zero, but the stored liquid water may be at any value from zero to the liquid water holding capacity of the snow, depending on past conditions. Therefore, if heat is removed, some or all of the liquid water in the pack, whether from rain or previous storage will be frozen. If more than enough heat is removed than is required to freeze all of the water, any remaining will act to create a heat deficit.

If heat is added to the snowpack, it is again desirable to consider the effect on a subfreezing pack and for a pack at 32°F.

A sub-freezing pack contains no stored liquid water and has a positive cold content. *Heat added* to the pack first must be applied to reduce this heat deficit, and then if enough heat has been added to raise the snow temperature to 32°F, any remaining heat will produce melt.

If the snowpack is already at 32°F, all of the heat supplied will be used to produce melt.

4.4.6 Liquid Water Storage and Time Delay to Runoff

If the effect of the addition of heat to the snowpack is to produce melt as discussed above, there will be an increase in the stored liquid water in the snow. The amount of liquid water that the pack can hold as storage is limited by its liquid water holding capacity. While it is not possible to determine the liquid water holding capacity, WHC, of the snow theoretically, it has been correlated with the snow's density, DN. Figure 4.6 shows how this correlation is represented in the model. Its value over various density ranges is given by

$$
\begin{aligned}
WHC &= 0.025 * DN + 0.03 &&, \text{ for } DN < 0.40 \\
WHC &= 0.20 * DN - 0.04 &&, \text{ for } .40 < DN < .55 \\
WHC &= 0.111 * DN + 0.131 &&, \text{ for } DN > .55
\end{aligned}
\tag{4.33}
$$

If the liquid water stored in the pack at any time exceeds the value of its liquid water holding capacity, the excess can no longer be held against gravity and begins to percolate through the pack and eventually will reach the ground to become runoff.

The time required for this water to percolate through a snowpack of given depth was shown in Figure 3.5. Rather than work with this time lag directly, it is more convenient to use a relationship which expresses the amount of melt formed at the surface that will reach the ground on an hourly basis. An empirical expression for this value as a function of snow depth was determined by fitting a curve to the data shown in Figure 4.7. This relationship was found to be:

$$PC = 21.0/(DP + 21.) \tag{4.34}$$

where PC is the percent of a given amount of melt at the surface that reaches the ground in each subsequent hour until all of the melt has

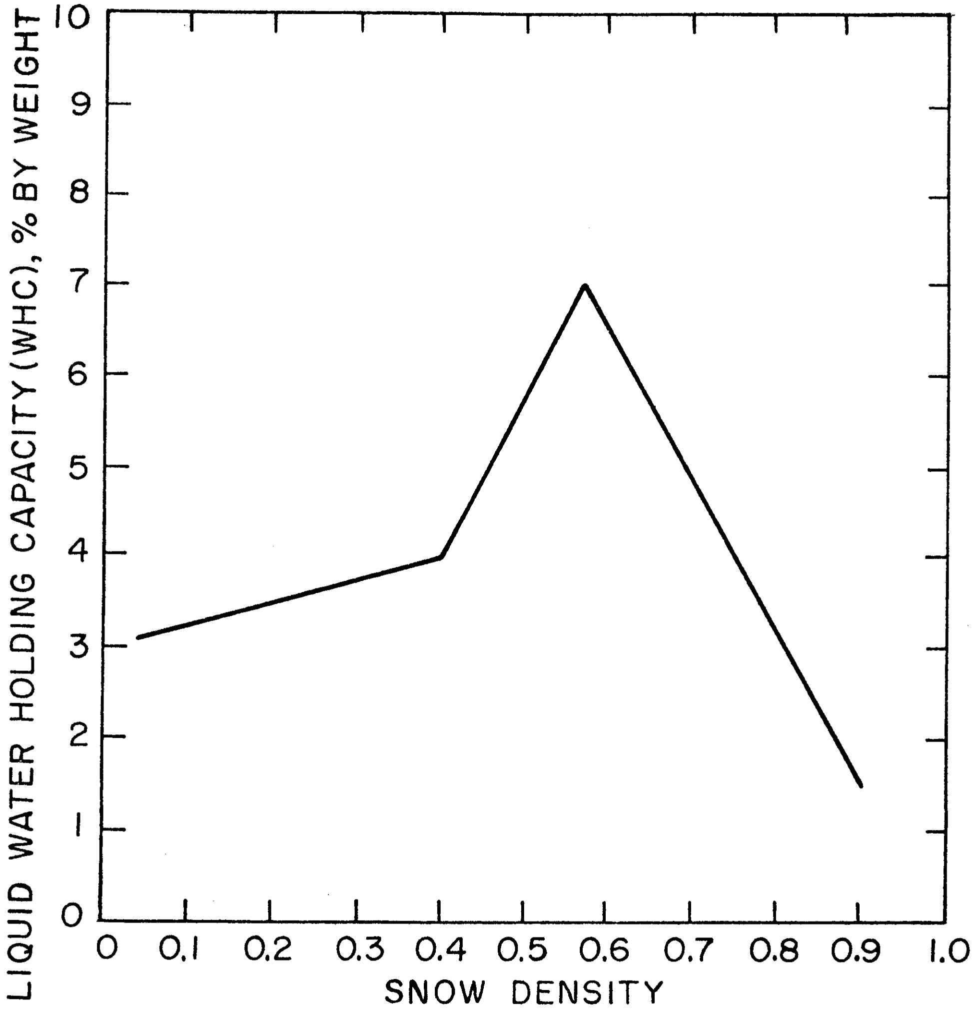

Figure 4.6 Variation of the Liquid Water Holding Capacity of Snow with Snow Density (Amorocho and Espildora, 1966)

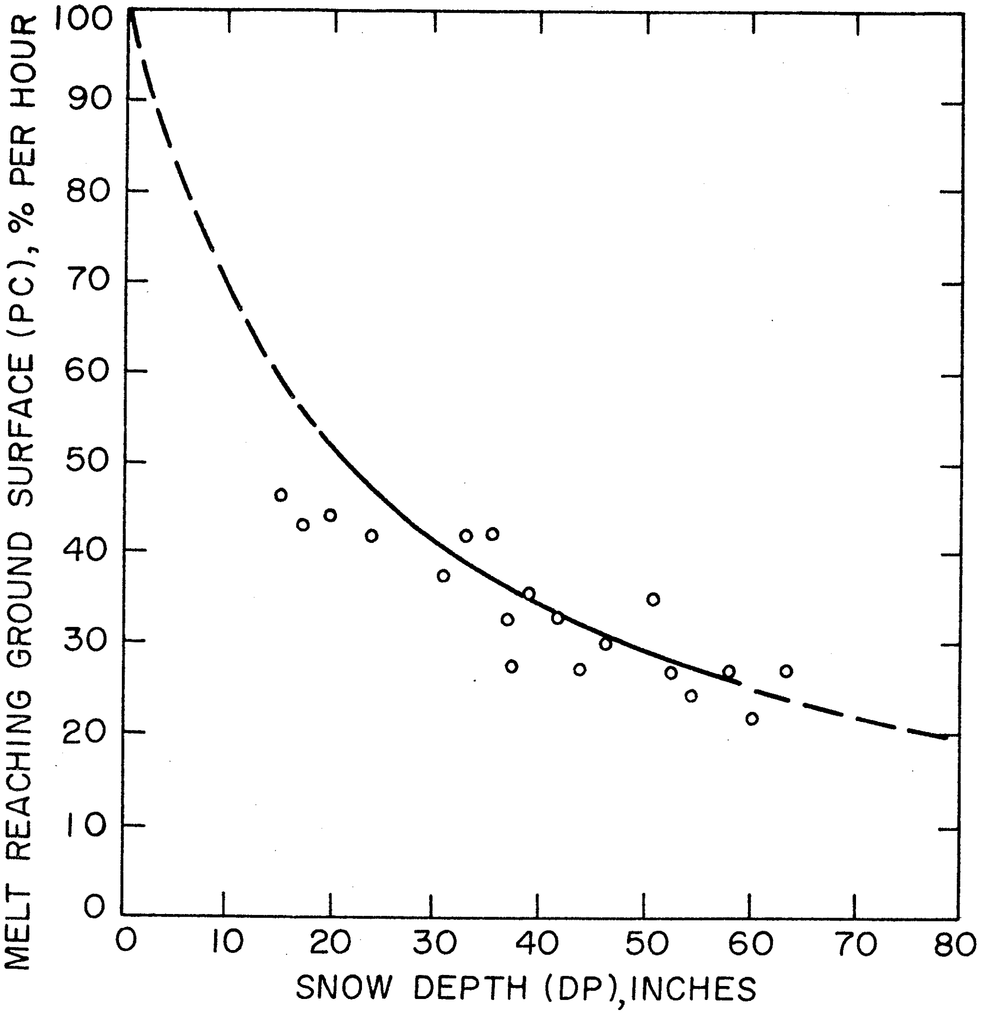

Figure 4.7 Coefficient for Routing Melt Water Through a Ripe Snowpack (Anderson, 1968)

been accounted for, and DP is the snowpack depth in inches.

4.4.7 Computation of Final Parameters

Having completed all the accumulation and melt computations for the time interval under consideration, it is necessary to compute the snowpack parameters to be used for the next interval. These parameters are:

DP = Depth, in

WEQ = Water equivalent, in

DN = Density, % of density of ice

CC = Cold content, in

TP = Snow temperature, °F

TS = Snow surface temperature, °F

WC = Liquid water content, in

WHC = Liquid water holding capacity, % by weight

QT = Thermal quality, % by weight

TX = Albedo index, days

Of these, the depth, water equivalent, cold content, and liquid water content are computed within the time interval based on previous conditions, water inputs or losses (e.g., precipitation, evaporation), and heat transfers. The remaining parameters are computed in the following ways.

The density of the snow is always taken to be the ratio of the water equivalent to the depth of snow:

$$DN = WEQ/DP \tag{4.35}$$

The snowpack temperature is computed by solving Equation 3.18 for the temperature of the snow:

$$TP = 32. - \left(\frac{CC}{0.00347 * DN * DP}\right) \tag{4.36}$$

The surface temperature of the snow was estimated to be the average of the air temperature and the snowpack temperature, but not greater than 32°F:

$$TS = \frac{TA+TP}{2} \quad , \text{ if } \frac{TA+TP}{2} \leq \quad 32°F$$

$$TS = 32°F \text{ , otherwise} \tag{4.37}$$

Knowing the snow density, the liquid water holding capacity of the snow may be determined from Equation 4.33.

For a subfreezing snowpack, or one at 32°F with no liquid water present, $L_{fs} = L_f$ in Equation 3.20 and the thermal quality is related to the snowpack temperature by

$$QT = 1.0 + 0.00347 * (32.-TP) \tag{4.38}$$

or for snow at 32°F with free water, L_{fs} is equal to $(1-WC * L_f)$ and the thermal quality is given by

$$QT = 1.0-WC \tag{4.39}$$

The albedo index, which is the age of the snow surface, is incremented by one at the end of each day. Rain on a snow surface decreases the albedo quickly, so the albedo index, TX, is also increased by a day each time a significant rainfall occurs.

4.5 Data Specification and Adjustments

The model for the simulation of snow melting processes which was discussed in the previous section was developed to be flexible in its data requirement. One way that this generality is introduced is through the referencing of the meteorological variables that are to be used with an identifying code number. On the basis of these code numbers, tests are performed to check the completeness, consistency, and sufficiency of the data supplied. Also, these codes serve as indications as to the proper methods to be utilized to model the physical processes.

Another means of introducing flexibility into the model involves various time considerations. The model performs its computations on the basis of a specified time interval and it is necessary that all the meteorological variables entering the snowmelt subroutine have this same time basis. Rather than require that all the input variables be defined in this way, which normally would not be the case in a practical situation, the model provides a check on each input variable to determine if it has the proper time basis, and if it is found that it does not, steps are taken to convert it to the proper basis to insure consistency of the computations in the snowmelt subroutine. Thus, the data can be input in slightly different time intervals than the actual computation interval and it will be corrected. This provision must be used with discretion, however, since the aggregation and disaggregation schemes employed are only approximate and for large time shifts the adjusted values may not be representative of the actual conditions.

The data that must be supplied is of three general types. Each of these will now be discussed in the sequence of their use in the model.

Run Description Data and General Constants

The first group of data is read in by SUBROUTINE CONST. This input describes the nature of the run, indicates the availability of data and includes the constants that relate to the entire watershed being modelled. Table 4.1 shows the characteristics of this data.

Card 1 - name of the watershed or location being modelled, up to 40 alphameric characters.

Card 2 - Specifies the output files as defined in Section 4.6.

Card 3 - MDC is a variable used to indicate which of the meteorological variables(See Table 4.4) will be supplied as data. A value of MDC(I)=1 indicates that variable I in Table 4.4 will be used, while MDC(I)=0 indicates that it will not.

Card 4 - NYR = Number of years to be simulated

NSUB = Number of subareas formed by the division of the watershed into uniform areas.

Table 4.1

Characteristics of Run Description and General Constants Data

Card Number	Variable(s)	Format
1	(TTT(I), I = 1,10)	10A4
2	IWP, IWD, IWO, IWR	20I2
3	(MDC(I), I=1,12)	20I2
4	NYR, NSUB	10I6
5	IFYR, IBEG, INO, JCS, ISA, ICA	10I6
6	LAT, NORS	10I6
7	PTI, CSI, CRI, SX	10I6
8[a]	(SEP(I), I = 1,37)	10F6.3

[a] Included only if MDC (I) = 0, for I = 2,3,5 and 6

Card 5 - IFYR = Calendar year in which the simulation begins.

IBEG = First day of the simulation, calendar day

INO = Number of days to be simulated

JCS = Computation interval used (hours)

ISA = Calendar day assumed as start of the accumulation season

ICA = Calendar day assumed as start of the melt season

Card 6 - LAT = Local latitude of the watershed, to the nearest degree

NORS = 1, for a location in the Northern Hemisphere

0, for a location in the Southern Hemisphere

Card 7 - PTI = Precipitation temperature index, the surface air temperature for distinguishing snow from rain, °F

CSI = Snow interception constant, % intercepted

CRI = Rain interception constant, % intercepted

SX = New snow accumulation, required to change the albedo index, inches

Card 8 - SEP is the average 10-day snow evaporation potential beginning on January 1. This input is to be supplied only if the data restrictions require it for the estimation of the evaporation. This is the case where the data contains no information about the vapor pressure gradient, i.e., none of the following are input:

Dew point temperature

Wet-bulb temperature

Relative humidity

Subarea Description Constants and Initial Conditions

This set of data defines those variables that may vary from area to area within the watershed, but are constant in time. Also specified are the initial conditions of the snowpack. This information is input through SUBROUTINE SDAT. The characteristics of this data are shown in Table 4.2. A set of the following cards must be provided for each subarea used.

Card 1 - Defines values related to the thermal exchange processes.

HT = Height of the air temperature measurement, feet above the ground.

HE = Height of the air moisture (dew point temperature, wet-bulb temperature, or relative humidity) measurement, feet above the ground

HV = Height of the wind velocity measurement, feet above the ground

Table 4.2

Characteristics of Subarea Description Constants and Initial Conditions Data

Card Number	Variable(s)	Format
1[b]	HT, HE, HV, FCV, FCN	10F6.2
2[c]	BDHF	10F6.2
3	PF, FC, FD, SCI, GH, ELT ELP, ELM	10F6.2
4	DPI, WEQI, DNI, CCI, TPI, TSI WCI, WHCI, QLTYI, TXI	10F6.2

[b] Included only if MDC(I) = 1, for I = (2,3,5, or 6), (7 and 8), (10 and 11, or 12)

[c] Included only if card number 1 is not

FCV = Convection constant

FCN = Condensation constant

This card is used only when there is sufficient data to use the heat budget approach in computing the heat transfer. This requires that the following variables as indicated by the value of MDC(I), be provided each day as meteorological data (see Table 4.4);

(i) Air temperature

(ii) A measure of the vapor pressure gradient of the air, that is, at least one of the following:

Dew point temperature
Wet-bulb temperature
Relative humidity

(iii) Wind Velocity

(iv) Precipitation

(v) An indication of sky conditions, i.e., either:

Cloud type index, and
Cloud cover

or,

Effective cloud cover.

Card 2 - BDHF is the basic degree-hour factor in langleys/hr/°F. This card will be included only if data limitations (as discussed for card 1) prevent the computation of the individual components of the heat budget.

Card 3 - PF = Factor to be applied to the observed precipitation to correct for elevation effects

FC = Forest cover, % of total area

FD = Forest canopy density, %

SCI = Minimum snow water equivalent for complete areal coverage, in

GH = Ground heat constant, ly/hr

ELT = Elevation of temperature measuring station, 1000 ft

ELP = Elevation of precipitation measuring station, 1000 ft

ELM = Mean elevation of the area, 1000 ft.

Card 4 - This card defines the initial conditions of the snowpack if one exists when the simulation is begun (otherwise, they all may be set equal to zero).

DPI = Depth, in

WEQI = Water equivalent, in

DNI = Density, % of density of ice

CCI = Cold content, in

TPI = Pack temperature, °F

TSI = Surface temperature, °F

WCI = Liquid water content, in

WHCI = Liquid water holding capacity, % by weight

QLTYI = Thermal Quality, % by weight

TXI = Age of snow surface, days

Meteorological Input

The final input the model receives is the available meteorological data. This input must be specified each day for each subdivision of the watershed, and, if more than one year is to be simulated, similar data must be provided for each year.

In order to remain as flexible as possible, this data is read in by a free format subroutine called SUBROUTINE INPT. This subroutine reads an entire card in single character alphameric format, temporarily storing each of the 80 characters. When a string of numeric characters is encountered, it is converted into the proper real number. The program continues to scan the information taken from the card, removing the input elements, until it encounters a special character or the 80th character (which must always be blank), in which case another card is read. The special characters recognized by this subroutine and their use are given in Table 4.3.

Each variable that is to be input must be preceded by an identification card of the following form:

Table 4.3

Characters Used in the Input of Meteorological Data

Character	Purpose
*	Indicates that any further information on this card is a comment, and not to be taken as data. When this character appears in the first two card positions, the end of the data for the variable is indicated.
'blank'	At least one blank character must separate all values being read.
-	Indicates a negative variable value.
.	Locates the decimal point if desired, otherwise the decimal is assumed after the final digit of the number
#	Indicates the variable identification card
$	Indicates the end of the meteorological data for the subarea

IC JTS IUC # Comment

where # is used to define a variable identification card and can be followed by any further identifying comments desired, and where IC is a variable code number, JTS is the time interval between observations of the variable, and IUC is an index indicating the units of the variable values. Table 4.4 summarizes the information provided by this card.

Having read the identification card, the input values are then read, card by card, and stored in a one-dimensional array until a card with '**' as the first two characters is encountered. This indicates the end of the data for this particular variable. The array is then transformed into the appropriate variable, with its elements associated with the proper day and time, before proceeding to the next variable identification card.

It has been noted that all the meteorological variables entering the snowmelt subroutine must be defined over the same time interval as the computation interval. Since it may happen that several of the variables are not observed on the same time basis as the rest, it is desirable to be able to convert them to the interval selected for computation. This has been provided for through use of simple averaging schemes. These schemes will be valid for minor adjustments, but they will not properly convert, say, daily values to hourly values. Thus, if it is found that a certain variable does not conform to the given computation interval, SUBROUTINE ADJ is called,

Table 4.4

Meteorological Variables Used in the Model

Code Number (IC)	Variable	Time Step (JCS), hrs	Unit Index (IUC)	Units
1	Air Temperature	1-24	1 0	°F °C
2	Dew Point Temperature	1-24	1 0	°F °C
3	Wet-bulb Temperature	1-24	1 0	°F °C
4	Maximum and Minimum Air Temperature	24	1 0	°F °C
5	Maximum and Minimum Dew Point Temperature	24	1 0	°F °C
6	Relative Humidity	1-24	1	
7	Wind Velocity	1-24	1 0	mi/hr m/sec
8	Precipitation	1-24	1 0	in cm
9	Incident Sclar Radiation	1-24	0	cal/cm^2
10	Cloud Type Index	1-24	1	
11	Cloud Cover	1-24	1	
12	Effective Cloud Cover	1-24	1	

which provides the indicated adjustment. For example, suppose it has been decided that the computations are to be performed on a 6-hour basis, and that the dew point temperature in °F as observed every 3 hours on a particular day are:

22 26 29 33 38 34 30 28

and the average cloud cover observed twice during the day is

0 3

These inputs will be adjusted to the following 6-hour values:

Dew point temperatures,

24 31 36 29

Cloud Cover,

0 0 3 3

The dew point temperatures are the averages of the two appropriate 3-hour values, while the resulting cloud covers are the result of assuming that the observed values were average readings for the twelve-hour periods.

Figure 4.8 illustrates the form of the input for a simple example. In this case the data is for a single area and is sufficient for the heat budget approach to be used. The indicated period of simulation is four days, using a 6-hour computation interval. Results of a test run using this input is shown in Figure 4.9.

