Chapter 5
Snow Analysis

5-1. General

The simulation of flood runoff may involve a key factor which affects the determination of precipitation excess; that is, precipitation may or may not fall in its liquid form and thus may not be immediately available for runoff. Furthermore, if snow has accumulated in the basin from previous storm events, then water input from this source may be available for a given flood event if hydrometeorological conditions permit snowmelt to occur. This chapter will describe the factors involved in the snow accumulation and ablation process and the techniques used to simulate these factors for flood runoff analysis. Two distinct types of floods are usually involved: rain-on-snow events, typical of the winter floods in the Cascade and Sierra Nevada mountains of the Western United States and the Appalachians in the East; and spring/summer floods - usually involving relatively little rain on the large rivers of the interior states, such as the Columbia, Missouri, and Colorado.

5-2. Physical Processes

a. Overview. Chapter 4 described the analysis of rainfall, leading to the estimation of basin-wide water excess that is potentially available for runoff. A special case of this hydrometeorological process occurs when air temperatures are cold enough to cause the precipitation to occur in its solid form and remain temporarily stored on the ground as snow. Once in place, a metamorphosis of the accumulated snow will eventually occur when heat energy is supplied from various sources. With enough heat energy, the snow will be transformed from a solid to liquid state and water will be available for runoff.

b. Precipitation, snowfall, and snow accumulation. In the middle latitudes, precipitation usually occurs as a result of the colloidal instability of a mixed water-ice cloud at temperatures below 32 °F. The formation of snow and, subsequently, rain in the atmosphere is a dynamic process. It has been observed that winter precipitation occurs initially in the form of snow crystals in subfreezing portions of clouds. As the snowflakes fall through the atmosphere, they later melt into raindrops when they fall through warmer, above-freezing air at lower elevations. The corresponding melting level air temperature of snowflakes falling through the atmosphere varies from 32 to 39 °F, but it is usually about 34 to 35 °F. Accordingly, on the earth's surface, snowfall occurs at elevations higher than the melting level, while rainfall occurs at elevations lower than the melting level. The most significant determinant of the occurrence of rain or snow is the elevation of the melting level. This is particularly important in mountainous regions. Factors which influence the amount and distribution of precipitation in the form of snow and the snowpack water equivalent may be classified as being meteorologic and topographic. Meteorologic factors include air temperature, wind, precipitable water, atmospheric circulation patterns, frontal activity, lapse rate (vertical temperature profile), and stability of the air mass. Topographic factors include elevation, slope, aspect, exposure, forest, and vertical curvature. The crystalline form of newly fallen snow is most commonly hexagonal.

c. Snow metamorphosis. Freshly fallen snow exists in a clearly defined crystalline state, with sharply defined edges and abrupt points in each snow crystal. Metamorphosis of the snow occurs over time as the individual crystals lose their original distinct form and become rounded and bound together, ultimately into uniform, coarse, large ice crystals. This process is commonly called "ripening." This transformation may take place in as short a time period as several hours, but commonly involves a period of days or weeks in intercontinental areas with a large, deep snowpack.

(1) The specific gravity of snow (a dimensionless ratio) is commonly called the snow density (which properly would be mass per unit volume). The density (percent water equivalent) of the newly fallen snow is typically on the order of 10 percent, with variations of 6 to 30 percent dependent upon the meteorological conditions involved, primarily air temperature and wind. As metamorphosis occurs, density increases, reaching values of 45 to 50 percent for a fully ripe snowpack. A snowpack ripe for melt also contains a small amount of free water, on the order of 3 to 5 percent. A ripe snowpack is said to be "primed" to produce runoff; that is, when it contains all the water it can hold against gravity.

(2) The temperature of the snowpack varies as a factor in the metamorphosis process. In its early stages, the variation throughout the depth may be marked, from approximately 32 °F near the ground to subfreezing temperatures at shallower depths. As the snow ripens, a more isothermal pattern develops, and in its "ripe" condition the snowpack is completely isothermal and near 32 °F. The amount of heat required per unit area to raise the temperature of the snowpack to 32 °F is termed the "cold content" of the snow. This is expressed in terms of liquid water (produced at the surface by rain or melt) which,

upon freezing within the snowpack, will warm the pack to 32 °F.

d. Snowmelt. The process of melting snow involves the transformation of snow/ice from its solid form to liquid water through the application of heat energy from outside sources. While the latent heat of ice is established at 80 cal/g, this factor usually must be adjusted to actual snow conditions since the snowpack is not in the form of pure ice at 0 °C. The ratio of heat necessary to produce water from snow (and associated free water) to the amount required to melt the same quantity of ice at 32 °F is termed the "thermal quality" of the snowpack. For a fully ripe snowpack, the thermal quality can be on the order of 0.95 to 0.97.

(1) The rate of snowmelt is dependent upon the many different processes of heat transfer to and from the snow-pack, but it is also somewhat dependent upon the snow-pack condition. The relative importance of these processes varies widely seasonally, as well as with the day-to-day variation of meteorological factors. The heat transfer processes also vary significantly under various conditions of forest environment, exposure, elevation, and other environmental factors.

(2) The four major natural sources of heat in melting snow are absorbed solar radiation, net long-wave (terrestrial) radiation, convective heat transfer from the air, and latent heat of vaporization by condensation from the air. Two additional minor sources of heat are conduction of heat from the ground and heat content of rainwater.