4.6 Model Output

Four options have been provided for output from the

```
 THE SKYLAND CREEK WATERSHED OF THE UCSL
 0 0 8 0
 1 1 0 0 0 0 1 1 1 1 1 0
     1      1
  1949      1      4      6    270    100
    48      1
   34.    0.1    0.1  0.25
   9.0    9.0   17.9 0.043 0.137
   1.2   0.80   0.75   7.3  0.17    5.3    5.3    5.8
  69.6   21.9   0.31   0.0  32.0   32.0    0.0   0.04   0.96    4.0
1 1 1 # AIR TEMPERATURE
* AIR TEMP      APRIL 1949      STA 12
18 17 16 15 15 14 14 19 24 35 43 47 48 49 44 41 40 37 34 28 25 24 23 21
20 20 21 20 18 17 17 21 28 35 43 39 42 48 41 41 39 36 32 28 27 28 30 30
31 31 30 30 30 30 30 32 35 41 47 47 46 47 45 42 41 38 34 33 31 29 28 27
26 25 24 24 23 22 22 26 34 42 48 50 51 52 52 50 47 43 39 38 40 39 40 44
**
2 1 1 # DEW POINT TEMPERATURE
* DEW POINT TEMP      APRIL 1949      STA 12
18 17 16 15 15 14 14 17 14 17 23 25 25 29 26 23 26 24 26 24 21 21 21 20
20 19 20 20 18 17 17 17 17 18 28 24 24 32 26 27 28 28 28 26 26 27 28 27
28 28 27 27 26 25 24 23 22 23 27 29 26 28 27 27 30 29 27 29 28 26 25 26
25 25 24 24 23 22 22 19 21 22 25 29 32 36 40 41 37 32 30 28 30 26 23 26
**
9 1 1 # SOLAR RADIATION
* SWR      APRIL 1949      STA 1A
0 0 0 0 0 0 0 8 32 48 64 71 75 73 65 55 40 22 5 0 0 0 0 0
0 0 0 0 0 0 0 10 31 49 58 37 32 64 37 51 41 18 3 0 0 0 0 0
0 0 0 0 0 0 1 5 8 15 43 48 55 75 72 55 37 22 4 0 0 0 0 0
0 0 0 0 0 0 0 11 31 41 56 56 53 69 76 62 46 26 6 0 0 0 0 0
**
7 1 1 # WIND VELOCITY
* WIND VEL      APRIL 1949      STA 1A
2 2 3 4 4 4 3 1 3 7 8 9 9 9 8 8 9 8 4 3 2 1 2 1
3 3 1 0 4 4 4 3 4 5 6 7 6 8 7 7 9 7 4 2 3 4 4 6
8 9 7 10 9 9 9 12 14 15 15 12 11 14 13 13 13 11 7 8 3 2 2 3
3 2 4 2 2 2 2 3 5 7 9 8 8 15 14 11 12 10 9 11 12 16 14 25
**
8 6 1 # PRECIPITATION
* PRECIP      APRIL 1949      STA 12
0 0 0 0 0 0 .1 0 0 .1 .2 .1 0 .1 0 0
**
10 24 1 # CLOUD TYPE INDEX
0 5 1 4
**
11 24 1 # CLOUD COVER
1. .4 .1 .5
**
$
```

Figure 4.8 Typical Form of Model Input

```
                SIMULATION OF THE SNOW ACCUMULATICN AND MELTING PROCESSES FOR

                             THE SKYLAND CREEK WATERSHED OF THE UCSL

                                        USING    1 SUBDIVISION(S)

                                       1 YEAR(S), BEGINNING IN  1949

**********
*  1949  *
* AREA 1 *
**********

ICAL  J    DP   WEQ     CC     TP     TS     WC    WCM     QT     TX RMELT TMELT

  1   1 70.68 21.91   0.27 28.48 23.16   0.0    0.88   1.00   4.00  0.0   0.0
      2 70.66 21.90   0.18 29.64 29.99   0.0    0.83   1.00   4.00  0.0   0.0
      3 70.51 21.86   0.0   32.00 32.00  0.03   0.83   1.00   4.00  0.0   0.0
      4 70.52 21.89   0.10 30.67 29.25   0.0    0.83   1.00   5.00  0.0   0.0

         DGL  DWEQ    DWC   DPPT   DCON DEVSL   DMEL
        0.00  0.01   0.0    0.0    0.0   0.01   0.0

        DHRS  DHRL   DHCV   DHCN    DHR    DHG    DHT
       70.40-59.46 10.51-43.93  0.0    4.08-18.39

ICAL  J    DP   WEQ     CC     TP     TS     WC    WCM     QT     TX RMELT TMELT

  2   1 70.54 21.89   0.24 28.87 25.10   0.0    0.83   1.00   5.00  0.0   0.0
      2 70.51 21.89   0.16 29.86 30.18   0.0    0.83   1.00   5.00  0.0   0.0
      3 70.38 21.85   0.0   32.00 32.00  0.14   0.82   1.00   5.00  0.0   0.0
      4 70.39 21.92   0.0   32.00 31.76  0.07   0.83   1.00   6.00  0.0   0.0

         DGL  DWEQ    DWC   DPPT   DCON DEVSL   DMEL
        0.00 -0.03  -0.07   0.12   0.0   0.02   0.0

        DHRS  DHRL   DHCV   DHCN    DHR    DHG    DHT
       57.31-34.29  9.72-25.07  0.54   4.08  11.75

ICAL  J    DP   WEQ     CC     TP     TS     WC    WCM     QT     TX RMELT TMELT

  3   1 70.40 21.99   0.04 31.47 31.90   0.0    0.83   1.00   6.00  0.0   0.0
      2 70.44 22.05   0.0   32.00 32.00  0.10   0.83   1.00   7.00  0.0   0.0
      3 69.79 21.85   0.0   32.00 32.00  0.54   0.83   1.00   8.00  0.0   0.0
      4 69.82 21.96   0.0   32.00 32.00  0.54   0.83   1.00   9.00  0.0   0.0

         DGL  DWEQ    DWC   DPPT   DCON DEVSL   DMEL
       -0.03 -0.04  -0.47   0.48   0.0  -0.00   0.0

        DHRS  DHRL   DHCV   DHCN    DHR    DHG    DHT
       64.75-23.54 26.13-58.05  1.45   3.06  12.36

ICAL  J    DP   WEQ     CC     TP     TS     WC    WCM     QT     TX RMELT TMELT

  4   1 69.83 22.08   0.0   32.00 29.09  0.42   0.84   1.00   9.00  0.0   0.0
      2 69.48 21.97   0.0   32.00 32.00  0.63   0.83   1.00  10.00  0.0   0.0
      3 68.03 21.51   0.0   32.00 32.00  0.82   0.82   1.00  10.00  0.28  0.199
      4 67.98 21.50   0.0   32.00 32.00  0.81   0.81   1.00  11.00  0.03  0.100

         DGL  DWEQ    DWC   DPPT   DCON DEVSL   DMEL
        0.00  0.46  -0.28   0.12   0.01  0.00   0.31

        DHRS  DHRL   DHCV   DHCN    DHR    DHG    DHT
       84.96-15.65 39.92-18.99 -0.19   4.08  94.32
```

Figure 4.9 Typical Form of Model Output

model. These alternatives may be selected individually or collectively, be defining file numbers for the following files of output, or by suppressing the outputs of any one of them by setting the file number equal to zero.

File IWP

The input data for the parameters defined in SUBROUTINE CONST and SUBROUTINE SDAT (See Section 4.5) are printed out in this file.

File IWD

This file will contain the meteorological variables after being read in and adjusted for any differences in time basis.

File IWO

The output contained in this file is a detailed, day by day record of the values of the snowpack parameters and resulting melt for each time period simulated. Also produced are daily summaries of the heat transfers and water balance components.

File IWR

This file contains only the quantities of melt leaving the snowpack for each time period simulated. This output can easily be converted into any form required for input into a runoff-routing model.

Figure 4.9 illustrates the results given in File IWO for the data shown in Figure 4.8.

Chapter 5

APPLICATION OF THE MODEL

5.1 Description of the Data Used

The model developed in Chapter 4 was coded in the FORTRAN IV LEVEL G language for use on an IBM 360/67 digital computer. A complete listing of the Fortran statements used in the model is given in the Appendix.

To test the accuracy of the model in representing the snow accumulation and melting processes for different computation intervals and various data inputs, rather extensive data was required. Data collected by the Cooperative Snow Investigation Program[5] at the Upper Columbia Snow Laboratory (UCSL) for the Skyland Creek watershed was found to satisfy this requirement and was used in testing the model. This data was published as a Hydrometeorological Log of the 1948-1949 water year.[6]

The UCSL was located at the extreme headwaters of the Columbia-Clark Fork-Flathead river system near Marias Pass, Montana. The Skyland Creek drainage basin comprises 8.1 sq.mi. of the UCSL and ranges in elevation from 4800 to 7600 feet above mean sea level. It has fairly deep soil mantle and is densely forested with lodgepole pine. The land surface has an average slope of thirty percent and an average orientation toward the west. The climate of the laboratory region is characterized by a cold snowy winter with mean temperatures during December to March of 15°F and short mild summers during July and August with temperatures averaging 55°F (extreme temperatures range from about -45°F to +90°F). The annual basin precipitation totals approximately 50 inches, or about 40 inches after interception, and is fairly evenly distributed over the year. Virtually all winter precipitation occurs as snow which accumulates to an average basin water equivalent of about 20 inches toward the end of March, just prior to the melting period.

The physical layout of the Skyland Creek basin and the location of the stations where data readings were taken is shown in Figure 5.1. A general summary of the measurements tabulated in the Hydrometeorological Log and used in the model (see Table 4.4) follows:

(i) Air Temperature. Hourly air temperature data in °F were taken from hygrothermograph charts.

(ii) Dew Point Temperature. Hourly dew point temperatures in °F were computed on a Weather Bureau psychromatic slide rule from air temperature and relative humidity traces taken from hygrothermograph charts.

(iii) Maximum and Minimum Temperatures. Daily maximum and minimum temperatures were taken as the extremes of the thermograph traces and do not always appear in the hourly tabulations.

(iv) Wind Data. Wind speed in miles per hour was measured by three-cup anemometers and recorded on Esterline-Angus strip charts. Hourly values were reduced from these charts.

(v) Precipitation. Six-hourly accumulations in inches of water equivalent were tabulated for amounts recorded on Stevens

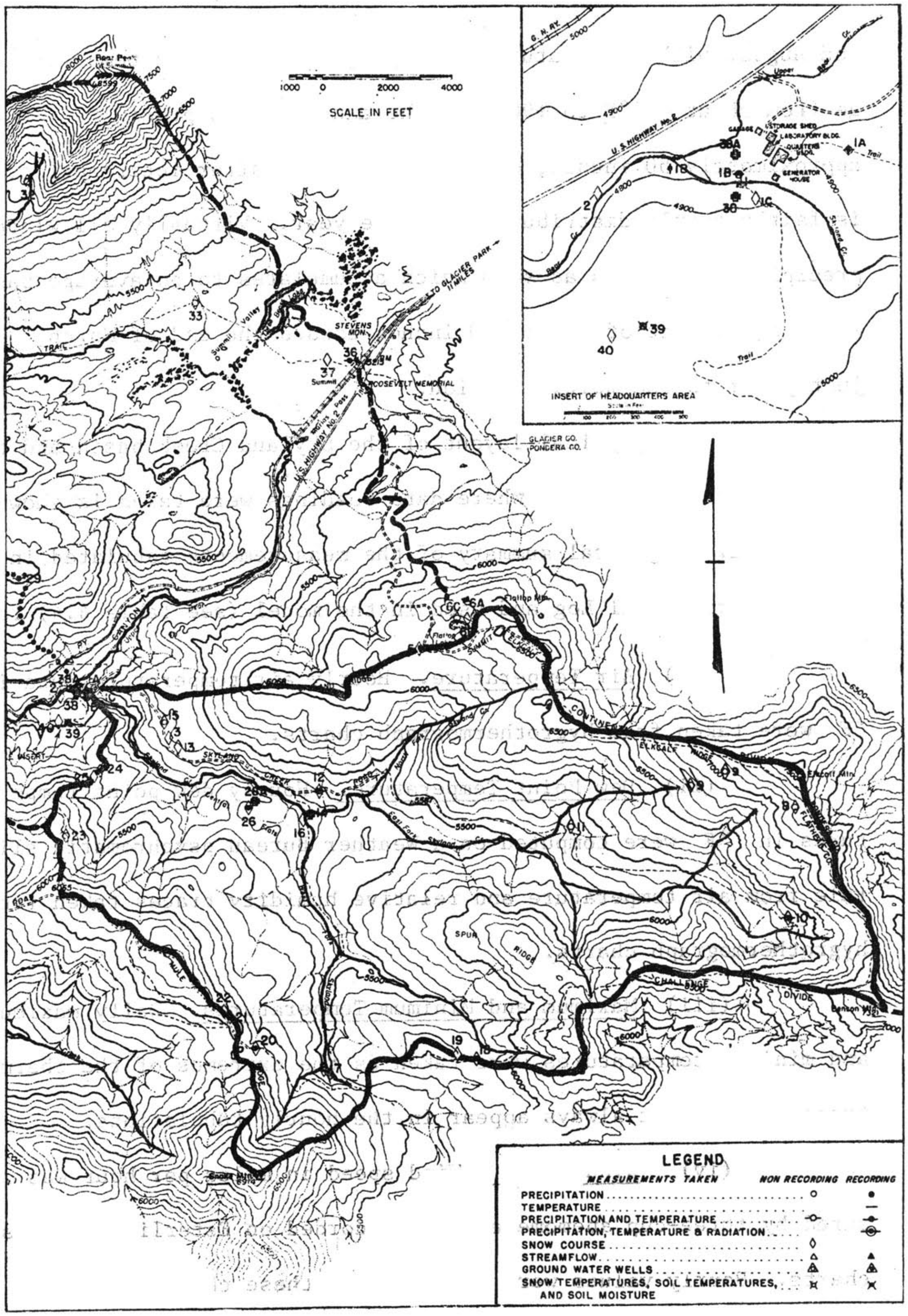

Figure 5.1 The Skyland Creek Watershed of the Upper Columbia Snow Laboratory

gage charts. Each gage was equipped with an Alter shield.

(vi) Incident Solar Radiation. Incident solar radiation values in langleys (cal/cm^2) per hour were measured by an Eppley pyrheliometer placed on top of a 27-foot tower.

(vii) Cloud Data. The type of cloud and fraction of cloud cover was observed daily at 4:00 p.m.

In addition to these meteorological variables, values of certain snowpack parameters were observed on a less frequent basis. These values were used in the determination of the initial conditions of the snowpack and to check the values of these parameters as computed by the model. These parameters were:

(i) Depth of Snowpack. Mean values of snowpack depth in inches above the ground were determined at several stations usually at weekly intervals using a series of snowtube measurements.

(ii) Mean Snowpack Water Equivalent and Density. The water equivalent of the snow as determined in the same manner as the snow depth. The mean snow density was determined as the ratio of the snow water equivalent to the snow depth.

(iii) Snow Temperature. The maximum and minimum daily snow temperature in °F was measured at several depths within the snowpack by means of thermohms. The mean snowpack temperature was computed from these values.

5.2 Results

Test runs of the model were conducted for three primary purposes. First, it was necessary to demonstrate that the model was capable of accurately simulating the actual accumulation and melting processes using several different sets of data input. Having established the validity of the model, runs were made to study the effects of varying the time interval over which the computations were made. Finally, it was desired to apply the model in conjunction with existing runoff and channel routing routines to predict the streamflow resulting from computed snowmelt values. The results of each of these sets of test runs are presented and discussed in the remainder of this chapter.

5.2.1 Adequacy of the Snowmelt Model

It was emphasized in the discussion in Chapter 4 of the formulations used to model the various snow accumulation and melting processes, that those formulations were not developed within the context of this study, but were developed and extensively tested in previous snowmelt models. The contribution of this study then is intended to be in the integration of these techniques into a more flexible model with a greater range of applicability.

Some of the results of the Amorocho and Espildora study[1], using heat budget considerations, are shown in Figures 5.2 and 5.3. Figure 5.2 shows that over the course of the snow season, the accumulated water released from the system being modelled is in very

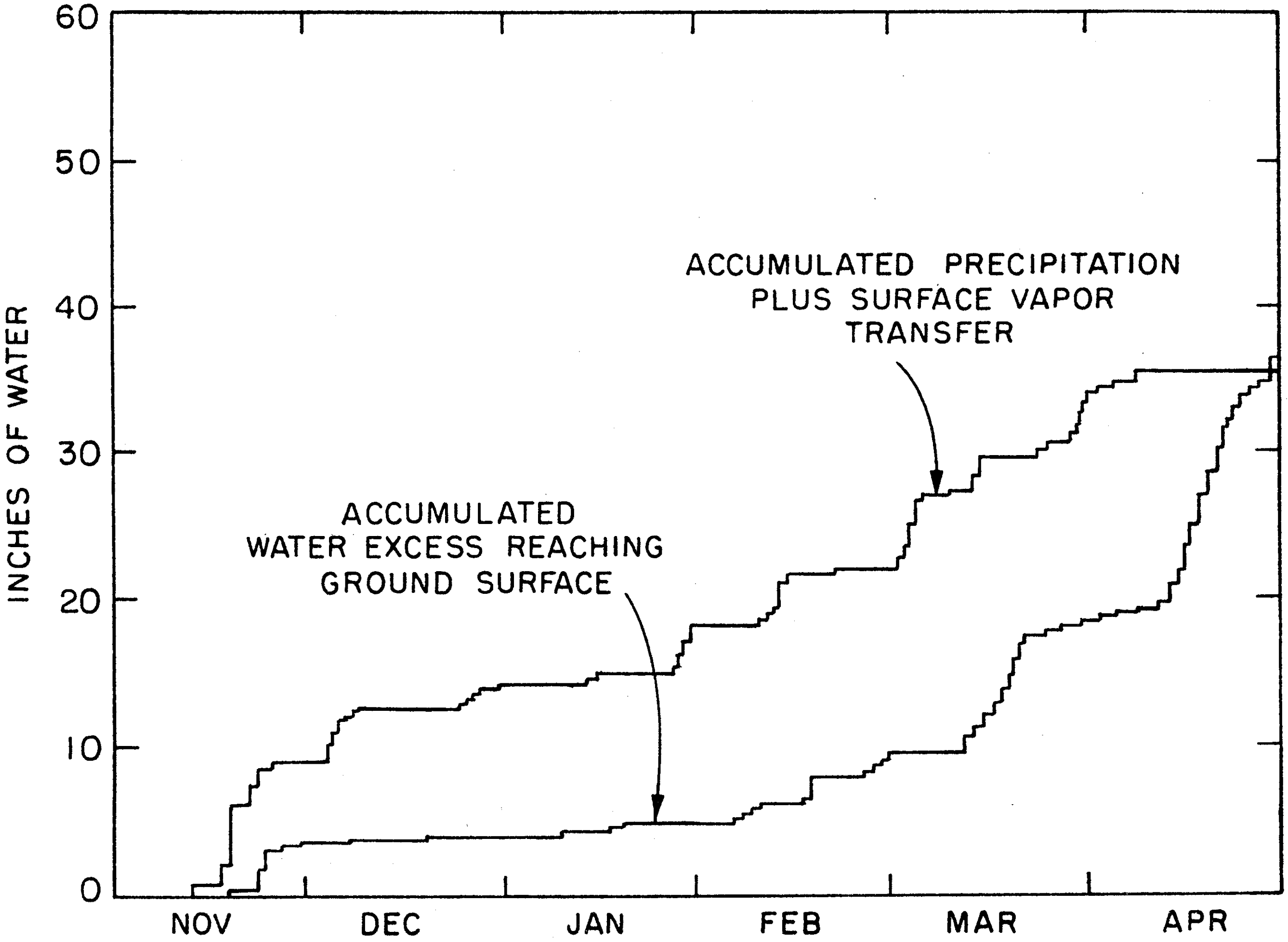

Figure 5.2 Synthesized Water Balance at the CSSL for the 1946-1947 Snow Season (Amorocho and Espildora, 1966)

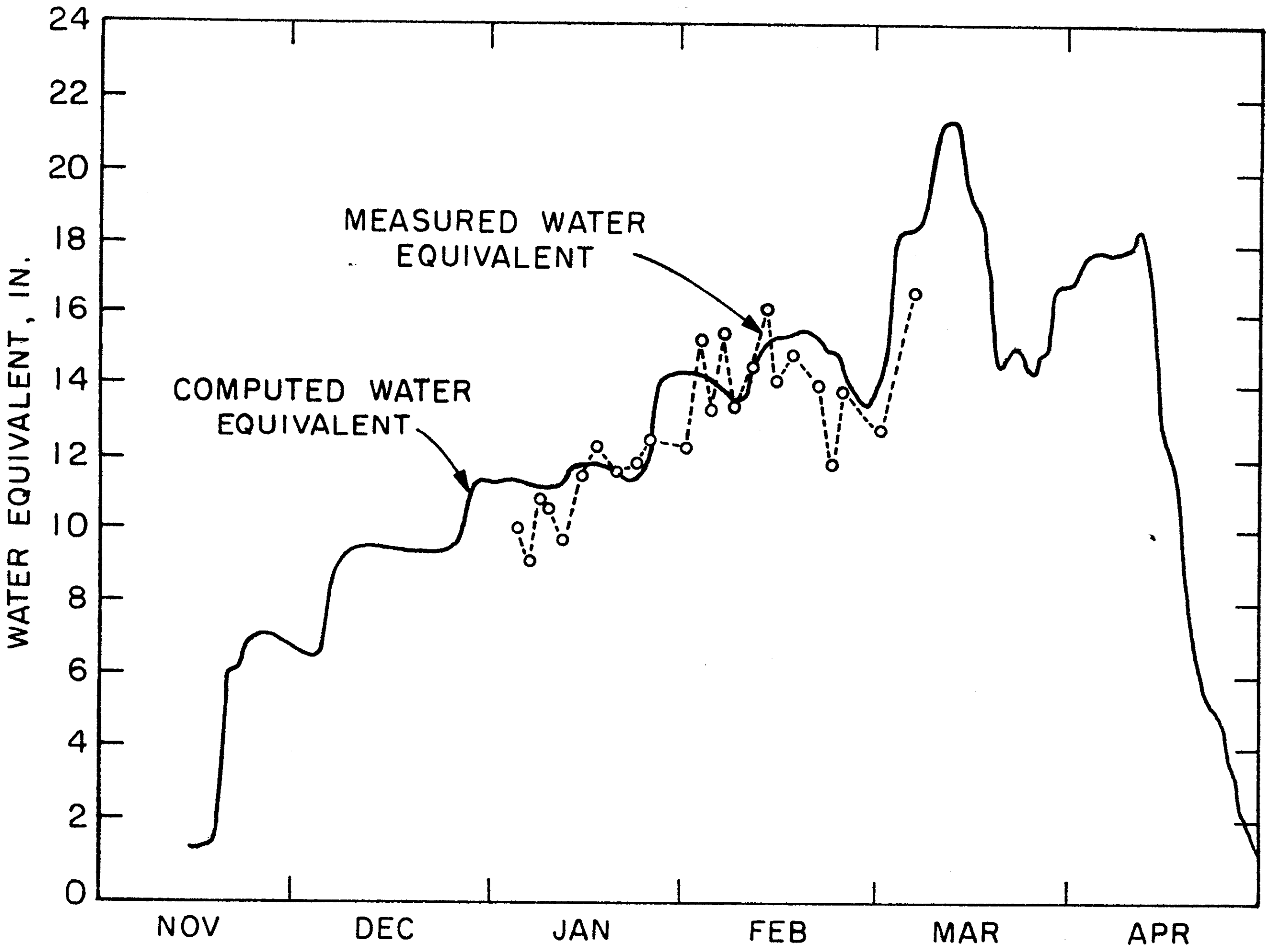

Figure 5.3 Synthesized and Measured Mean Water Equivalents at the CSSL for the 1946-1947 Snow Season (Amorocho and Espildora, 1966)

good agreement with the total water input. In Figure 5.3 it is apparent that the changes in snowpack water equivalent may be simulated with reasonable accuracy over an extended period of time. These two results, taken together, support the conclusion that the time distribution and the magnitude of the snow accumulation and melting events are being modelled reasonably accurately.

A result typical of those found in the Anderson and Crawford study[3], using a temperature index method, is shown in Figure 5.4. Here, the streamflows estimated by the Stanford Watershed Model for the computed snowmelt quantities are compared with those actually observed. Again, it may be seen that the time distribution and volumes of runoff are in good agreement with the observations, indicating that the snow accumulation and melt processes have been estimated in a reasonable way.

On the basis of these and similar results for other snow seasons and other locations, it was concluded that with proper estimation of the required model parameters, these models are generally applicable. Since these results were obtained using essentially the same techniques as were used in this study, no need was seen to test this model over extended periods of time or for a wide range of topographical conditions. Rather, it was felt that the model would be adequately tested through the demonstration that proper results were obtained in several test runs, which collectively utilize each of the computational procedures that have been extensively tested in the past.

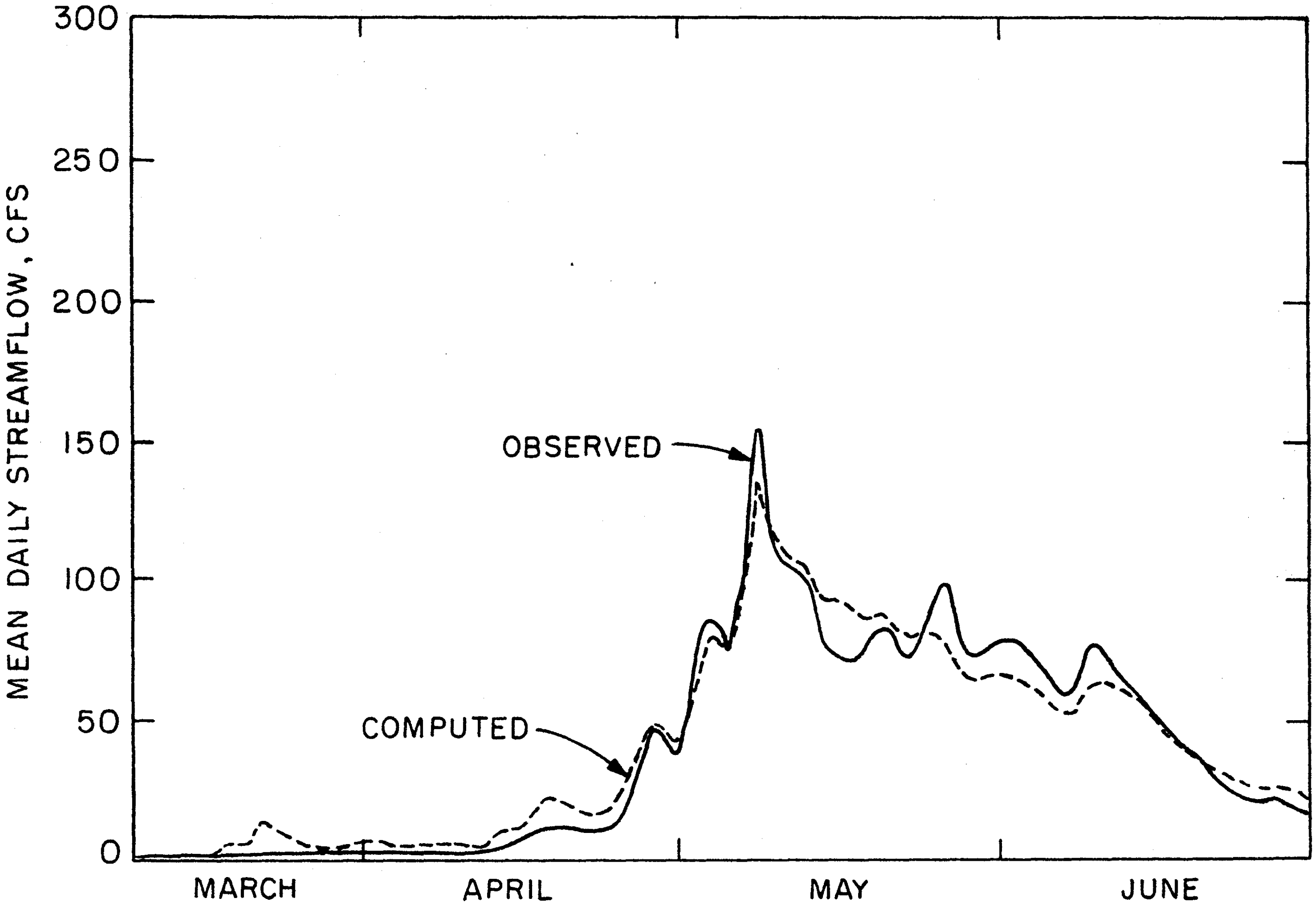

Figure 5.4 Synthesized and Observed Mean Daily Streamflows for the Skyland Creek of the UCSL for the 1946-1947 Snow Season (Anderson and Crawford, 1964)

For the purposes of testing the model using the Skyland Creek watershed, the basin was divided into four sections, each considered to be relatively uniform with respect to its data observation stations. This division of the watershed and the location of the gages used is shown in Figure 5.5. Area IV was used for testing the model with various data inputs because it was the smallest, most uniform, and its gaging stations were centrally located.

It was desirable to run the tests over a period of time in which there was both snowfall and significant melting. For the Skyland Creek watershed the month of April satisfied this requirement best, and was used for most of the test runs.

Three sets of data were used in testing the various computational procedures utilized by the model. The purpose of each and the meteorological variables used are indicated below. In each case, Area IV was modelled for April 1949 using a one-hour computation interval.

(i) Data Set I - Tests the model using the temperature index method. Includes the following data:

Air Temperature (hourly)
Precipitation (6-hour total)

Daily summaries of several important snowpack parameters for results using this data are shown in Table 5.1.

(ii) Data Set II - Tests the model using the heat budget approach for very limited data. Includes:

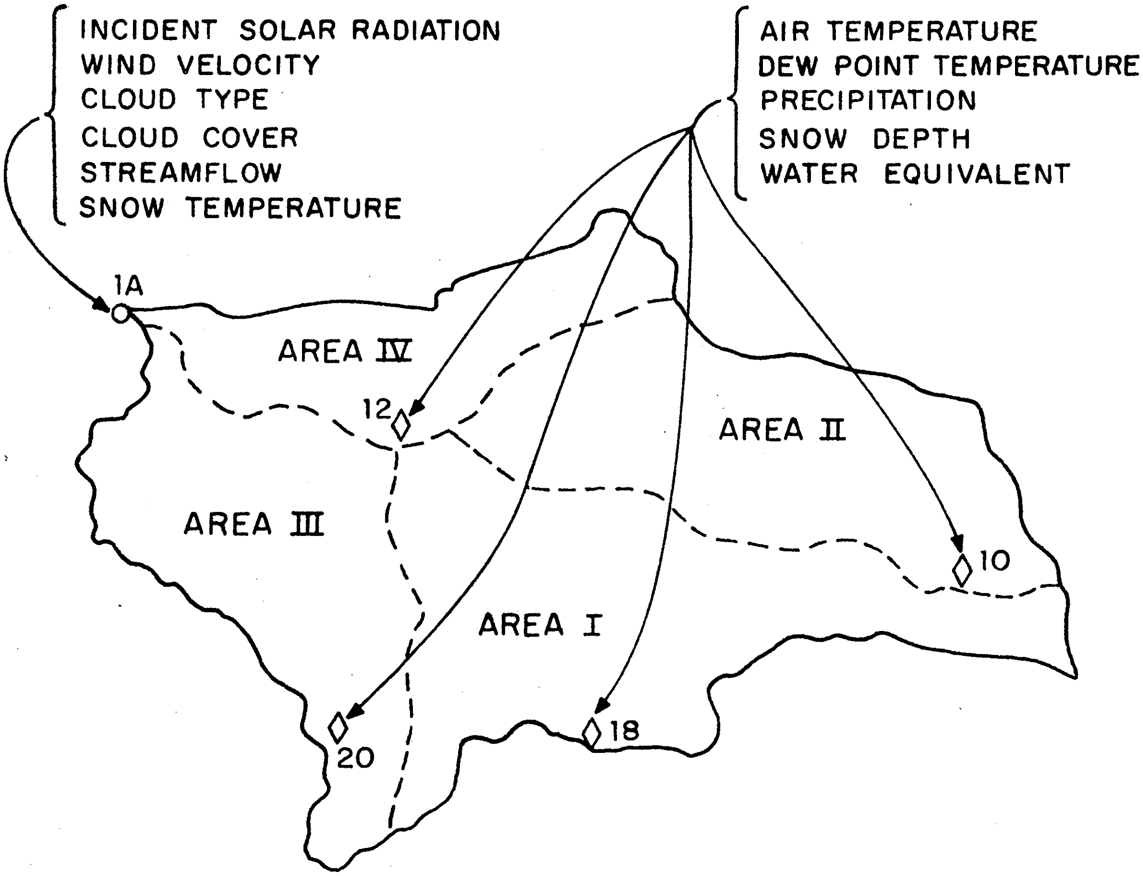

Figure 5.5 Sub-divisions of the Skyland Creek Watershed and the Location of the Gaging Stations

Table 5.1 Daily Summaries of Selected Snowpack Parameters Using Data Set I and a 1-hour Computation Interval

DAY	AVERAGE SNOW DEPTH, IN.	AVERAGE WATER EQUIVALENT, IN.	AVERAGE SNOW TEMP., DEG F	TOTAL MELT, IN.
1	69.60	21.90	30.85	0.0
2	69.60	21.90	30.29	0.0
3	69.42	21.84	31.57	0.0
4	68.69	21.70	32.00	0.0
5	67.10	21.21	32.00	0.16
6	65.77	20.79	32.00	0.47
7	64.22	20.30	32.00	0.55
8	62.81	19.85	32.00	0.34
9	62.07	19.81	32.00	0.04
10	60.97	19.60	32.00	0.34
11	59.12	19.02	32.00	0.58
12	58.43	18.90	32.00	0.03
13	58.60	19.11	31.99	0.05
14	58.92	19.32	31.74	0.03
15	58.63	19.29	32.00	0.14
16	57.46	18.91	32.00	0.51
17	56.12	18.58	32.00	0.36
18	54.48	18.14	32.00	0.54
19	52.78	17.63	32.00	0.54
20	52.23	17.55	31.98	0.07
21	52.46	17.71	31.90	0.04
22	52.56	17.80	31.53	0.13
23	52.27	17.74	32.00	0.49
24	52.35	17.91	31.96	0.24
25	51.99	17.81	32.00	0.18
26	51.07	17.56	32.00	0.40
27	49.37	17.02	32.00	0.69
28	47.28	16.31	32.00	0.71
29	45.72	15.77	32.00	0.33
30	45.83	15.83	31.91	0.01

Air temperature (daily extremes)
Dew point temperature (daily extremes)
Wind velocity (6-hour average)
Precipitation (6-hour total)
Cloud type (daily average)
Cloud cover (daily average)

Daily summaries for this data are shown in Table 5.2.

(iii) Data Set III - Tests the model using the heat budget approach for high data availability. Includes:

Air temperature (hourly)
Dew point temperature (hourly)
Wind velocity (hourly)
Precipitation (6-hour total)
Incident Solar Radiation (hourly)
Cloud type (daily average)
Cloud cover (daily average)

Daily summaries for this data are shown in Table 5.3.

The values of each of the four snowpack parameters tabulated in Tables 5.1-5.3 are shown plotted versus time in Figures 5.6-5.9. Although points indicating actual observations of the plotted variables are scarce, those shown indicate reasonably close agreement between the computed depths, water equivalents and snow

Table 5.2 Daily Summaries of Selected Snowpack Parameters Using Data Set II and a 1-hour Computation Interval

DAY	AVERAGE SNOW DEPTH, IN.	AVERAGE WATER EQUIVALENT, IN.	AVERAGE SNOW TEMP., DEG F	TOTAL MELT, IN.
1	70.52	21.88	31.16	0.0
2	70.14	21.86	31.53	0.0
3	69.60	21.85	31.62	0.0
4	68.21	21.59	32.00	0.08
5	65.77	20.85	32.00	0.73
6	63.86	20.25	32.00	0.63
7	61.80	19.68	32.00	0.69
8	60.20	19.27	32.00	0.23
9	59.17	19.17	32.00	0.16
10	57.61	18.88	32.00	0.45
11	55.90	18.36	32.00	0.45
12	55.15	18.21	31.96	0.01
13	55.24	18.33	31.77	0.0
14	55.52	18.51	31.71	0.0
15	55.34	18.53	31.37	0.0
16	54.42	18.35	31.95	0.0
17	52.52	17.90	32.00	0.41
18	50.30	17.34	32.00	0.62
19	48.22	16.72	32.00	0.78
20	47.04	16.48	32.00	0.18
21	47.04	16.55	29.70	0.0
22	47.13	16.62	30.56	0.22
23	46.32	16.43	31.99	0.87
24	46.10	16.45	31.59	0.14
25	45.94	16.69	32.00	0.0
26	44.57	16.38	32.00	0.54
27	42.15	15.66	32.00	0.89
28	39.62	14.80	32.00	0.84
29	37.97	14.26	32.00	0.32
30	38.08	14.42	31.99	0.00

Table 5.3 Daily Summaries of Selected Snowpack Parameters Using Data Set III and a 1-hour Computation Interval

DAY	AVERAGE SNOW DEPTH, IN.	AVERAGE WATER EQUIVALENT, IN.	AVERAGE SNOW TEMP., DEG F	TOTAL MELT, IN.
1	70.65	21.91	30.87	0.0
2	70.64	21.93	30.64	0.0
3	70.73	21.96	30.50	0.0
4	70.26	21.81	31.11	0.0
5	68.62	21.33	32.00	0.26
6	66.78	20.77	32.00	0.65
7	64.74	20.19	32.00	0.65
8	63.04	19.69	32.00	0.31
9	62.32	19.66	32.00	0.07
10	61.10	19.49	32.00	0.37
11	59.00	18.86	32.00	0.74
12	57.86	18.60	31.96	0.01
13	57.69	18.64	31.78	0.35
14	57.69	18.76	31.71	0.06
15	57.28	18.85	32.00	0.08
16	56.27	18.76	32.00	0.23
17	54.61	18.38	32.00	0.48
18	52.59	17.89	32.00	0.56
19	50.51	17.28	32.00	0.77
20	49.63	17.12	31.95	0.07
21	49.93	17.30	30.81	0.0
22	50.13	17.42	31.12	0.07
23	49.65	17.37	31.98	0.69
24	49.57	17.44	30.14	0.16
25	49.78	17.51	25.87	0.0
26	49.75	17.51	28.01	0.12
27	48.36	17.16	32.00	0.74
28	45.75	16.31	32.00	0.97
29	43.82	15.65	32.00	0.33
30	44.01	15.84	31.77	0.0

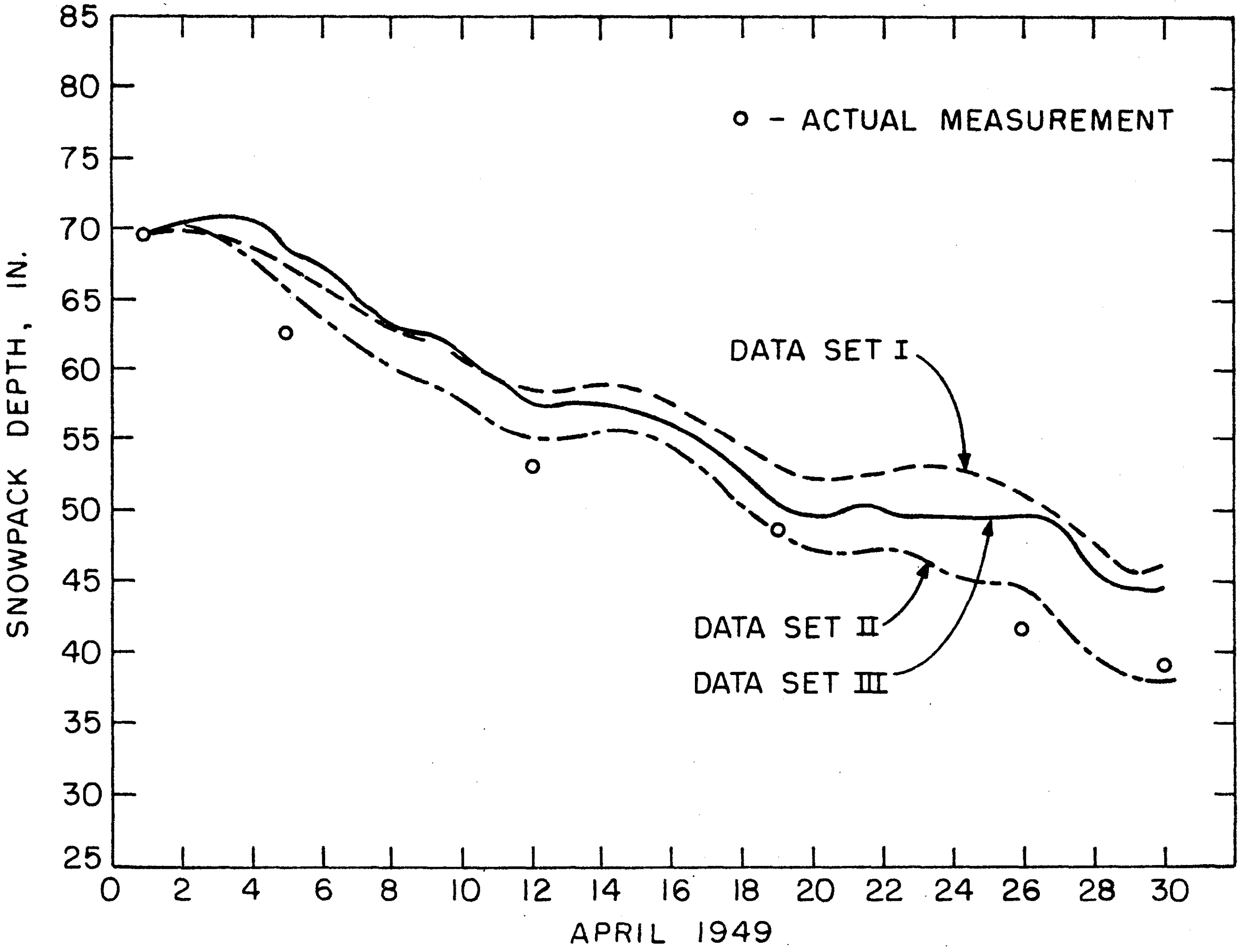

Figure 5.6 Synthesized Snowpack Depths for Various Data Inputs

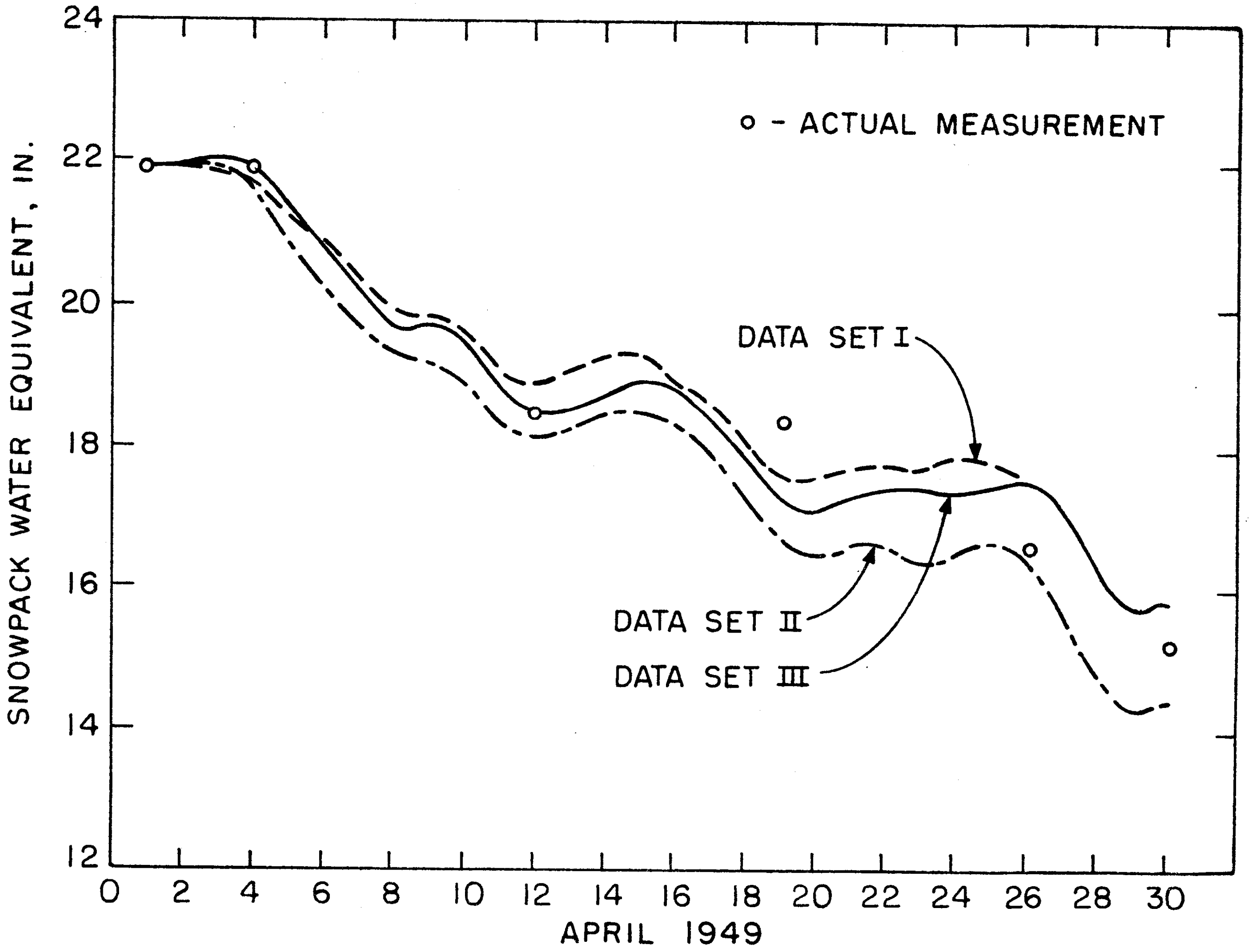

Figure 5.7 Synthesized Snowpack Water Equivalents for Various Data Inputs

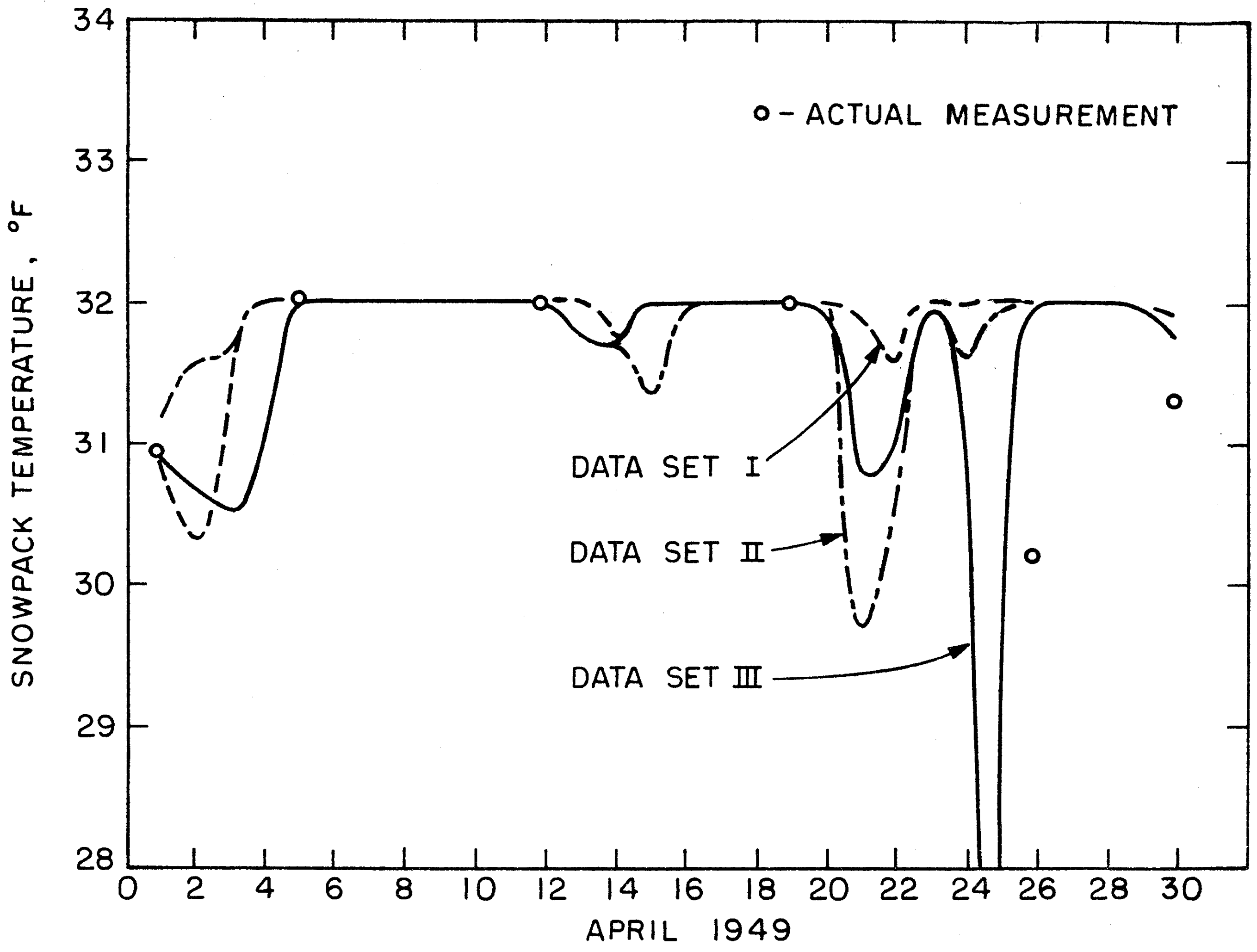

Figure 5.8 Synthesized Snowpack Temperatures for Various Data Inputs

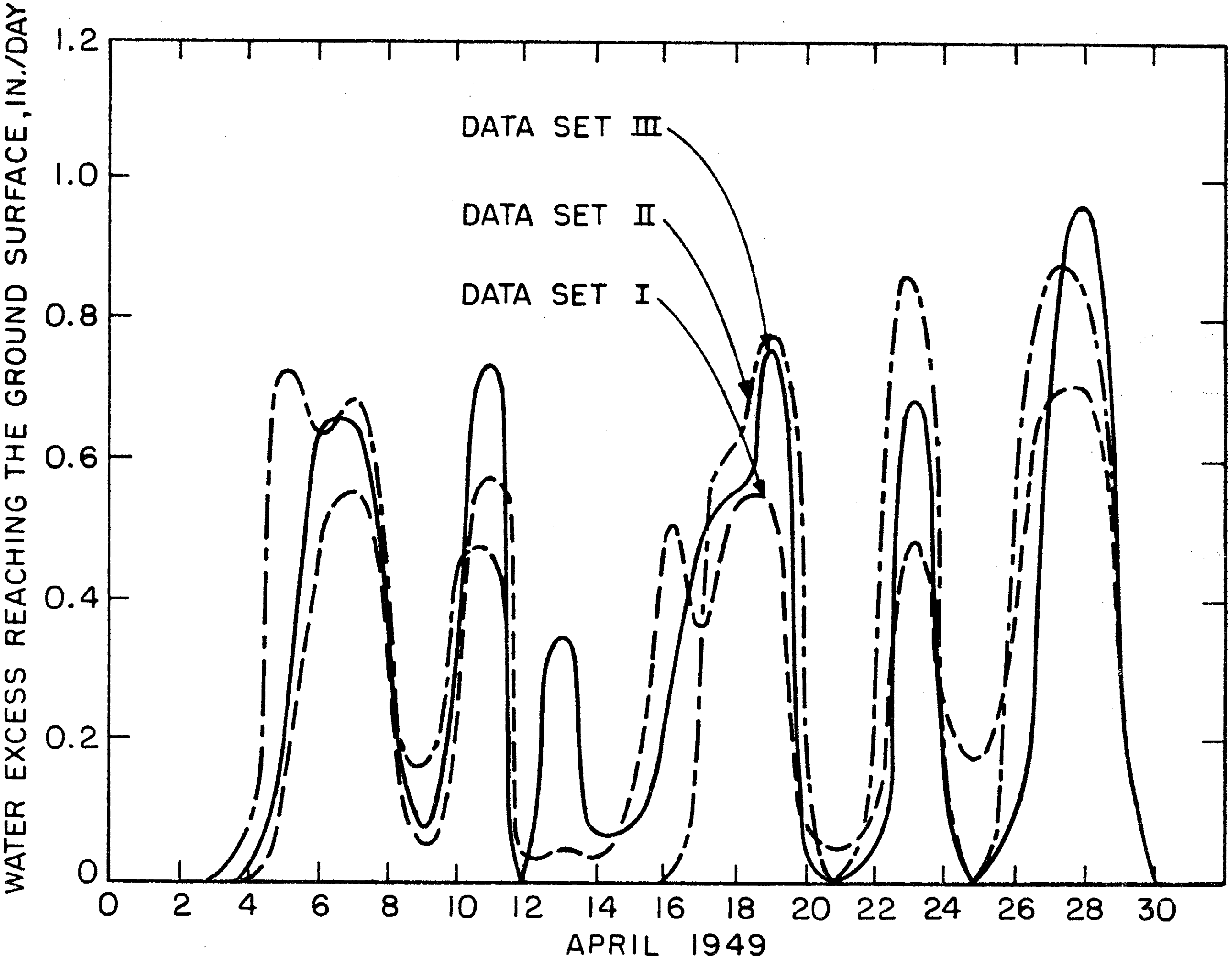

Figure 5.9 Synthesized Water Excess Reaching the Ground Surface for Various Data Inputs

temperatures, and the actual values.

The plot of the variation with time of snowpack water equivalent in Figure 5.7 is of particular importance because changes in this parameter indicate the time variation of the volume of water stored in the snowpack due to a snowfall or to melt water leaving the pack. A check of the conservation of mass equation for a typical section of the snowpack on a daily basis showed all of the water being accounted for properly. Therefore it can be concluded that the snowmelt computed by the model is directly related to the accuracy of the computed water equivalent. Examination of the curves of Figure 5.7 yields the following maximum errors in the magnitude of the water equivalent, computed only on those days where measurements were taken:

Data Set I - 6%
Data Set II - 9%
Data Set III - 6%

The timing of the melt as shown in Figure 5.9 is in good agreement for all three data sets used. On the basis of these considerations it can be concluded the modelling techniques developed previous to this study have remained valid through the process of integrating them into a single more flexible snowmelt model.

With regard to the variation of data inputs, several general comments about the sensitivity of the results to some of the model parameters are in order. Although no systematic approach was attempted to determine the relative importance or the optimal value of the parameters, a number of runs were made to examine the effect that a change in a specific parameter would have on the results.

In instances where the heat budget approach was being used to determine the heat transfer, the components found to account for the greatest amount of variability by far were the shortwave radiation component and the evaporation/condensation component. On a daily basis, these two components varied over a range of about 100 cal/cm^2 each, whereas the total heat transfer only varied over a range of about 150 cal/cm^2. The model variables affecting these components most directly were the forest cover and albedo in the case of the shortwave radiation component, and the condensation constant, FCN, in the case of the evaporation/condensation component. Careful estimation of the model parameters that determine these variables, either through physical considerations or by repeated trials, is required to produce accurate results.

In the case where the temperature index method is used to determine the heat transfer, the important variables were the basic degree-hour factor, BDHF, and the albedo. Special care must be exercised in the estimation of the basic degree-hour factor because of the very direct role that it has in determining the heat transfer.

5.2.2 Influence of the Computation Interval on Model Results

Having established that the model could reliably be used to simulate the snow accumulation and melting processes actually occurring over a period of time, the effect of the computation interval on the results obtained was then examined. In order to study the effect of the computation interval two approaches were considered. One of these was to determine analytically certain properties of the model results as the computation interval was varied over the desired range of values. This approach was not used because the underlying equations are non-linear and have time-varying coefficients. To take this approach would require the non-linear equations to be linearized about an appropriate trajectory of meteorological inputs and physical parameters. In other words, it would be necessary to select a specific example, analyse the effects of the computation interval for this example, and thereby obtain results that applied strictly to that specific example. The second approach, which was chosen, was to select the particular example and then to use the computer model to determine the effects of the computation time interval by varying the time interval used.

The example used to carry out this test was based on data used in the previous section from Area IV of the test catchment shown in Figure 5.5 for the month of April in 1949. The snowmelt computations were made on the basis of the detailed heat budget approach using the same data as the so-called Data Set III of the previous section. Several runs were made for different computation intervals; only the computation interval was varied from run to run.

The purpose of the different computer runs was to determine how the four snowpack parameters - depth, water equivalent, snow temperature, and snowmelt - were influenced by the computation interval. Four computation intervals - 1 hour, 3 hours, 6 hours, and 24 hours - were used. The computed variation over time of the water equivalent of the snow, for each of these time intervals, is shown in Figure 5.10; the variation of the snowmelt over time is shown in Figure 5.11. The computed values of each of the four snowpack parameters appear in Tables 5.3 to 5.6.

Examination of Figure 5.10 reveals that the four curves, representing computed water equivalents for the different computation intervals, differ slightly from each other. Assuming that the computed quantities for an interval of one hour are the most reliable, it is interesting to compare the other curves to the one-hour curve. Computed water equivalents based on the 3-hour time step are less than those based on the one-hour time step for the entire month. On the other hand, the computed water equivalents for the 6-hour and 24-hour time steps oscialiate above and below the corresponding values for the one-hour time step. The only general conclusion that seems appropriate is that there appears to be significant persistence in the direction of the deviations. The deviations tend to remain above or below the one-hour curve depending on previous deviations.

The computed water excess reaching the ground surface, as shown in Figure 5.11, also exhibits a tendency for values computed on the basis of different time intervals to differ from one another over the course of the month. Here, the values for the longer time intervals show higher peaks than for shorter intervals.

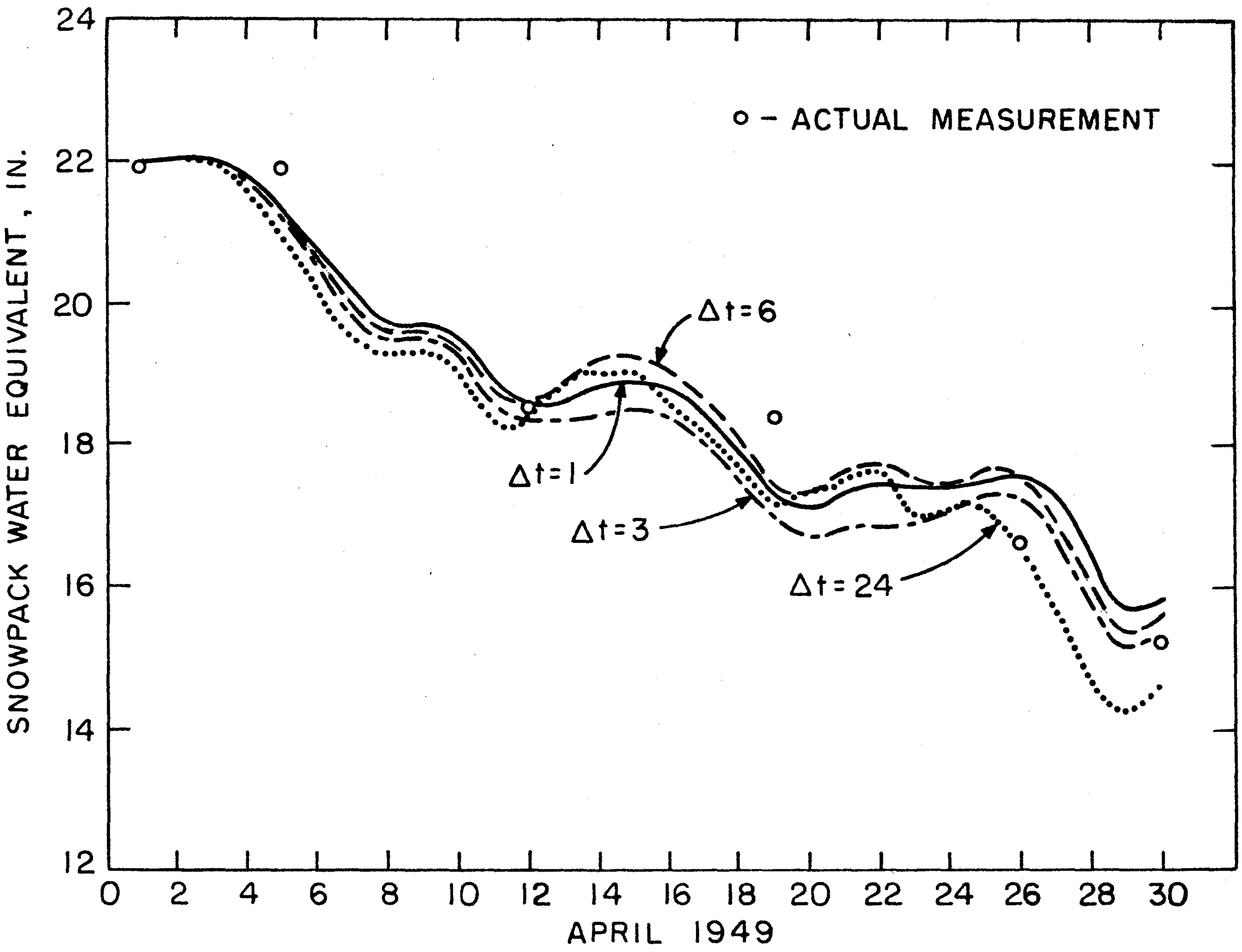

Figure 5.10 Synthesized Snowpack Water Equivalents for Various Computation Intervals

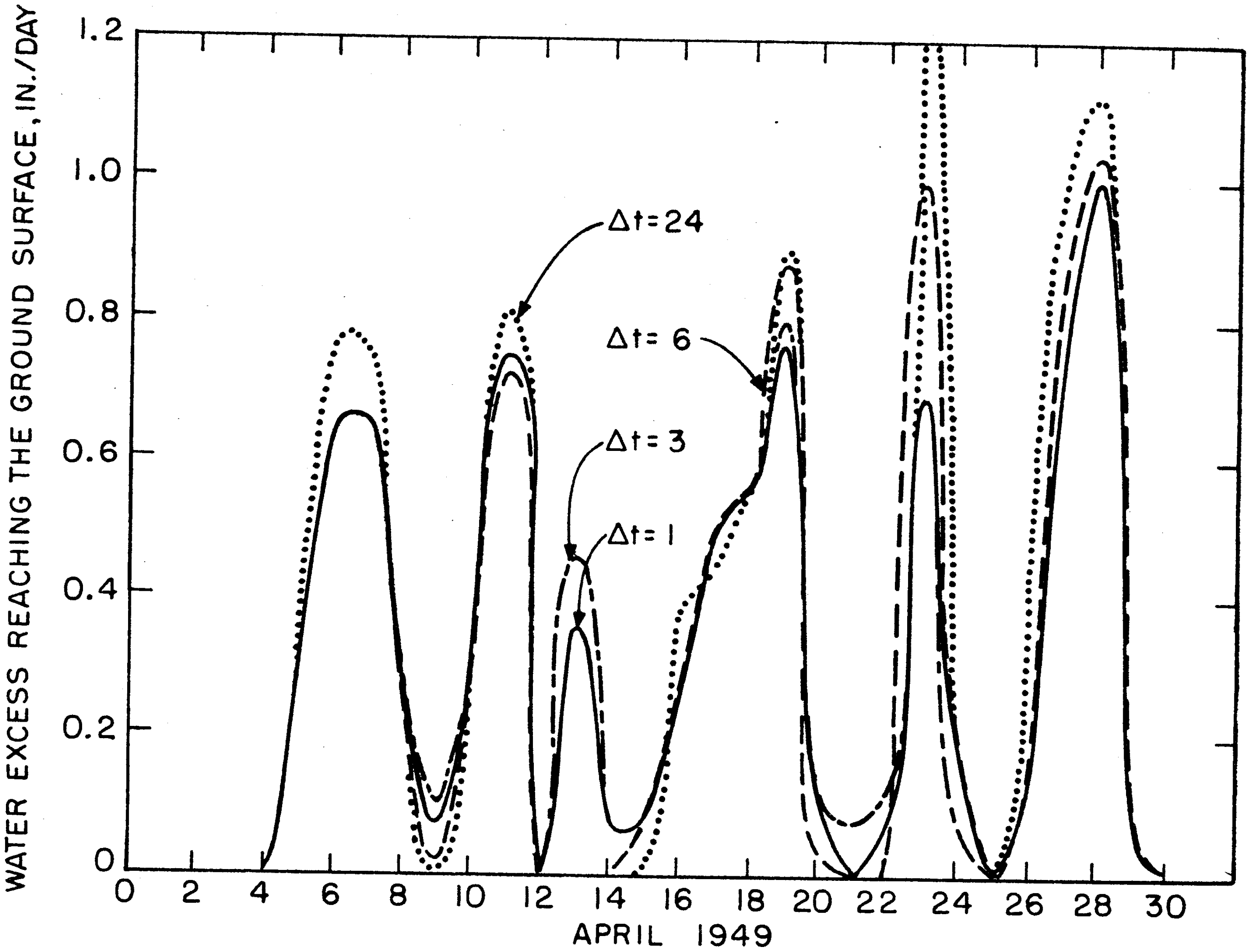

Figure 5.11 Synthesized Water Excess Reaching the Ground Surface for Various Computation Intervals

Table 5.4 Daily Summaries of Selected Snowpack Parameters Using Data Set III and a 3-hour Computation Interval

DAY	AVERAGE SNOW DEPTH, IN.	AVERAGE WATER EQUIVALENT, IN.	AVERAGE SNOW TEMP., DEG F	TOTAL MELT, IN.
1	70.56	21.89	30.82	0.0
2	70.41	21.91	31.03	0.0
3	70.31	21.92	31.00	0.0
4	69.51	21.72	31.41	0.0
5	67.73	21.17	32.00	0.36
6	65.89	20.61	32.00	0.65
7	63.90	20.03	32.00	0.65
8	62.31	19.54	32.00	0.30
9	61.49	19.50	32.00	0.10
10	60.16	19.28	32.00	0.36
11	58.08	18.63	32.00	0.75
12	57.04	18.42	32.00	0.00
13	56.56	18.40	31.99	0.45
14	56.38	18.44	31.72	0.10
15	55.92	18.52	32.00	0.07
16	54.88	18.41	32.00	0.22
17	53.21	18.02	32.00	0.49
18	51.22	17.51	32.00	0.55
19	49.18	16.89	32.00	0.81
20	48.37	16.71	31.98	0.08
21	48.51	16.83	31.17	0.09
22	48.51	16.88	31.21	0.12
23	48.06	16.85	32.00	0.69
24	48.01	17.02	31.75	0.08
25	48.04	17.33	32.00	0.0
26	47.11	17.23	32.00	0.15
27	45.00	16.59	32.00	0.79
28	42.40	15.69	32.00	1.00
29	40.61	15.06	32.00	0.32
30	40.94	15.31	31.63	0.0

Table 5.5 Daily Summaries of Selected Snowpack Parameters Using Data Set III and a 6-hour Computation Interval

DAY	AVERAGE SNOW DEPTH, IN.	AVERAGE WATER EQUIVALENT, IN.	AVERAGE SNOW TEMP., DEG F	TOTAL MELT, IN.
1	70.59	21.89	30.20	0.0
2	70.47	21.88	30.49	0.0
3	70.47	21.89	30.61	0.0
4	69.79	21.69	31.10	0.0
5	68.09	21.16	32.00	0.30
6	66.28	20.60	32.00	0.64
7	64.32	20.02	32.00	0.65
8	62.83	19.57	32.00	0.29
9	62.15	19.58	32.00	0.02
10	60.84	19.37	32.00	0.32
11	58.78	18.72	32.00	0.72
12	57.97	18.58	32.00	0.0
13	58.14	18.90	32.00	0.0
14	58.27	19.18	31.56	0.0
15	57.66	19.21	32.00	0.09
16	56.55	19.04	32.00	0.26
17	54.78	18.62	32.00	0.49
18	52.62	18.08	32.00	0.56
19	50.49	17.43	32.00	0.87
20	49.71	17.27	32.00	0.03
21	49.88	17.55	32.00	0.0
22	49.97	17.65	31.16	0.0
23	49.38	17.54	32.00	0.99
24	48.83	17.39	31.92	0.19
25	48.64	17.63	32.00	0.0
26	47.70	17.49	32.00	0.15
27	45.51	16.81	32.00	0.78
28	42.87	15.87	32.00	1.03
29	41.22	15.28	32.00	0.31
30	41.61	15.56	31.36	0.0

Table 5.6 Daily Summaries of Selected Snowpack Parameters Using Data Set III and a 24-hour Computation Interval

DAY	AVERAGE SNOW DEPTH, IN.	AVERAGE WATER EQUIVALENT, IN.	AVERAGE SNOW TEMP., DEG F	TOTAL MELT, IN.
1	70.79	21.94	27.83	0.0
2	70.79	21.94	28.44	0.0
3	70.76	21.94	31.53	0.0
4	69.91	21.67	32.00	0.0
5	67.45	20.91	32.00	0.38
6	65.10	20.18	32.00	0.77
7	62.81	19.47	32.00	0.74
8	61.90	19.19	32.00	0.30
9	62.04	19.33	32.00	0.0
10	61.12	19.04	32.00	0.22
11	58.60	18.26	32.00	0.81
12	58.71	18.37	31.99	0.0
13	58.96	18.82	31.99	0.0
14	59.01	18.94	31.99	0.0
15	59.18	18.99	31.51	0.0
16	58.03	18.62	32.00	0.37
17	56.77	18.22	32.00	0.43
18	55.16	17.70	32.00	0.55
19	53.17	17.06	32.00	0.90
20	53.37	17.29	32.00	0.0
21	53.59	17.51	32.00	0.0
22	53.68	17.55	32.00	0.0
23	51.76	16.93	32.00	1.43
24	51.86	16.96	32.00	0.15
25	52.02	17.01	32.00	0.01
26	50.50	16.51	32.00	0.53
27	47.83	15.64	32.00	0.91
28	44.61	14.59	32.00	1.12
29	43.49	14.22	32.00	0.39
30	44.18	14.56	31.95	0.0

The variation of these variables for different computation intervals may be illustrated more clearly using an error criterion to determine how the computed results differ from the one-hour results as the computations proceed in time. The criterion selected for this purpose was the rms (root-mean-square) error up to time, t, between the values of a snowpack parameter computed with a time step, Δt, and the corresponding values computed with a one-hour time step. Let $x(t, \Delta t)$ be the value of a snowpack parameter (e.g., water equivalent, snowmelt) computed at time t, using a time step of Δt. The rms error criterion $\varepsilon(t, \Delta t)$ at time t for a snowpack parameter computed using a time step Δt is then defined as

$$\varepsilon(t,\Delta t) = \sum_{j=1}^{t/\Delta t} [x(j,\Delta t) - x(j\Delta t,1)]^2 \frac{\Delta t}{t}$$

It is important to note that in this expression the one-hour values are sampled from the computed one-hour values only at intervals of Δt in order to correspond in time to the values computed using a time step of Δt.

The results of computing the error according to this criterion for computation intervals, Δt, of 3 hours, 6 hours, and 24 hours, are shown in Figures 5.12 and 5.13 for the computed water equivalents and water excesses, respectively. There is a tendency for the errors to increase with the duration of the simulation, but they appear to approach a steady-state level. In general, it can be seen that the relative error is greater for larger computation intervals.

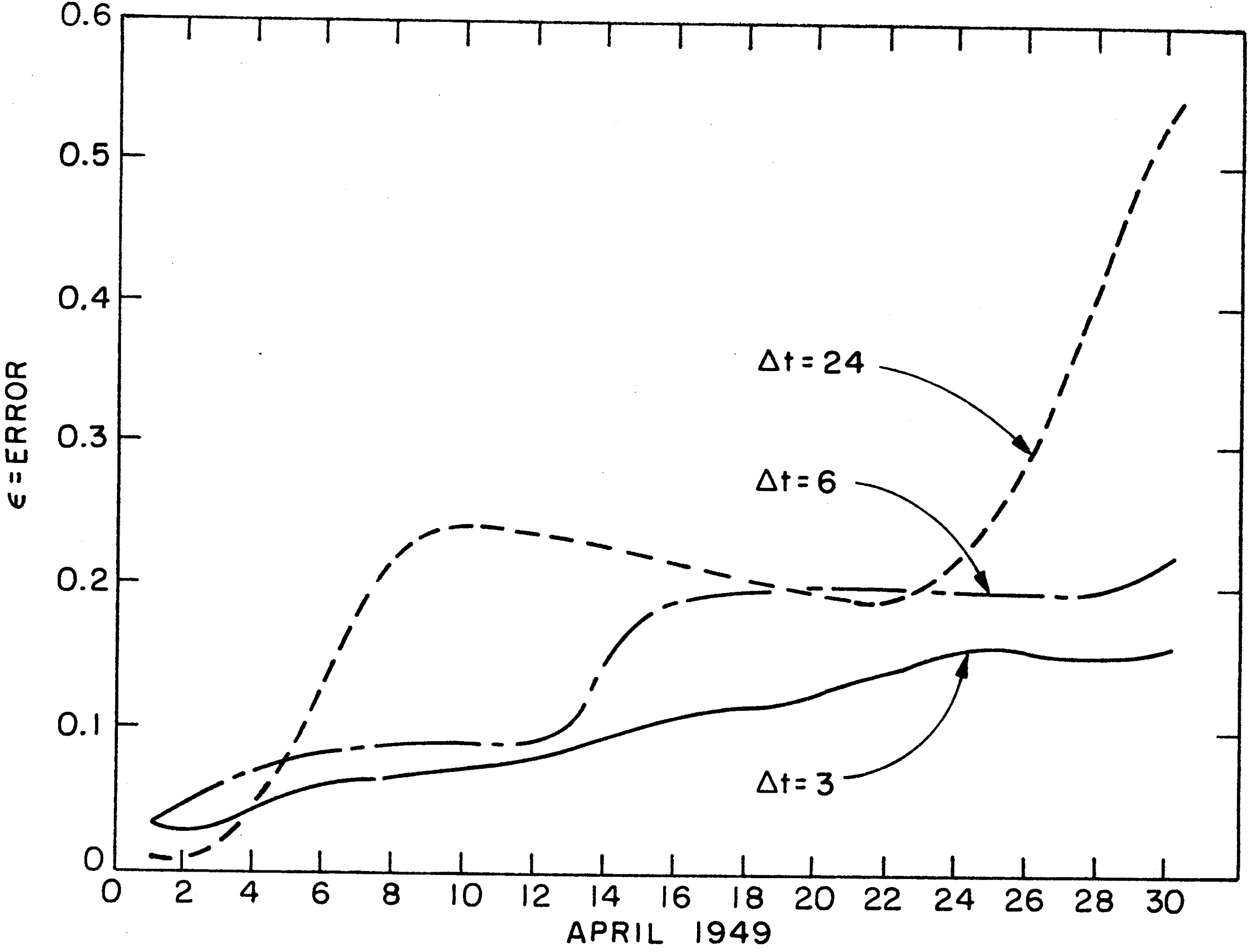

Figure 5.12 RMS Error in Synthesized Water Equivalents

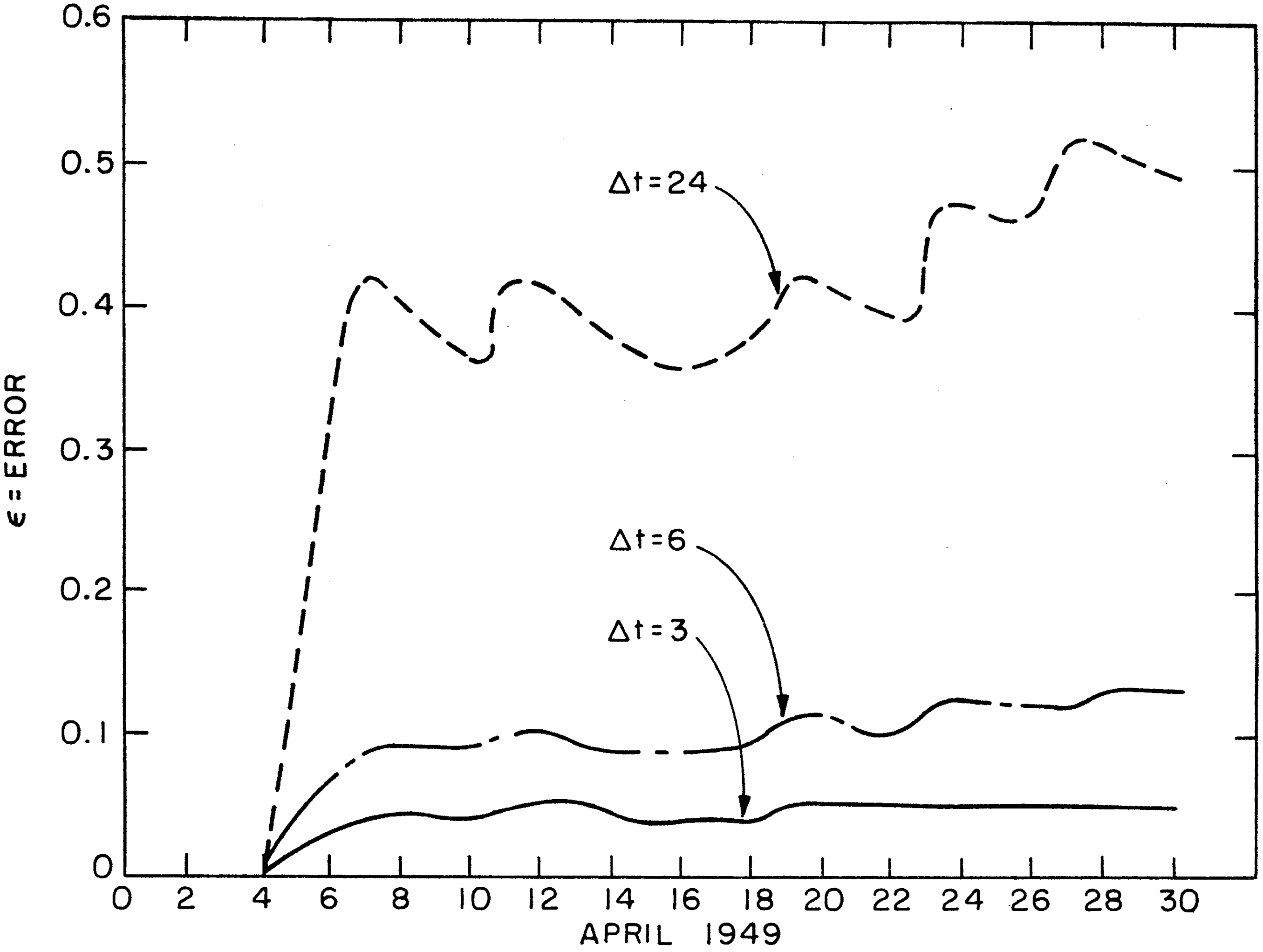

Figure 5.13 RMS Error in Synthesized Water Excess Values

5.2.3 Synthesis of Streamflows

As a practical demonstration of the use of the snowmelt model, streamflows were synthesized for the Skyland Creek of the UCSL, based on computed snowmelts. Since the purpose of the model developed in this study is to compute only the water excess reaching the ground surface, and not to route this excess downstream, the snowmelt model must be used in conjunction with an existing runoff model. This runoff model must have the capability of representing the overland flow and channel routing of the computed snowmelts.

The runoff model selected for this purpose was developed by Schaake[14], based on the theoretical motion of kinematic waves in uniform channels with both lateral and upstream inflows. Although a detailed description of this model will not be given here, some comments regarding its general nature and operation are in order.

For the use of this model, a catchment is divided into segments to account for the essential catchment characteristics. These segments are of two basic types: overland flow and flow in a channel. The kinematic wave equation to be solved for each segment is

$$\frac{\delta A}{\delta t} + \frac{\delta Q}{\delta x} = q \tag{5.2}$$

where A is the area of flow, Q is the rate of flow, q is the rate of lateral inflow, t denotes time, and x denotes distance along the segment in the downstream direction. The dependent variables are A and Q, and these are functions of the independent variables x and t. The variables A and Q are related by

$$Q = \alpha A^{m} \tag{5.3}$$

which, substituted into Equation 5.2, gives

$$\frac{\delta A}{\delta t} + \alpha\ m\ A^{m-1} \frac{\delta A}{\delta x} = q \tag{5.4}$$

This equation contains only one dependent variable, so it can be solved to give a relationship for A in terms of x, t, and q. This result can then be used in Equation 5.3 to give Q(t), the outflow hydrograph from the segment. The constants α and m are model parameters related to the physical characteristics of the segments.

For the application of this model to the Skyland Creek, the four subdivisions of the watershed shown in Figure 5.1 were taken as overland flow segments draining into two channel segments as shown schematically in Figure 5.14. The lateral inflow, q, in Equation 5.4 for the overland flow segments is the effective snowmelt rate (in/hr), and for the channel flow segments, q is the calculated flow rate from the appropriate overland flow segments.

The rate of snowmelt was computed in the snowmelt model for each of the four overland flow segments for the month of April in 1949, using a computation interval of one hour. The results, corrected for a base flow, of routing these computed values through the runoff model discussed above, are shown in Figure 5.15. The streamflows actually observed in the Skyland Creek are also shown for comparison.

The response of the system to snowmelt inputs was found to be very slow, indicating that the rate of overland flow is slow for

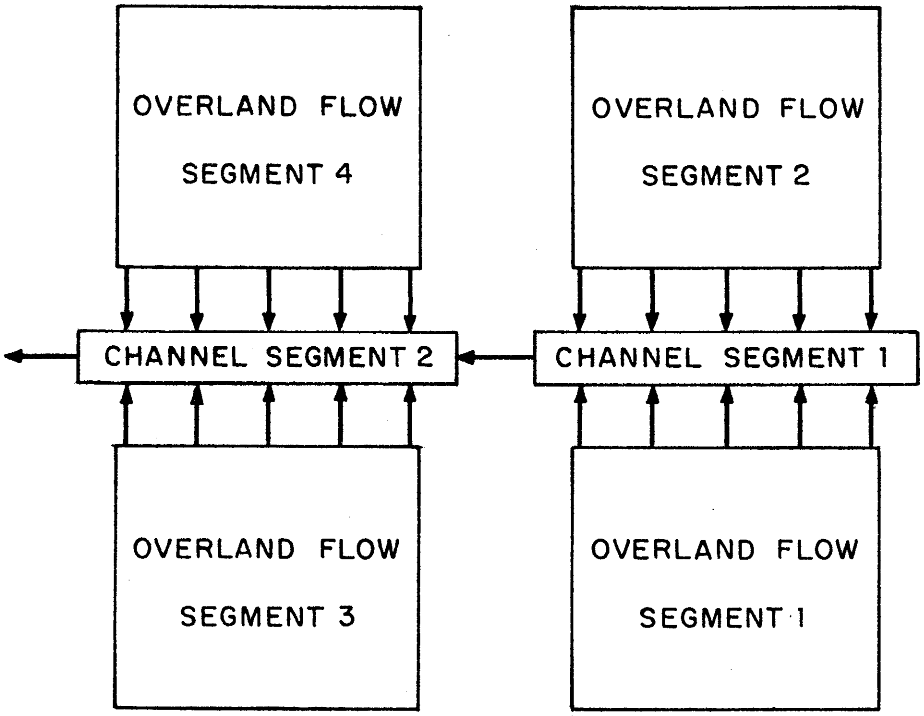

Figure 5.14 Schematic Representation of Segmentation of the Skyland Creek Watershed

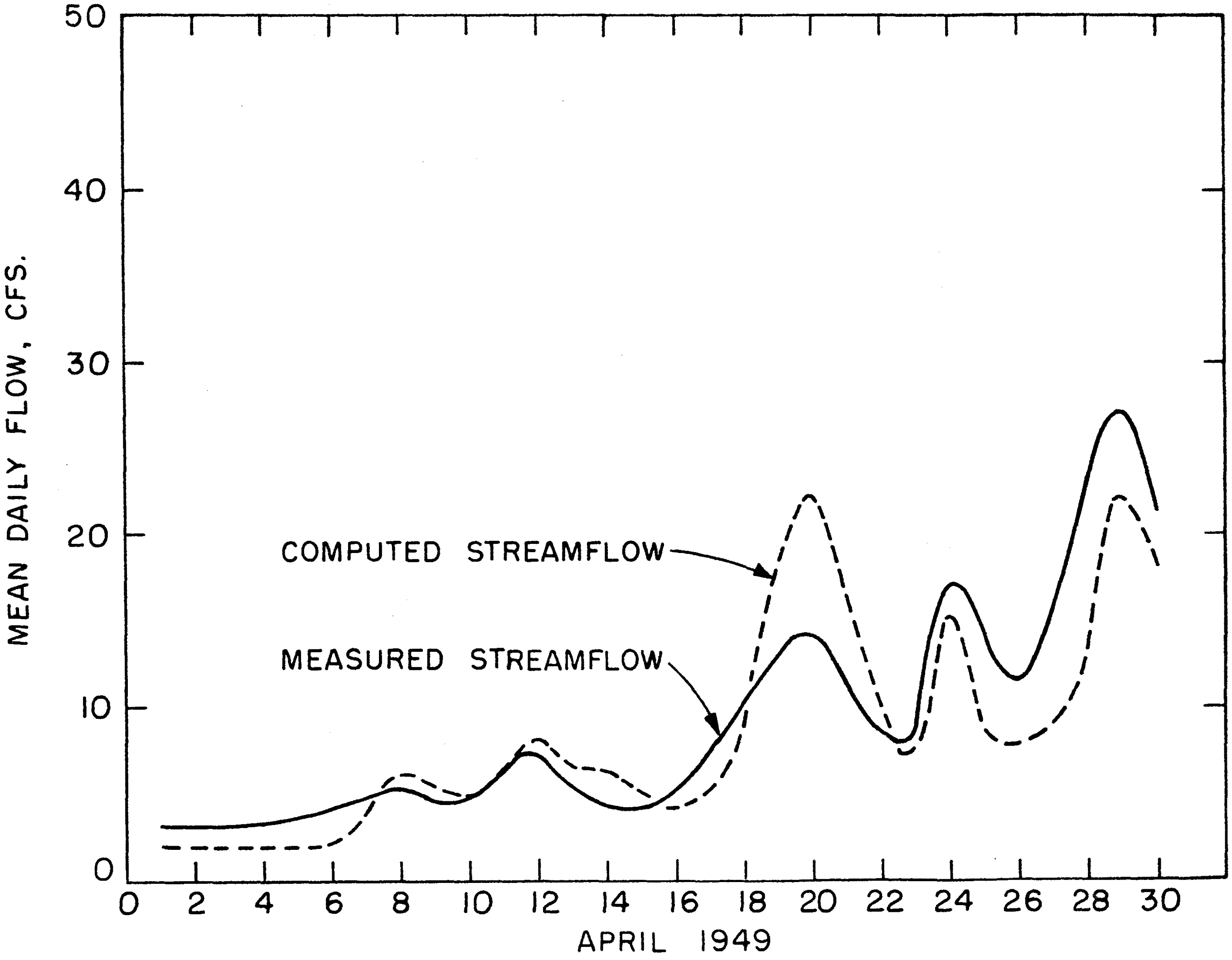

Figure 5.15 Synthesized and Observed Mean Daily Streamflows for the Skyland Creek

a snow-covered basin. In fact, this rate of flow was found to resemble porous media flow more closely than surface flow over a rough surface. The α in Equation 5.3 is the velocity of flow in the segment. Values of α of about 0.02 ft/sec were used to obtain the streamflows shown in Figure 5.15. The velocity of flow through a porous media is given by

$$\alpha = k \cdot s \tag{5.5}$$

where k is the coefficient of permeability and s is the slope. A value of α of 0.02 ft/sec for the slopes used corresponds to a coefficient of permeability of the order of 0.1 ft/sec, which is approximately the value for coarse sand. It is believed that improvements in the computed streamflow hydrographs could be obtained through further refinements in the estimates of the values of α and m.

Chapter 6

SUMMARY AND CONCLUSIONS

6.1 Summary

The objective of this study was to extend the range of applicability of previous snowmelt models by integrating appropriate parts of each into a single, more general model. It was decided that this could best be accomplished by providing the following capabilities in the model:

(i) The ability to accept many of the commonly recorded meteorological variables as data input, and based on the extent of the data provided in a given situation, apply the appropriate procedures in the simulation of the snow accumulation and melting processes.

(ii) The ability to perform the simulation computations over any specified time interval and to accept input data with any sampling interval.

Test runs of the model showed that the snow accumulation and melting processes could be successfully simulated over a wide range of data availability. Runs were made for a given set of data, and the computation interval was varied from one hour to one day. Results showed that as the computation interval increased, errors could be introduced. Finally, the snowmelt model was applied, in conjunction with an existing runoff-routing model, to an experimental catchment to estimate streamflows. It was found that the synthesized streamflows were in good general agreement with the actual observed flows, but that further refinements in certain model parameters would improve these results.

6.2 Suggestions for Future Work

This study has shown the need for further investigation of a number of topics. The following areas are suggested for future research:

1. Studies to establish a better understanding of how the variation of snow albedo with the age of the snow surface changes over the course of a year.
2. Investigation of the processes by which a snowpack is compacted, and the development of better means of expressing compaction in terms of its causes.
3. Studies of the heat exchange processes between a snowpack and the ground to develop a relationship expressing the seasonal variation of ground heat.
4. Studies of the vertical profile of snowpack temperature and liquid water content, and how these quantities vary throughout the snow season, especially during the transition to the melt season.
5. Investigations into the behavior of the melt water upon reaching the ground surface. This would involve the study of infiltration into snow-covered soil and the lateral flow of water through snow.

6. The improvement of runoff and channel routing models to better estimate streamflows on the basis of computed snowmelt quantities.

7. Systematic investigations of the relative importance of various components of the model to determine the relative time and accuracy warranted in the estimation of each of the input parameters.

8. Optimization studies to determine the distribution and nature of the best possible data collection systems. Also, studies to determine how the selection of the computation interval used effects the results, and the estimation of the best time interval to use to obtain a given level of accuracy in the results.

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APPENDIX

COMPUTER PROGRAMS

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C     ****************************************************************
C
C           MIT SNOWMELT MODEL
C           DEVELOPED BY R. LARAMIE                           MAY 1971
C           PROGRAMMED FOR THE IBM SYSTEM 360/67
C
C     ****************************************************************
C
C     MAIN PROGRAM - CONTROLS THE CALLING SEQUENCE OF THE SUBROUTINES
C     AND PREPARES INPUT FOR THE SNOWMELT SUBROUTINE.
C
      DIMENSION IC(15),CK1(7),CK2(7)
      COMMON /RITE/ IWP,IWD,IWO,IWR
      COMMON /CONST1/ LAT,NORS,ISA,ICA
      COMMON /CONST2/ TTT(10),SEP(37),SROM,PTI,CSI,CRI,SX
      COMMON /DAT/ Z1(10),Z2(10),F1(10),F2(10),DHF(10),PCF(10),EF(10),
     1SC(10),EB(10),G(10),D1(10),D2(10)
      COMMON /SUB/ ZFCV,ZFCN,FCV,FCN,BDHF,PF,EFC,SCI,B,GH,TDIF,PDIF,
     1DP,WEQ,DN,CC,TP,TS,WC,WHC,QT,TX
      COMMON /MET/ TA(65,24),TD(65,24),TW(65,24),TMAX(65),TMIN(65),
     1DMAX(65),DMIN(65),REL(65,24),V(65,24),PPT(65,24),
     2SWR(65,24),CT(65,24),CN(65,24),ECK(65,24)
      COMMON /INIT/ DPI(10),WEQI(10),DNI(10),CCI(10),TPI(10),TSI(10),
     1WCI(10),WHCI(10),QTI(10),TXI(10)
      COMMON /DTOT/ DPPT,DCON,DEVSL,DMEL,DHT,DHRS,DHRL,DHCV,DHCN,DHR,
     1DHG
      DATA CK1 /0.80,0.75,0.45,0.40,0.30,0.25,0.20/
      DATA CK2 /0.25,0.50,0.50,0.50,0.75,0.75,0.75/
C
      IRD=3
C           IRD = FILE WHERE INPUT IS LOCATED
C
      IRC=IRD
      IRS=IRD
      IRI=IRD
C
      IWM=6
C           IWM = FILE FOR OUTPUT FROM MAIN PROGRAM AND FOR ERROR
C                 MESSAGES
C
      CALL CONST (MDC,NYR,NSUB,IFYR,IBEG,INO,JCS,JCNO,MX,IRC)
      DO 20 IS=1,NSUB
      CALL SDAT (IS,NSUB,MX,IRS,IWP)
   20 CONTINUE
C           BEGIN YEAR LOOP
      DO 10 IY=1,NYR
      IYEAR=IFYR+IY-1
C           BEGIN AREA LOOP
      DO 8 IS=1,NSUB
      IF (IWO.EQ.0) GO TO 18
      IF (IY.NE.1) GO TO 17
      WRITE(IWO,90)
   90 FORMAT (/////,18X,'SIMULATION OF THE SNOW ACCUMULATION AND',
     1' MELTING PROCESSES FOR',/)
      WRITE(IWO,91) (TTT(I), I=1,10)
```

```
   91 FORMAT (30X,10A4)
      WRITE(IWO,92) NSUB
   92 FORMAT (//,40X,'USING',I4,' SUBDIVISION(S)')
      WRITE(IWO,93) NYR,IFYR
   93 FORMAT (/,35X,I4,' YEAR(S), BEGINNING IN',I6)
   17 WRITE(IWO,94) IYEAR,IS
   94 FORMAT (//,' ***********',/,' * ',I5,'  *',/,' * AREA',I2,
     1' *',/,' **********')
   18 K=0
C         SUBAREA CONSTANTS
      IF (MX.EQ.0) GO TO 21
      ZFCV=Z1(IS)
      ZFCN=Z2(IS)
      FCV=F1(IS)
      FCN=F2(IS)
      GO TO 22
   21 BDHF=DHF(IS)
   22 PF=PCF(IS)
      EFC=EF(IS)
      SCI=SC(IS)
      B=BB(IS)
      GH=G(IS)
      TDIF=D1(IS)
      PDIF=D2(IS)
C         INITIAL CONDITIONS
      DP=DPI(IS)
      WEQ=WEQI(IS)
      DN=DNI(IS)
      CC=CCI(IS)
      TP=TPI(IS)
      TS=TSI(IS)
      WC=WCI(IS)
      WHC=WHCI(IS)
      QT=QTI(IS)
      TX=TXI(IS)
      CALL MDAT (I,IC,INO,JCS,JCNO,IRI,IWM,MX)
      IF (IWD.EQ.0) GO TO 12
      CALL PRMV (IC,INO,JCNO,IWD)
C         BEGIN DAY LOOP
   12 DO 6 I=1,INO
      CALL CALDAY (IYEAR,IBEG,I,ICA,ISA,IALB,ICAL,IDM,CM)
      WEQ1=WEQ
      WC1=WC
      IF (MX.EQ.1) GO TO 13
      CALL INSOL (SRO,MX,ICAL,1,JCS,LAT,NOPS)
      FADJ=SRO/SROM
      IF (IC(4).EQ.1) GO TO 15
      DO 14 J=1,JCNO
      IF (J.EQ.1) TMIN(I)=TA(I,J)
      IF (TA(I,J).LT.TMIN(I)) TMIN(I)=TA(I,J)
   14 CONTINUE
   15 TMN=TMIN(I)
   13 DPPT=0.0
      DCON=0.0
      DEVSL=0.0
```

```
      DMEL=0.0                                                          MAP01110
      DHRS=0.0                                                          MAP01120
      DHRL=0.0                                                          MAP01130
      DHCV=0.0                                                          MAP01140
      DHCN=0.0                                                          MAP01150
      DHR=0.0                                                           MAP01160
      DHG=0.0                                                           MAP01170
      DHT=0.0                                                           MAP01180
C          COMPUTATION TIME STEP LOOP                                   MAP01190
      DO 4 J=1,JCNO                                                     MAP01200
      IF (IC(1).EQ.1) TAIR=TA(I,J)                                      MAP01210
      IF (IC(2).EQ.1) TDP=TD(I,J)                                       MAP01220
      IF (IC(7).EQ.1) WV=V(I,J)                                         MAP01230
      IF (IC(8).EQ.1) PP=PF*PPT(I,J)                                    MAP01240
      IF (IC(9).EQ.1) RAD=SWR(I,J)                                      MAP01250
      IF (IC(10).NE.1) GO TO 34                                         MAP01260
      ICT=CT(I,J)                                                       MAP01270
      IF (ICT.GE.1) GO TO 32                                            MAP01280
      CKS=1.0                                                           MAP01290
      CKL=0.0                                                           MAP01300
      GO TO 34                                                          MAP01310
32    CKS=CK1(ICT)                                                      MAP01320
      CKL=CK2(ICT)                                                      MAP01330
34    IF (IC(11).EQ.1) CNI=CN(I,J)                                      MAP01340
      IF (IC(12).EQ.12) ECKI=ECK(I,J)                                   MAP01350
C          SIMULATE SNOW ACCUM AND MELT PROCESS                         MAP01360
      CALL SNOW (TAIR,TDP,WV,PP,RAD,CKS,CKL,CNI,ECKI,IC,I,J,JCS,JCNO,   MAP01370
     1ICAL,FADJ,TMN,IALB,RMELT,TMELT,WCM,MX,IWM)                        MAP01380
C          OUTPUT DESIRED OPTION(S)                                     MAP01390
      CALL OTPT (I,INO,ICAL,J,JCNO,K,WEQ1,WC1,WCM,RMELT,TMELT,MX,1)     MAP01400
4     CONTINUE                                                          MAP01410
      CALL OTPT (I,INO,ICAL,J,JCNO,K,WEQ1,WC1,WCM,RMELT,TMELT,MX,2)     MAP01420
6     CONTINUE                                                          MAP01430
8     CONTINUE                                                          MAP01440
10    CONTINUE                                                          MAP01450
      CALL EXIT                                                         MAP01460
      END                                                               MAP01470
```

```
      SUBROUTINE CONST (MDC,NYR,NSUB,IFYR,IBEG,INO,JCS,JCNO,MX,IRC)
C
C     SUBROUTINE TO INPUT RUN DESCRIPTION DATA AND
C     GENERAL CONSTANTS.
C
      DIMENSION MDC(12)
      COMMON /RITE/ IWP,IWD,IWO,IWR
      COMMON /CONST1/ LAT,NORS,ISA,ICA
      COMMON /CONST2/ TTT(10),SEP(37),SROM,PTI,CSI,CRI,SX
C           READ TITLE CARD
      READ(IRC,1000) (TTT(I), I=1,10)
1000  FORMAT (10A4)
C           READ OUTPUT FILES CARD
      READ(IRC,1001) IWP,IWD,IWO,IWR
C           IWM = FILE FOR OUTPUT FROM MAIN PROGRAM
C           IWP =  "    "     "    OF INPUT PARAMETERS
C           IWD =  "    "     "     "  METEOROLOGICAL DATA
C           IWO =  "    "     "     "  DETAILED SNOWMELT PARAMETERS
C           IWR =  "    "     "     "  SNOWMELT VALUES ONLY
C
C.....NOTE:  TO SUPPRESS OUTPUT OF ANY OF THESE FILES SET THE FILE
C              NUMBER = 0
C
      IWC=IWP
C           READ DATA AVAILABILITY CARD
      READ(IRC,1001) (MDC(I), I=1,12)
1001  FORMAT (20I2)
      READ(IRC,1002) NYR,NSUB
1002  FORMAT (10I6)
C           NYR = NO. OF YEARS TO BE SIMULATED
C           NSUB =NO. OF SUBAREAS TO BE SIMULATED
      READ(IRC,1002) IFYR,IBEG,INO,JCS,ISA,ICA
C           IFYR =FIRST YEAR OF SIMULATION, CAL.YR.
C           IBEG =FIRST DAY OF SIMULATION, CAL.DAY
C           INO = NO. OF DAYS TO BE SIMULATED
C           JCS = COMPUTATION TIME INTERVAL, HRS
C           ISA = START OF ACCUM SEASON, CAL.DAY
C           ICA = END OF      "     "        "
      JCNO=24/JCS
      READ(IRC,1002) LAT,NORS
C           LAT = LOCAL LATITUDE OF WATERSHED
C           NORS =1, IN NORTHERN HEMISPHERE
C                 0, IN SOUTHERN HEMISPHERE
      READ(IRC,1003) PTI,CSI,CRI,SX
1003  FORMAT (10F6.2)
C           PTI  =AIR TEMP AT WHICH PPT BECOMES SNOW
C           CSI  =SNOW INTERCEPTION CONSTANT
C           CRI  =RAIN      "          "
C           SX   = SNOW ACCUM DEPTH FOR CHANGING ALBEDO INDEX
C           CHECK DATA AVAILABILITY
      M=0
      MX=0
      IF(MDC(2).EQ.1.OR.MDC(3).EQ.1.OR.MDC(5).EQ.1.OR.MDC(6).EQ.1) M=M+1
      IF (MDC(7).EQ.1.AND.MDC(8).EQ.1) M=M+1
      IF ((MDC(10).EQ.1.AND.MDC(11).EQ.1).OR.MDC(12).EQ.1) M=M+1
```

```
      IF (M.EQ.3) MX=1                                                  CON00560
      IF (MX.EQ.1) GO TO 8                                              CON00570
C           READ POTENTIAL SNOW EVAPORATION CARD                        CON00580
      READ(IRC,1003) (SEP(I), I=1,37)                                   CON00590
C           DETERMINE MOST INTENSE INSOLATION                           CON00600
      IF (NORS.EQ.1) ICAL=62                                            CON00610
      IF (NORS.EQ.0) ICAL=355                                           CON00620
      CALL INSOL (SROM,MX,ICAL,1,JCS,LAT,NORS)                          CON00630
C  IF DESIRED, PRINT OUT THIS INPUT                                     CON00640
8     IF (IWC.EQ.0) GO TO 10                                            CON00650
      WRITE(IWC,1011)                                                   CON00660
1011  FORMAT (/,' TITLE;')                                              CON00670
      WRITE(IWC,1010) (TTT(I), I=1,10)                                  CON00680
1010  FORMAT (10X,10A4)                                                 CON00690
      WRITE(IWC,1012)                                                   CON00700
1012  FORMAT (/,' IWP IWD IWO IWR')                                     CON00710
      WRITE(IWC,1009) IWP,IWD,IWO,IWR                                   CON00720
1009  FORMAT (4I4)                                                      CON00730
      WRITE(IWC,1013)                                                   CON00740
1013  FORMAT (/,' MDC(I);')                                             CON00750
      WRITE(IWC,1001) (MDC(I), I=1,12)                                  CON00760
      WRITE(IWC,1014)                                                   CON00770
1014  FORMAT (/,'    NYR  NSUB')                                        CON00780
      WRITE(IWC,1002) NYR,NSUB                                          CON00790
      WRITE(IWC,1015)                                                   CON00800
1015  FORMAT (/,'  IFYR  IBEG   INO   JCS  JCNO   ISA   ICA')           CON00810
      WRITE(IWC,1002) IFYR,IBEG,INO,JCS,JCNO,ISA,ICA                    CON00820
      WRITE(IWC,1016)                                                   CON00830
1016  FORMAT (/,'    LAT  NORS')                                        CON00840
      WRITE(IWC,1002) LAT,NORS                                          CON00850
      WRITE(IWC,1017)                                                   CON00860
1017  FORMAT (/,'    PTI   CSI   CRI    SX')                            CON00870
      WRITE(IWC,1003) PTI,CSI,CRI,SX                                    CON00880
      IF (MX.EQ.1) GO TO 10                                             CON00890
      WRITE(IWC,1018)                                                   CON00900
1018  FORMAT (/,' SEP(I);')                                             CON00910
      WRITE(IWC,1003) (SEP(I), I=1,37)                                  CON00920
10    RETURN                                                            CON00930
      END                                                               CON00940
```

```
      SUBROUTINE SDAT (IS,NSUB,MX,IRS,IWS)
C
C     SUBROUTINE TO INPUT SUBAREA CONSTANTS AND INITIAL CONDITIONS.
C
      COMMON /DAT/ Z1(10),Z2(10),F1(10),F2(10),DHF(10),PCF(10),EF(10),
     1SC(10),BB(10),G(10),D1(10),D2(10)
      COMMON /INIT/ DPI(10),WEQI(10),DNI(10),CCI(10),TPI(10),TSI(10),
     1WCI(10),WHCI(10),QTI(10),TXI(10)
      IF (MX.EQ.0) GO TO 10
      READ(IRS,1000) HT,HE,HV,FCV,FCN
 1000 FORMAT (10F6.2)
C           HT  = HEIGHT OF TEMP OBS ABOVE GROUND, FT.
C           HE  =  "     " AIR MOISTURE OBS ABOVE GROUND, FT.
C           HV  =  "     "  WIND         "     "      "    "
C           FCV = CONVECTIVE FUNCTION CONSTANT, LY.
C           FCN = CONDUCTION    "           "      "
      Z1(IS)=((HT*HV)**(-0.167))
      Z2(IS)=((HE*HV)**(-0.167))
      F1(IS)=FCV
      F2(IS)=FCN
      GO TO 12
   10 READ(IRS,1000) BDHF
C           BDHF =BASIC DEGREE-HOUR FACTOR, LY/HR/DEG F
      DHF(IS)=BDHF
   12 READ(IRS,1000) PF,FC,FD,SCI,GH,ELT,ELP,ELM
C           PF  = PRECIPITATION CORRECTION FACTOR
C           FC  = FOREST COVER, PC OF AREA
C           FD  = FOREST DENSITY, PC
C           SCI = SNOW WATER EQUIVALENT FOR COMPLETE COVER, IN.
C           GH  = GROUND HEAT CONSTANT, LY/HR
C           ELT = ELEV OF TEMP OBS, 1000'S OF FT ABOVE MSL
C           ELP = ELEV OF PPT OBS, 1000'S OF FT ABOVE MSL
C           ELM = MEAN ELEV OF THE AREA, 1000'S OF FT ABOVE MSL
      PCF(IS)=PF
      EF(IS)=FC*FD
      SC(IS)=SCI
      BB(IS)=ALOG(SCI+1.)
      G(IS)=GH
      D1(IS)=ELT-ELM
      D2(IS)=ELP-ELM
      READ(IRS,1000) DPI(IS),WEQI(IS),DNI(IS),CCI(IS),TPI(IS),TSI(IS),
     1WCI(IS),WHCI(IS),QTI(IS),TXI(IS)
C           DPI   = INITIAL PACK DEPTH, IN.
C           WEQI  =    "     "  WATER EQUIVALENT, IN.
C           DNI  =    "     "  DENSITY
C           CCI   =    "     "  COLD CONTENT, IN.
C           TPI   =    "     "  TEMP, DEG F
C           TSI   =    "     "  SURFACE TEMP, DEG F
C           WCI  =    "     "  WATER CONTENT
C           WHCI  =    "     "  WATER HOLDING CAPACITY
C           QTI =    "     "  THERMAL QUALITY
C           TXI   =    "     "  ALBEDO INDEX (AGE OF SNOW SURFACE)
      IF (IS.NE.NSUB) RETURN
      IF (IWS.EQ.0) RETURN
      WRITE(IWS,999)
```

```
999   FORMAT (/,' SUBAREA CONSTANTS')                                   SDA00560
      IF (MX.EQ.0) GO TO 15                                             SDAC0570
      WRITE(IWS,1001)                                                   SDA00580
1001  FORMAT (/,'   AREA      ZFCV   ZFCN    FCV    FCN     PR    EFC', SDA00590
     1'    SCI     GH    TDIF    PDIF',/)                               SDA00600
      DO 20 K=1,NSUB                                                    SDA00610
20    WRITE(IWS,1002) K,Z1(IS),Z2(IS),F1(IS),F2(IS),PCF(IS),EF(IS),     SDA00620
     1SC(IS),G(IS),D1(IS),D2(IS)                                        SDA00630
1002  FORMAT (3X,I4,3X,10F7.3)                                          SDA00640
      GO TO 18                                                          SDAC0650
15    WRITE(IWS,1003)                                                   SDA00660
1003  FORMAT (/,'   AREA      BDHF     PF    EFC    SCI      B',        SDA00670
     1'      GH   TDIF   PDIF',/)                                       SDA00680
      DO 21 K=1,NSUB                                                    SDA00690
21    WRITE(IWS,1002) K,DHF(IS),PCF(IS),EF(IS),SC(IS),BB(IS),G(IS),     SDA00700
     1D1(IS),D2(IS)                                                     SDA00710
18    WRITE(IWS,1005)                                                   SDA0C720
1005  FORMAT (/,' INITIAL SNOWPACK PARAMETERS')                         SDA00730
      WRITE(IWS,1004)                                                   SDA00740
1004  FORMAT (/,'   AREA       DPI   WEQI    DNI     CCI     TPI',      SDA00750
     1'    TSI    WCI   WHCI    QTI     TXI',/)                         SDA00760
      DO 22 K=1,NSUB                                                    SDA00770
22    WRITE(IWS,1002) K,DPI(K),WEQI(K),DNI(K),CCI(K),TPI(K),TSI(K),     SDA00780
     1WCI(K),WHCI(K),QTI(K),TXI(K)                                      SDA00790
      RETURN                                                            SDAC0800
      END                                                               SDA00810
```

```
      SUBROUTINE MDAT (I,IC,INO,JCS,JCNO,IRI,IWM,MX)
C
C     SUBROUTINE TO INPUT METEOROLOGICAL VARIABLES AND PERFORM THE
C     REQUIRED ADJUSTMENTS.
C
      DIMENSION IC(15),A(2500)
      COMMON /MET/ TA(65,24),TD(65,24),TW(65,24),TMAX(65),TMIN(65),
     1DMAX(65),DMIN(65),REL(65,24),V(65,24),PPT(65,24),
     2SWR(65,24),CT(65,24),CN(65,24),ECK(65,24)
      DATA VEND /'$'/
      DO 100 IK=1,15
100   IC(IK)=0
200   CALL INPT (IK,JTS,IUC,A,IRI,IWM)
      JTNO=24/JTS
      IC(IK)=1
      IF (A(1).EQ.VEND) GO TO 250
      DO 300 I=1,INO
      IF (IK.NE.4) GO TO 140
      TMAX(I)=A(2*I-1)
      TMIN(I)=A(2*I)
      IF (IUC.EQ.1) GO TO 300
      TMAX(I)=1.80*TMAX(I)+32.
      TMIN(I)=1.80*TMIN(I)+32.
      GO TO 300
140   IF (IK.NE.5) GO TO 150
      DMAX(I)=A(2*I-1)
      DMIN(I)=A(2*I)
      IF (IUC.EQ.1) GO TO 300
      DMAX(I)=1.80*DMAX(I)+32.
      DMIN(I)=1.80*DMIN(I)+32.
      GO TO 300
150   IN=0
      IJ=0
      SUM=0.0
      DO 290 J=1,JTNO
      IA=JTNO*(I-1)+J
      GO TO (201,202,203,300,300,206,207,208,209,210,211,212), IK
201   TA(I,J)=A(IA)
      IF (IUC.EQ.1) GO TO 21
      TA(I,J)=1.80*TA(I,J)+32.
21    IF (JTS.NE.JCS) CALL ADJ (TA,I,J,JTS,JTNO,JCS,JCNO,IK,IN,IJ,SUM)
      GO TO 290
202   TD(I,J)=A(IA)
      IF (IUC.EQ.1) GO TO 22
      TD(I,J)=1.80*TD(I,J)+32.
22    IF (JTS.NE.JCS) CALL ADJ (TD,I,J,JTS,JTNO,JCS,JCNO,IK,IN,IJ,SUM)
      GO TO 290
203   TW(I,J)=A(IA)
      IF (IUC.EQ.1) GO TO 23
      TW(I,J)=1.80*TW(I,J)+32.
23    IF (JTS.NE.JCS) CALL ADJ (TW,I,J,JTS,JTNO,JCS,JCNO,IK,IN,IJ,SUM)
      GO TO 290
206   REL(I,J)=A(IA)
      IF (JTS.NE.JCS) CALL ADJ (REL,I,J,JTS,JTNO,JCS,JCNO,IK,IN,IJ,SUM)
      GO TO 290
```

```
207     V(I,J)=A(IA)                                                    MDA00560
        IF (IUC.EQ.1) GO TO 27                                          MDA00570
        V(I,J)=0.621*V(I,J)                                             MDA00580
27      IF (JTS.NE.JCS) CALL ADJ (V,I,J,JTS,JTNO,JCS,JCNO,IK,IN,IJ,SUM) MDA00590
        GO TO 290                                                       MDA00600
208     PPT(I,J)=A(IA)                                                  MDA00610
        IF (IUC.EQ.1) GO TO 28                                          MDA00620
        PPT(I,J)=PPT(I,J)/2.54                                          MDA00630
28      IF (JTS.NE.JCS) CALL ADJ (PPT,I,J,JTS,JTNO,JCS,JCNO,IK,IN,IJ,SUM) MDA00640
        GO TO 290                                                       MDA00650
209     SWR(I,J)=A(IA)                                                  MDA00660
        IF (JTS.NE.JCS) CALL ADJ (SWR,I,J,JTS,JTNO,JCS,JCNO,IK,IN,IJ,SUM) MDA00670
        GO TO 290                                                       MDA00680
210     CT(I,J)=A(IA)                                                   MDA00690
        IF (JTS.NE.JCS) CALL ADJ (CT,I,J,JTS,JTNO,JCS,JCNO,IK,IN,IJ,SUM) MDA00700
        GO TO 290                                                       MDA00710
211     CN(I,J)=A(IA)                                                   MDA00720
        IF (JTS.NE.JCS) CALL ADJ (CN,I,J,JTS,JTNO,JCS,JCNO,IK,IN,IJ,SUM) MDA00730
        GO TO 290                                                       MDA00740
212     ECK(I,J)=A(IA)                                                  MDA00750
        IF (JTS.NE.JCS) CALL ADJ (ECK,I,J,JTS,JTNO,JCS,JCNO,IK,IN,IJ,SUM) MDA00760
290     CONTINUE                                                        MDA00770
300     CONTINUE                                                        MDA00780
        GO TO 200                                                       MDA00790
250     IF (IC(4).EQ.1) CALL TEMP (TA,TMAX,TMIN,IC,1,INO,JCNO,JCS)      MDA00800
        IF (IC(5).EQ.1) CALL TEMP (TD,DMAX,DMIN,IC,2,INO,JCNO,JCS)      MDA00810
        IF (MX.EQ.1.AND.IC(2).NE.1) CALL VPG (I,IC,JCNO,IWM)            MDA00820
        RETURN                                                          MDA00830
        END                                                             MDA00840
```

```
      SUBROUTINE INPT (IC,JTS,IUC,A,IRI,IWI)
C
C     SUBROUTINE TO READ DATA IN FREE FORMAT.
C
      DIMENSION V(15),COL(80),VAR(30),A(2500)
      DATA V /'*',' ','-','.','#','0','1','2','3','4','5','6','7',
     1'8','9'/
      DATA VEND /'$'/
      II=0
      NC=80
      DO 2 I=1,2500
2     A(I)=0.0
4     READ(IRI,100) (COL(I), I=1,NC)
100   FORMAT(80A1)
      IF (COL(1).EQ.V(1).AND.COL(2).EQ.V(1)) GO TO 30
      M=0
      N=1
      ISIGN=0
      DO 10 I=1,NC
      DO 8 J=1,15
      IF (COL(I).EQ.V(J)) GO TO 9
8     CONTINUE
      IF (COL(1).NE.VEND) GO TO 5
      A(1)=VEND
      RETURN
5     WRITE(IWI,101) I
101   FORMAT(' ILLEGAL CHARACTER ENCOUNTERED IN COLUMN',I3)
      RETURN
9     IF (J.GE.6) GO TO 12
      GO TO (4,20,11,15,17), J
11    ISIGN=1
      GO TO 10
15    N=N+1
      MN=1
      GO TO 10
17    IC=A(1)
      JTS=A(2)
      IUC=A(3)
      II=0
      GO TO 4
12    M=M+1
      VAR(M)=J-6
      IF (N.GT.1) GO TO 14
      IF (M.EQ.1) GO TO 10
      MM=M-1
      DO 6 MJ=1,MM
6     VAR(MJ)=10.*VAR(MJ)
      GO TO 10
14    VAR(M)=VAR(M)/10.**MN
      MN=MN+1
      GO TO 10
20    IF (I.EQ.1) GO TO 10
      IF (I.LT.NC) GO TO 21
      IF (COL(NC).EQ.V(2)) GO TO 4
      WRITE(IWI,102)
```

```
102     FORMAT (' FINAL CARD COLUMN IS NOT BLANK')                              INP00560
21      IF (COL(I-1).EQ.V(2)) GO TO 10                                          INP00570
        II=II+1                                                                 INP00580
        A(II)=0.                                                                INP00590
        DO 25 K=1,M                                                             INP00600
25      A(II)=A(II)+VAR(K)                                                      INP00610
        IF (ISIGN.EQ.1) A(II)=-A(II)                                            INP00620
        M=0                                                                     INP00630
        N=1                                                                     INP00640
        ISIGN=0                                                                 INP00650
10      CONTINUE                                                                INP00660
30      RETURN                                                                  INP00670
        END                                                                     INP00680
                                                                                INP00690
```

```
      SUBROUTINE ADJ (VAR,I,J,JTS,JTNO,JCS,JCNO,KK,IN,IJ,SUM)
C
C     SUBROUTINE TO CORRECT ANY DIFFERENCE BETWEEN DATA SAMPLING
C     INTERVAL AND MODEL COMPUTATION INTERVAL, USING SIMPLE AVERAGING
C     SCHEMES.
C
      DIMENSION VAR(65,24),DUM(65,24)
      IF (JTS.GT.JCS) GO TO 10
      NUM=JCS/JTS
      NO=NUM
      IF (KK.EQ.8) NO=1
      IN=IN+1
      SUM=SUM+VAR(I,J)
      IF (IN.LT.NUM) GO TO 30
      IJ=IJ+1
      DUM(I,IJ)=SUM/NO
      IN=0
      SUM=0.0
      IF (J.LT.JTNO) GO TO 30
      DO 8 IJ=1,JCNO
8     VAR(I,IJ)=DUM(I,IJ)
      GO TO 30
10    NUM=JTS/JCS
      NO=1
      IF (KK.EQ.8) NO=NUM
      DO 12 IJ=1,NUM
      IK=NUM*(J-1)+IJ
12    DUM(I,IK)=VAR(I,J)/NO
      IF (J.LT.JTNO) GO TO 30
      DO 14 IJ=1,JCNO
14    VAR(I,IJ)=DUM(I,IJ)
30    RETURN
      END
```

```
      SUBROUTINE TEMP (T,TMX,TMN,IC,IK,INO,JCNO,JCS)
C
C     SUBROUTINE TO CONVERT THE INPUT TEMPERATURE DATA INTO
C     THE VALUES AS THEY WILL BE USED IN THE SNOWMELT SUBROUTINE.
C
      DIMENSION T(65,24),TMX(65),TMN(65),IC(15)
C          SINCE IC(4)=1 OR IC(5)=1, HAVE MAX AND MIN DAILY TEMPS.
C          WANT TO CONVERT THIS INTO AVG TEMP OVER THE TIME STEP
C          USED.
      DO 20 I=1,INO
      DO 6 J=1,JCNO
      K=J*JCS
      IF (K.GT.4) GO TO 8
      IF (I.GT.1) GO TO 5
      T1=TMX(I)
      GO TO 3
    5 T1=TMX(I-1)
    3 T2=TMN(I)
      KK=K+8
      GO TO 12
    8 IF (K.GT.16) GO TO 10
      T1=TMN(I)
      T2=TMX(I)
      KK=K-4
      GO TO 12
   10 T1=TMX(I)
      IF (I.LT.INO) GO TO 2
      T2=TMN(I)
      GO TO 4
    2 T2=TMN(I+1)
    4 KK=K-16
   12 PH=(3.14*KK)/12.
    6 T(I,J)=((T1+T2)+(T1-T2)*COS(PH))*0.5
   20 CONTINUE
      IC(IK)=1
      RETURN
      END
```

```
      SUBROUTINE VPG (I,IC,JCNO,IWM)                                    VPG00010
C                                                                       VPG00020
C     SUBROUTINE TO DETERMINE DEW POINT TEMPERATURES FROM AIR           VPG00030
C     TEMPERATURES AND EITHER WET-BULB TEMPERATURES OR                  VPG00040
C     RELATIVE HUMIDITIES.                                              VPG00050
C                                                                       VPG00060
      DIMENSION IC(15)                                                  VPG00070
      COMMON /MET/ TA(65,24),TD(65,24),TW(65,24),TMAX(65),TMIN(65),     VPG00080
     1DMAX(65),DMIN(65),REL(65,24),V(65,24),PPT(65,24),                 VPG00090
     2SWR(65,24),CT(65,24),CN(65,24),ECK(65,24)                         VPG00100
      IF (IC(3).EQ.1.OR.IC(4).EQ.1) GO TO 20                            VPG00110
      WRITE(IWM,100)                                                    VPG00120
  100 FORMAT (' ERROR - VPG')                                           VPG00130
      CALL EXIT                                                         VPG00140
   20 DO 51 J=1,JCNO                                                    VPG00150
      F1=0.12 + 0.008*TA(I,J)                                           VPG00160
      F2=F1*TA(I,J)                                                     VPG00170
      IF (IC(3).NE.1) GO TO 25                                          VPG00180
      TD(I,J)=TA(I,J) + (TW(I,J)-TA(I,J))/F1                            VPG00190
      GO TO 51                                                          VPG00200
   25 TD(I,J)=(3.63*(REL(I,J)-1.0)-0.372*F2)/(0.339*(REL(I,J)-1.0)-0.372VPG00210
     1*F1)                                                              VPG00220
   51 CONTINUE                                                          VPG00230
      IC(2)=1                                                           VPG00240
      RETURN                                                            VPG00250
      END                                                               VPG00260
```

```
      SUBROUTINE PRMV (IC,INO,JCNO,IWD)                                 OTT00010
C                                                                       OTT00020
C     SUBROUTINE TO OUTPUT THE ADJUSTED METEOROLOGICAL VARIABLES        OTT00030
C     AS THEY WILL BE USED IN THE SNOWMELT SUBROUTINE.                  OTT00040
C                                                                       OTT00050
      DIMENSION IC(15)                                                  OTT00060
      COMMON /MET/ TA(65,24),TD(65,24),TW(65,24),TMAX(65),TMIN(65),     OTT00070
     1DMAX(65),DMIN(65),REL(65,24),V(65,24),PPT(65,24),                 OTT00080
     2SWR(65,24),CT(65,24),CN(65,24),ECK(65,24)                         OTT00090
      DO 400 IK=1,12                                                    OTT00100
      IF (IC(IK).NE.1) GO TO 400                                        OTT00110
      GO TO (401,402,403,404,405,406,407,408,409,410,411,412), IK       OTT00120
401   WRITE(IWD,1001)                                                   OTT00130
1001  FORMAT (/,' AIR TEMP',/)                                          OTT00140
      DO 501 I=1,INO                                                    OTT00150
501   WRITE(IWD,1000) (TA(I,J), J=1,JCNO)                               OTT00160
1000  FORMAT (12F6.2)                                                   OTT00170
      GO TO 400                                                         OTT00180
402   WRITE(IWD,1002)                                                   OTT00190
1002  FORMAT (/,' DEW POINT TEMP',/)                                    OTT00200
      DO 502 I=1,INO                                                    OTT00210
502   WRITE(IWD,1000) (TD(I,J), J=1,JCNO)                               OTT00220
      GO TO 400                                                         OTT00230
403   WRITE(IWD,1003)                                                   OTT00240
1003  FORMAT (/,' WET BULB TEMP',/)                                     OTT00250
      DO 503 I=1,INO                                                    OTT00260
503   WRITE(IWD,1000) (TW(I,J), J=1,JCNO)                               OTT00270
      GO TO 400                                                         OTT00280
404   WRITE(IWD,1004)                                                   OTT00290
1004  FORMAT (/,' TMAX, TMIN',/)                                        OTT00300
      WRITE(IWD,1000) (TMAX(I),TMIN(I), I=1,INO)                        OTT00310
      GO TO 400                                                         OTT00320
405   WRITE(IWD,1005)                                                   OTT00330
1005  FORMAT (/,' DMAX, DMIN',/)                                        OTT00340
      WRITE(IWD,1000) (DMAX(I),DMIN(I), I=1,INO)                        OTT00350
      GO TO 400                                                         OTT00360
406   WRITE(IWD,1006)                                                   OTT00370
1006  FORMAT (/,' RELATIVE HUMIDITY',/)                                 OTT00380
      DO 506 I=1,INO                                                    OTT00390
506   WRITE(IWD,1000) (REL(I,J), J=1,JCNO)                              OTT00400
      GO TO 400                                                         OTT00410
407   WRITE(IWD,1007)                                                   OTT00420
1007  FORMAT(/,' WIND VELOCITY',/)                                      OTT00430
      DO 507 I=1,INO                                                    OTT00440
507   WRITE(IWD,1000) (V(I,J), J=1,JCNO)                                OTT00450
      GO TO 400                                                         OTT00460
408   WRITE(IWD,1008)                                                   OTT00470
1008  FORMAT(/,' PPT AMOUNT',/)                                         OTT00480
      DO 508 I=1,INO                                                    OTT00490
508   WRITE(IWD,1000) (PPT(I,J), J=1,JCNO)                              OTT00500
      GO TO 400                                                         OTT00510
409   WRITE(IWD,1009)                                                   OTT00520
1009  FORMAT(/,' INCIDENT SOLAR RADIATION',/)                           OTT00530
      DO 509 I=1,INO                                                    OTT00540
509   WRITE(IWD,1000) (SWR(I,J), J=1,JCNO)                              OTT00550
```

```
      GO TO 400                                                         OTT00560
410   WRITE(IWD,1010)                                                   OTT00570
1010  FORMAT (/,' CLOUD TYPE INDEX',/)                                  OTT00580
      DO 510 I=1,INO                                                    OTT00590
510   WRITE(IWD,1000) (CT(I,J), J=1,JCNO)                               OTT00600
      GO TO 400                                                         OTT00610
411   WRITE(IWD,1011)                                                   OTT00620
1011  FORMAT(/,' CLOUD COVER',/)                                        OTT00630
      DO 511 I=1,INO                                                    OTT00640
511   WRITE(IWD,1000) (CN(I,J), J=1,JCNO)                               OTT00650
      GO TO 400                                                         OTT00660
412   WRITE(IWD,1012)                                                   OTT00670
1012  FORMAT(/,' EFFECTIVE CLOUD COVER',/)                              OTT00680
      DO 512 I=1,INO                                                    OTT00690
512   WRITE(IWD,1000) (ECK(I,J), J=1,JCNO)                              OTT00700
400   CONTINUE                                                          OTT00710
      RETURN                                                            OTT00720
      END                                                               OTT00730
```

```
      SUBROUTINE CALDAY (IYEAR,IBEG,I,ICA,ISA,IALB,ICAL,IDM,CM)          CALC0010
C                                                                       CALC0020
C     SUBROUTINE TO DETERMINE THE CALENDAR MONTH AND DAY.               CALC0030
C                                                                       CALC0040
      DIMENSION VMO(12),IDIM(12)                                        CAL00050
      DATA VMO /'JAN','FEB','MAR','APR','MAY','JUN','JUL','AUG',        CAL00060
     1'SEP','OCT','NOV','DEC'/                                          CAL00070
      DATA IDIM /31,28,31,30,31,30,31,31,30,31,30,31/                   CAL00080
      L=0                                                               CALC0090
      IDAY=IBEG                                                         CAL00100
11    IF (MOD(IYEAR,4).EQ.0) L=1                                        CAL00110
      LDF=59+L                                                          CAL00120
      IEND=365+L                                                        CAL00130
      LAG=IDAY-1                                                        CALC0140
      ICAL=I+LAG                                                        CALC0150
      IF (ICAL.LE.IEND) GO TO 12                                        CALC0160
      IYEAR=IYEAR+1                                                     CALC0170
      IDAY=1                                                            CALC0180
      GO TO 11                                                          CAL00190
12    IF (ICA.GT.ISA) GO TO 14                                          CAL00200
      IF (ICAL.LT.ISA.AND.ICAL.GT.ICA) GO TO 15                         CAL00210
      GO TO 16                                                          CAL00220
14    IF (ICAL.LT.ICA.AND.ICAL.GT.ISA) GO TO 16                         CAL00230
15    IALB=1                                                            CAL00240
      GO TO 17                                                          CALC0250
16    IALB=0                                                            CAL00260
17    IF (I.GT.1) GO TO 28                                              CAL00270
      K=0                                                               CAL00280
      LDM=0                                                             CAL00290
23    K=K+1                                                             CAL00300
      IF (K.NE.2) GO TO 21                                              CAL00310
      LDM=LDM+IDIM(K)+L                                                 CAL00320
      GO TO 22                                                          CAL00330
21    LDM=LDM+IDIM(K)                                                   CAL00340
22    IF (IBEG.GT.LDM) GO TO 23                                         CAL00350
      IDM=IDIM(K)-(LDM-IBEG)-1                                          CAL00360
28    IDM=IDM+1                                                         CALC0370
      IF (IDM.LE.IDIM(K)) GO TO 30                                      CAL00380
      K=K+1                                                             CAL00390
      IF (K.GT.12) K=1                                                  CALC0400
      IDM=1                                                             CAL00410
30    CM=VMO(K)                                                         CAL00420
      RETURN                                                            CAL00430
      END                                                               CAL00440
```

```
      SUBROUTINE SNOW (TA,TD,V,PPT,HRS,CKS,CKL,CN,ECK,IC,I,J,JCS,JCNO,
     1ICAL,FADJ,TMN,IALB,RMELT,TMELT,WCM,MX,IWM)
C
C      SUBROUTINE TO MODEL THE SNOW ACCUMULATION AND
C      MELTING PROCESSES.
C
      DIMENSION IC(15)
      COMMON /CONST1/ LAT,NORS,ISA,ICA
      COMMON /CONST2/ TTT(10),SEP(37),SROM,PTI,CSI,CRI,SX
      COMMON /SUB/ ZFCV,ZFCN,FCV,FCN,BDHF,PF,EFC,SCI,B,GH,TDIF,PDIF,
     1DP,WEQ,DN,CC,TP,TS,WC,WHC,QT,TX
      COMMON /DTOT/ DPPT,DCON,DEVSL,DMEL,DHT,DHRS,DHRL,DHCV,DHCN,DHR,
     1DHG
      DATA SIG /0.496E-8/
      ROS=0.0
      SVT=0.0
      RMELT=0.0
      TMELT=0.0
      IF (I.EQ.1.AND.J.EQ.1) GO TO 2
      GO TO 4
2     SUMSN=0.0
      SUMRN=0.0
      TL=0.0
      WRITE(IWM,350) TA,TD,V,PPT,HRS,CKS,CKL,CN,ECK
350   FORMAT (8F10.4)
      WRITE(IWM,351) I,JCS,JCNO,IALB,MX
351   FORMAT (6I6)
      WRITE(IWM,351) LAT,NORS,ISA,ICA
      WRITE(IWM,350) SROM,PTI,CSI,CRI,SX
      WRITE(IWM,350) ZFCV,ZFCN,FCV,FCN,BDHF,PF,EFC,SCI,B,GH,TDIF,PDIF
      WRITE(IWM,350) FADJ
      WRITE(IWM,350) DP,WEQ,DN,CC,TP,TS,WC,WHC,QT,TX
C
C...ELEV EFFECTS. - MEAN TEMP AS A FUNCTION OF AMBIENT LAPSE RATE
C         AND ELEV DIFFERENCE.
4     JJ=J*JCS
      ALR1=3.3*TL/4.0
      ALR2=-3.3-(0.7*(4.0-TL)/4.0)
      IF (PPT.LE.0.0.OR.TL.GE.4.0) GO TO 27
      ALR1=-0.825+ALR1
      ALR2=0.175+ALR2
      TL=TL+1.0
27    IF (PPT.NE.0.0.OR.TL.LE.0.0) GO TO 28
      ALR1=0.175+ALR1
      ALR2=-0.875+ALR2
      TL=TL-1.0
28    IF (JJ.GT.6.AND.JJ.LE.18) ALR=ALR1
      IF (JJ.LE.6.OR.JJ.GT.18) ALR=ALR2
      TA=TA+ALR*TDIF
      IF (MX.EQ.0) GO TO 29
      TD=TD+ALR*TDIF
      F1=0.12+0.008*TA
      TW=TA-F1*(TA-TD)
29    IF (MX.EQ.0) TW=TA
C
```

```
C...IS THERE PPT?
      IF (PPT.GT.0.0) GO TO 30
C
C...THERE IS NO PPT. - IS THERE A SNOW PACK?
      IF (WEQ.GT.0.0) GO TO 100
C
C...THERE IS NO SNOWPACK.
      RETURN
C
C...THERE IS PPT. - WHAT FORM IS IT?
30    IF (TA.GT.PTI) GO TO 80
C
C...PPT IS IN FORM OF SNOW. - COMPUTE ITS PARAMETERS.
C          INTERCEPTION
      SI=CSI*EFC*PPT
      DPPT=DPPT+PPT
      PPT=PPT-SI
      SVT=SVT+SI
      DEVSL=DEVSL+SI
C          NEW SNOW DENSITY
      IF (TA.LE.0.0) GO TO 63
      DNS=0.05+((0.01*TA)**2)
      GO TO 65
63    DNS=0.05
C          ACCUM OF NEW SNOW
65    DPNS=PPT/DNS
      SUMSN=SUMSN+PPT
C          EFFECT ON ALBEDO INDEX
      IF (SUMSN.LT.SX) GO TO 68
      TX=0.0
      SUMSN=SUMSN-SX
      IF (SUMSN.LT.0.0) SUMSN=0.0
      SUMRN=0.0
C          NEW SNOW TEMPS AND COLD CONTENT
68    TNS=TA
      IF (TA.LT.32.) GO TO 70
      CCNS=0.0
      GO TO 72
70    CCNS=DNS*DPNS*(32.-TNS)*0.00347
C
C          WAS THERE S.O.G. PREVIOUSLY?
72    IF (WEQ.GT.0.0) GO TO 75
C
C          THERE WAS NO S.O.G. PREVIOUSLY. - THEREFORE NEW SNOW
C          FORMS THE PACK.
      DP=DPNS
      DN=DNS
      WEQ=DPNS*DNS
      CC=CCNS
      GO TO 220
C
C          THERE WAS S.O.G. PREVIOUSLY. - COMPUTE COMPACTION.
75    REDUCT=(PPT*DP/WEQ)*((0.1*DP)**0.35)
      WEQNS=DPNS*DNS
      DP=DP-REDUCT+DPNS
```

```
      WEQ=WEQ+WEQNS
      DN=WEQ/DP
      CC=CC+CCNS
      GO TO 210
C
C...PPT IS IN FORM OF RAIN.
C          INTERCEPTION
 80   RI=CRI*EFC*PPT
      DPPT=DPPT+PPT
      PPT=PPT-RI
      SVT=SVT+RI
      DEVSL=DEVSL+RI
C          EFFECT ON ALBEDO INDEX
      SUMRN=SUMRN+PPT
      RX=SX/2.
      IF (SUMRN.LT.RX) GO TO 81
      TX=TX+1.
      SUMSN=0.0
      SUMRN=SUMRN-RX
      IF (SUMRN.LT.0.0) SUMRN=0.0
C          DISTRIBUTION OF RAIN TO SNOWPACK AND BARE GROUND
 81   IF (WEQ.GE.SCI) GO TO 100
      AESC=ALOG(WEQ+1.)/B
      ROS=(1.0-AESC)*PPT
      PPT=PPT-ROS
C
C...HEAT BUDGET
C
C          COMPUTE NET ENERGY FLUX OF RADIATION
 100  IF (WEQ.LE.0.0) GO TO 210
      IF (MX.EQ.1) GO TO 106
      DHF=BDHF*FADJ
      HTI=(TA-32.)*DHF
      IF (TMN.GE.32.OR.J.NE.12) GO TO 127
      LE=(ICAL/10)+1
      DEVSL=DEVSL+SEP(LE)
      GO TO 127
 106  IF (IC(12).EQ.1) GO TO 120
      IF (IC(10).EQ.1.AND.IC(11).EQ.1) GO TO 123
 120  ECKS=ECK
      ECKL=ECK
      GO TO 121
 123  ECKS=(1.-CKS)*CN
      ECKL=CKL*CN
 121  IF (IC(9).EQ.1) GO TO 122
      CALL INSOL (SRO,MX,ICAL,J,JCS,LAT,NORS)
      HRS=0.9*(1.-ECKS)*SRO
 122  TAK=(0.555*(TA-32.))+273.
      TSK=(0.555*(TS-32.))+273.
      RC=SIG*(0.757*(TAK**4)-(TSK**4))*(1-ECKL)
      RF=SIG*((TAK**4)-(TSK**4))
      HRL=(EFC*RF+(1.0-EFC)*RC)*JCS
      DHRL=DHRL+HRL
C          COMPUTE ALBEDO
 127  IF (IALB.EQ.1) GO TO 128
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      TXG=TX**0.58                                                      SNO01660
      ALB=0.85*0.94**TXG                                                SNO01670
      GO TO 129                                                         SNO01680
128   TXG=TX**0.46                                                      SNO01690
      ALB=0.85*0.82**TXG                                                SNO01700
129   FTC=1./((10.*EFC)+1.)                                             SNO01710
      IF (MX.EQ.1) GO TO 131                                            SNO01720
      HTI=HTI*(1.-ALB)*(1.-EFC*(1.-FTC))*JCS                            SNO01730
      AWAT=0.0                                                          SNO01740
      GO TO 136                                                         SNO01750
C         NET RADIATION FLUX                                            SNO01760
131   HRS=(1.-EFC*(1.-FTC))*HRS*(1.-ALB)*JCS                            SNO01770
      DHRS=DHRS+HRS                                                     SNO01780
      HRNET=HRS+HRL                                                     SNO01790
      IF (TS.LT.32.0.AND.HRNET.GT.0.0) GO TO 126                        SNO01800
      GO TO 130                                                         SNO01810
C         SUBLIM DUE TO RADIATION                                       SNO01820
126   QR=HRNET/(677.*2.54*QT)                                           SNO01830
      WEQ=WEQ-QR                                                        SNO01840
      DP=WEQ/DN                                                         SNO01850
      SVT=SVT+QR                                                        SNO01860
      DEVSL=DEVSL+QR                                                    SNO01870
C                                                                       SNO01880
C         COMPUTE HEAT OF CONVECTION                                    SNO01890
130   HCV=FCV*ZFCV*(TA-TS)*V*JCS                                        SNO01900
      DHCV=DHCV+HCV                                                     SNO01910
C                                                                       SNO01920
C         COMPUTE HEAR OF CONDENSATION/EVAPORATION/SUBLIMATION          SNO01930
      HCN=FCN*ZFCN*(TD-TS)*V*JCS                                        SNO01940
      DHCN=DHCN+HCN                                                     SNO01950
      IF (TS.LT.32.) GO TO 135                                          SNO01960
C         COND OR EVAP                                                  SNO01970
      ALH=597.                                                          SNO01980
      GO TO 138                                                         SNO01990
C         SUBLIM                                                        SNO02000
135   ALH=677.                                                          SNO02010
138   QCN=HCN/(ALH*2.54*QT)                                             SNO02020
      IF (TD.GT.TS) DCON=DCON+QCN                                       SNO02030
      IF (TD.LE.TS) DEVSL=DEVSL+QCN                                     SNO02040
      IF (HCN.GE.0.0) GO TO 133                                         SNO02050
      AWAT=0.0                                                          SNO02060
      WEQ=WEQ-QCN                                                       SNO02070
      DP=WEQ/DN                                                         SNO02080
      GO TO 139                                                         SNO02090
133   AWAT=QCN                                                          SNO02100
139   SVT=SVT+QCN                                                       SNO02110
136   IF (PPT.LE.0.0) GO TO 140                                         SNO02120
C                                                                       SNO02130
C         COMPUTE HEAT FROM RAIN WATER                                  SNO02140
      HR=1.41*(TW-32.)*PPT                                              SNO02150
      DHR=DHR+HR                                                        SNO02160
C                                                                       SNO02170
C         HEAT FROM GROUND                                              SNO02180
140   HR=0.0                                                            SNO02190
      HG=GH*JCS                                                         SNO02200
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      DHG=DHG+HG                                            SNO02210
      PPT=PPT + AWAT                                        SNO02220
C                                                           SNO02230
C...TOTAL HEAT SUPPLIED OR REMOVED                          SNO02240
C                                                           SNO02250
      IF (MX.EQ.0) HT=HTI+HR+HG                             SNO02260
      IF (MX.EQ.1) HT=HRNET+HCV+HCN+HR+HG                   SNO02270
      DHT=DHT+HT                                            SNO02280
      IF (WEQ.GE.SCI) GO TO 145                             SNO02290
      AESC=ALOG(WEQ+1.0)/B                                  SNO02300
      HT=AESC * HT                                          SNO02310
C                                                           SNO02320
C          DETERMINE HEAT ALLOCATION TO MELT OR CC          SNO02330
145   IF (HT.GT.0.0) GO TO 150                              SNO02340
C                                                           SNO02350
C...HEAT REMOVED                                            SNO02360
      ACC=-(HT/(80.*2.54*QT))                               SNO02370
C          ACC=ADDED COLD CONTENT, IN.                      SNO02380
      IF (TP.GE.32.) GO TO 155                              SNO02390
C          TP<32, WC=0, CC>0 (INCREASES), PPT FREEZES       SNO02400
      IF (PPT.GE.ACC) GO TO 152                             SNO02410
      WEQ=WEQ+PPT                                           SNO02420
      CC=CC+ACC-PPT                                         SNO02430
      GO TO 200                                             SNO02440
152   PPT=PPT-ACC                                           SNO02450
      WEQ=WEQ+ACC                                           SNO02460
      CC=CC-PPT                                             SNO02470
      IF (CC.GT.0.0) GO TO 200                              SNO02480
153   WC=PPT-CC                                             SNO02490
      CC=0.0                                                SNO02500
      GO TO 200                                             SNO02510
C          TP=32,WC>0 (DECREASES), CC=0                     SNO02520
155   WC=WC+PPT                                             SNO02530
      IF (WC.GE.ACC) GO TO 156                              SNO02540
      WEQ=WEQ+WC                                            SNO02550
      CC=ACC-WC                                             SNO02560
      WC=0.0                                                SNO02570
      GO TO 200                                             SNO02580
156   WC=WC-ACC                                             SNO02590
      WEQ=WEQ+ACC                                           SNO02600
      GO TO 200                                             SNO02610
C                                                           SNO02620
C...HEAT ADDED                                              SNO02630
150   RM=HT/(80.*2.54*QT)                                   SNO02640
C          RM=POTENTIAL MELT, IN.                           SNO02650
      IF (TP.GE.32.) GO TO 165                              SNO02660
C          TP<32, WC=0, CC>0 (DECREASES)                    SNO02670
      IF (RM.GT.CC) GO TO 162                               SNO02680
      CC=CC-RM                                              SNO02690
      IF (PPT.GT.CC) GO TO 153                              SNO02700
      CC=CC-PPT                                             SNO02710
      GO TO 200                                             SNO02720
162   RM=RM-CC                                              SNO02730
      CC=0.0                                                SNO02740
C          TP=32, WC>0 (INCREASES), CC=0                    SNO02750
```

```
165   IF (RM.GT.WEQ) GO TO 208                                           SNO02760
      WC=WC+RM+PPT                                                       SNO02770
      WEQ=WEQ-RM                                                         SNO02780
      DP=(WEQ/DN)                                                        SNO02790
C                                                                        SNO02800
C...LIQUID WATER STORAGE                                                 SNO02810
C                                                                        SNO02820
200   WCM=WHC*WEQ                                                        SNO02830
      IF (WC.LE.WCM) GO TO 205                                           SNO02840
      RMELT=WC-WCM                                                       SNO02850
      WC=WCM                                                             SNO02860
C                                                                        SNO02870
C...TIME DELAY TO RUNOFF AND COMPUTATION OF FINAL PARAMETERS             SNO02880
C                                                                        SNO02890
205   IF (RMELT.LT.WEQ) GO TO 210                                        SNO02900
208   RMELT=WEQ+WC                                                       SNO02910
      DMEL=DMEL+RMELT                                                    SNO02920
      TMELT=RMELT                                                        SNO02930
209   WEQ=0.0                                                            SNO02940
      DP=0.0                                                             SNO02950
      CC=0.0                                                             SNO02960
      WC=0.0                                                             SNO02970
      RETURN                                                             SNO02980
210   CALL STORR (I,JCS,DP,RMELT,TMELT)                                  SNO02990
C           SUBROUTINE STORR COMPUTES 'TMELT', THE MELT REACHING THE     SNO03000
C           GROUND DURING THIS PERIOD.                                   SNO03010
      TMELT=TMELT+ROS                                                    SNO03020
      DMEL=DMEL+RMELT                                                    SNO03030
      IF (WEQ.LE.0.0.OR.DP.LE.0.0) GO TO 209                             SNO03040
220   DN=WEQ/DP                                                          SNO03050
      TP=32.-((CC*1000.)/(DN*DP*3.47))                                   SNO03060
      TS=(TA+TP)/2.                                                      SNO03070
      IF (TS.GT.32.) TS=32.0                                             SNO03080
      IF (DN.GT.0.40) GO TO 226                                          SNO03090
      WHC=0.025*DN+0.03                                                  SNO03100
      GO TO 229                                                          SNO03110
226   IF (DN.LT.0.55) GO TO 228                                          SNO03120
      WHC=0.20*DN-0.04                                                   SNO03130
      GO TO 229                                                          SNO03140
228   WHC=0.111*DN+0.131                                                 SNO03150
229   ~~IF (TP.GE.32.) GO TO 223~~                                       SNO03160
      QT=1.0-(WC/WEQ)                                                    SNO03170
      GO TO 224                                                          SNO03180
223   QT=1.0+0.00347*(32-TP)                                             SNO03190
224   IF (J.NE.JCNO) GO TO 225                                           SNO03200
      TX=TX+1.0                                                          SNO03210
225   RETURN                                                             SNO03220
      END                                                                SNO03230
```

IF (TP.LT. 32. .OR.
WC.LE. 0.0) GO TO 223

```
      SUBROUTINE INSOL (SRO,MX,ICAL,J,JCS,LAT,NORS)
C
C     SUBROUTINE TO DETERMINE INSOLATICN FROM CELESTIAL
C     SPHERICAL TRIGONCMETRY.
C
C          COMPUTE THE SOLAR DECLINATION. ASSUME A SINE WAVE WITH A
C          MAXIMUM AMPLITUDE OF 23.45 DEG, OCCURRING ON JUNE 21 IN
C          THE NORTHERN HEMISHPERE AND ON DEC 21 IN THE SOUTHERN
C          HEMISPHERE.
      IF (NORS.EQ.1) THETA=ICAL-80
      IF (NORS.EQ.0) THETA=ICAL-254
      DELTA=(2.*3.14*23.45/360.)*SIN((2.*3.14*THETA)/365.)
C          COMPUTE LOCAL LATITUDE
      PHI=(2.*3.14*LAT)/360.
C          COMPUTE THE SUN'S HOUR ANGLE.  ASSUME A 12-HOUR PERIOD
C          OF LIGHT BEGINNING AT 6 AM (TAU=-PI/2) AND ENDING AT
C          6 PM (TAU=PI/2), WITH TAU=0 AT NOON.
      IF (MX.EQ.1) GO TO 6
      TAU=0.0
      GO TO 8
6     TIME=J*JCS-0.5*JCS
      TAU=((2.*3.14*TIME)/24.)-3.14
8     SINALF=SIN(DELTA)*SIN(PHI)+COS(DELTA)*COS(PHI)*COS(TAU)
      IF (SINALF.GE.0.0) GO TO 9
      SINALF=0.0
9     ALFA=ATAN(SINALF/(SQRT(1.-SINALF**2.)))
      SRO=116.3*SINALF
      RETURN
      END
```

```
      SUBROUTINE STORR (I,JCS,DP,RMELT,TMELT)                           ST000010
C                                                                       ST000020
C     SUBROUTINE TO ROUTE MELT WATER VERTICALLY THROUGH A               ST000030
C     RIPE SNOWPACK.                                                    ST000040
C                                                                       ST000050
      DIMENSION STOR(50)                                                ST000060
      DATA IK /1/                                                       ST000070
      B=RMELT                                                           ST000080
      IF (IK.NE.1) GO TO 4                                              ST000090
      DO 3 K=1,50                                                       ST000100
3     STOR(K)=0.0                                                       ST000110
      IK=0                                                              ST000120
4     PC=21./(DP+21.)                                                   ST000130
      PC=PC*(JCS/2.)                                                    ST000140
      IF (PC.GE.1.0) PC=1.0                                             ST000150
      AM=PC*RMELT                                                       ST000160
      KK=0                                                              ST000170
      DO 8 K=1,49                                                       ST000180
      IF (KK.EQ.1) GO TO 6                                              ST000190
      RMELT=RMELT-AM                                                    ST000200
      IF (RMELT.GT.0.0) GO TO 6                                         ST000210
      STOR(K)=STOR(K+1) + AM + RMELT                                    ST000220
      KK=1                                                              ST000230
      AM=0.0                                                            ST000240
      GO TO 8                                                           ST000250
6     STOR(K)=STOR(K+1) + AM                                            ST000260
8     CONTINUE                                                          ST000270
      RMELT=B                                                           ST000280
      TMELT=STOR(1)                                                     ST000290
      RETURN                                                            ST000300
      END                                                               ST000310
```

```
      SUBROUTINE OTPT (I,INO,ICAL,J,JCNO,K,WEQ1,WC1,WCM,RMELT,TMELT,
     1MX,N)
C
C     SUBROUTINE TO PREPARE DESIRED OUTPUT FILES.
C
      DIMENSION VMEL(24)
      COMMON /RITE/ IWP,IWD,IWO,IWR
      COMMON /SUB/ ZFCV,ZFCN,FCV,FCN,BDHF,PF,EFC,SCI,B,GH,TDIF,PDIF,
     1DP,WEQ,DN,CC,TP,TS,WC,WHC,QT,TX
      COMMON /DTOT/ DPPT,DCON,DEVSL,DMEL,DHT,DHRS,DHRL,DHCV,DHCN,DHR,
     1DHG
      IF (N.NE.1) GO TO 5
      IF (IWR.EQ.0) GO TO 25
      K=K+1
      VMEL(K)=TMELT
      IF (I.EQ.INO.AND.J.EQ.JCNO) GO TO 26
      IF (K.NE.12) GO TO 25
26    WRITE(IWR,125) (VMEL(KK), KK=1,K)
125   FORMAT (4X,12F6.2)
      K=0
25    IF (IWO.EQ.0) GO TO 4
      IF (J.GT.1) GO TO 27
      WRITE(IWO,104)
104   FORMAT (/,' ICAL  J    DP   WEQ    CC    TP    TS',
     1'    WC   WCM    QT    TX RMELT TMELT')
      WRITE(IWO,105) ICAL,J,DP,WEQ,CC,TP,TS,WC,WCM,QT,TX,RMELT,
     1TMELT
105   FORMAT (/,I4,I4,10F6.2,2F6.3)
      GO TO 4
27    WRITE(IWO,106) J,DP,WEQ,CC,TP,TS,WC,WCM,QT,TX,RMELT,TMELT
106   FORMAT (4X,I4,10F6.2,2F6.3)
      GO TO 4
5     IF (IWO.EQ.0) GO TO 4
      DWEQ=WEQ1-WEQ
      DWC=WC1-WC
      DGL=DWEQ+DWC+DPPT+DCON-DEVSL-DMEL
      WRITE(IWO,126)
126   FORMAT (/,8X,'   DGL  DWEQ   DWC  DPPT  DCON DEVSL  DMEL')
      WRITE(IWO,127) DGL,DWEQ,DWC,DPPT,DCON,DEVSL,DMEL
127   FORMAT (8X,10F6.2)
      IF (MX.EQ.0) GO TO 29
      WRITE(IWO,128)
128   FORMAT (/,8X,'  DHRS  DHRL  DHCV  DHCN   DHR   DHG   DHT')
      WRITE(IWO,127) DHRS,DHRL,DHCV,DHCN,DHR,DHG,DHT
      GO TO 4
29    WRITE(IWO,129)
129   FORMAT (/,8X,'   DHT')
      WRITE(IWO,127) DHT
4     RETURN
      END
```