(3) Solar radiation is the prime source of all energy at the earth's surface. The amount of heat transferred to the snowpack by solar radiation varies with latitude, aspect, season, time of day, atmospheric conditions, forest cover, and reflectivity of the snow surface (termed the "albedo"). The albedo ranges from 40 to 80 percent. Long-wave radiation is also an important process of energy exchange to the snowpack. Snow is very nearly a perfect black body, with respect to long-wave radiation. Long-wave radiation exchange between the snow surface and the atmosphere is highly variable, depending upon conditions of cloud cover, atmospheric water vapor, nighttime cooling, and forest cover. Heat exchange by convection and condensation of heat and water vapor from or to the snow surface and the atmosphere is dependent upon the atmospheric air temperature and vapor pressure gradients, together with the wind gradient in the atmosphere immediately above the snow surface. These processes are particularly important under storm conditions with warm air advection and high relative humidity. In summary, there is no one process of heat exchange to the snowpack that may be universally applied, but the relative importance of each of the processes is dependent on atmospheric, environmental, and geographic conditions for a particular location and a particular time or season.

5-3. Data Requirements, Collection, and Processing

a. Data requirements. Data required for snow analysis and simulation include those required for rain-only situations plus additional data necessary for the snow accumulation/snow melt processes involved. These include air temperature data and snow measurements as a minimum but could include windspeed, dewpoint, and solar radiation if energy budget computations are being performed.

(1) Air temperature data are quite critical in any modeling or analysis effort, since freezing level must be known during the snow accumulation process to distinguish between precipitation type in the basin. Temperature is also frequently (almost exclusively) used as an index to determine snowmelt. An additional parameter needed in modeling is the lapse rate, which must either be a fixed value or estimated from observed temperature readings. If calculated, temperature stations at different elevations are necessary.

(2) Snow data are collected in the form of snow water equivalent, frequently on a daily basis in the case of automated stations using snow pillows, or monthly in the case of manually read snow courses. Snow water equivalent data as applied to flood-runoff analysis would be needed as an independent variable for simplified analyses and seasonal runoff forecasting, and as data to assist in calibrating and verifying simulation models. Since snow stations may be the only source of high-elevation precipitation, they also can be used to help estimate basin-wide precipitation input to simulation or statistical models.

b. Data collection. The collection of precipitation data in areas subject to snow accumulation presents additional problems in gauging, due to considerations of gauge freezing, "capping" of the gauge by snow, and shielding of the gauge. Equipment and field procedures for such conditions are well documented (USACE 1956). The selection of appropriate precipitation, snow, and temperature gauges for analysis of a mountainous environment subject to snow conditions warrants careful consideration of vertical factors in addition to areal considerations used in rain-only situations, since the vertical distribution of precipitation and the vertical temperature profile must be considered. Bearing on this consideration is the application involved; for simple indexing applications, for instance, a high-elevation snow gauge may be very important. For detailed simulation, a gauge placed in mid-elevations may be more important for defining the distribution of precipitation in the vertical direction and giving a field reference of snow conditions during critical times of snowmelt.

c. Data processing. There are no significant additional requirements for processing snow-related data as compared to nonsnow situations. Special treatment of monthly snow course data may be required if daily increments are to be estimated; this can be accomplished through correlation with a nearby station. Temperature is usually expressed in terms of daily maximum/minimum, or hourly data may be used. In the case of the former, the maximum/minimum data can be expressed as two separate stations, and model preprocessors apply weights to each as desired.

5-4. Simulating Snow Accumulation

a. Applications. Hydrologic engineering analyses involving snow typically require an estimate of snow water equivalent for the basin being studied as input into the runoff derivation. This estimate must directly or indirectly consider the process of snow accumulation and distribution, which includes factors such as the effects of geography and elevation in the distribution of snow and the accounting of the rain/snow threshold. The complexity of this determination can vary depending upon data availability and application, from simple estimates of a single basin value, to detailed simulation using a distributed formulation of the basin. Table 5-1 summarizes three possible approaches of varying complexity.

b. Watershed definition. Because temperature, and therefore elevation, play such an important role in defining the conditions of the basin during a precipitation event, the watershed being simulated needs to be defined with independent subunits. The most common approach is to divide the basin into zones or bands of equal elevation. On each band, precipitation, snow, soil moisture, etc. can be independently accounted for as illustrated in Figure 5-1. In a spatially distributed model, the configuration of computational nodes would likewise have to consider these elevation effects. Available models such as HEC-1 (USACE 1990a) and SSARR (USACE 1987) provide for the watershed definition to be established relatively easily. Simplifying assumptions, such as defining zone characteristics through generalized functions for the basin, are often employed. Such assumptions are not unreasonable since detailed information on subbasin definition is not likely available.

c. Simulation elements. Figure 5-2 illustrates the process that must be considered in simulating snow accumulation. For a given elevation zone or subbasin element and a given time period, these steps include: (1) find base temperature; (2) calculate lapse rate (fixed or variable); (3) calculate temperature at elevation of zone or subelement; (4) calculate zone precipitation; (5) get rain-freeze temperature; (6) calculate breakdown of rain versus snow; and (7) accumulate snow; recalculate snowline. There are no complex equations involved in this process, which is largely a detailed accounting process. The lapse rate is usually taken as a fixed input parameter (often 3.3 deg per 1,000 ft of elevation), but may be a specified or

Table 5-1
Alternatives For Estimating Snow Water Equivalent (SWE)

Approach	Possible Application	Comment
Simple estimate of SWE	1. Single event rain-on-snow computation 2. Forecasting in rain-dominated areas	Simple estimate based upon historical records. May be adequate where rain dominates
Detailed estimate of SWE, considering elevation distribution	Design flood derivation, snow-dominated basin	More detailed analysis of historical records
Simulation of snow accumulation through the accumulation season	1. Detailed design flood derivation 2. Forecasting water supply	Requires a continuous-simulation model

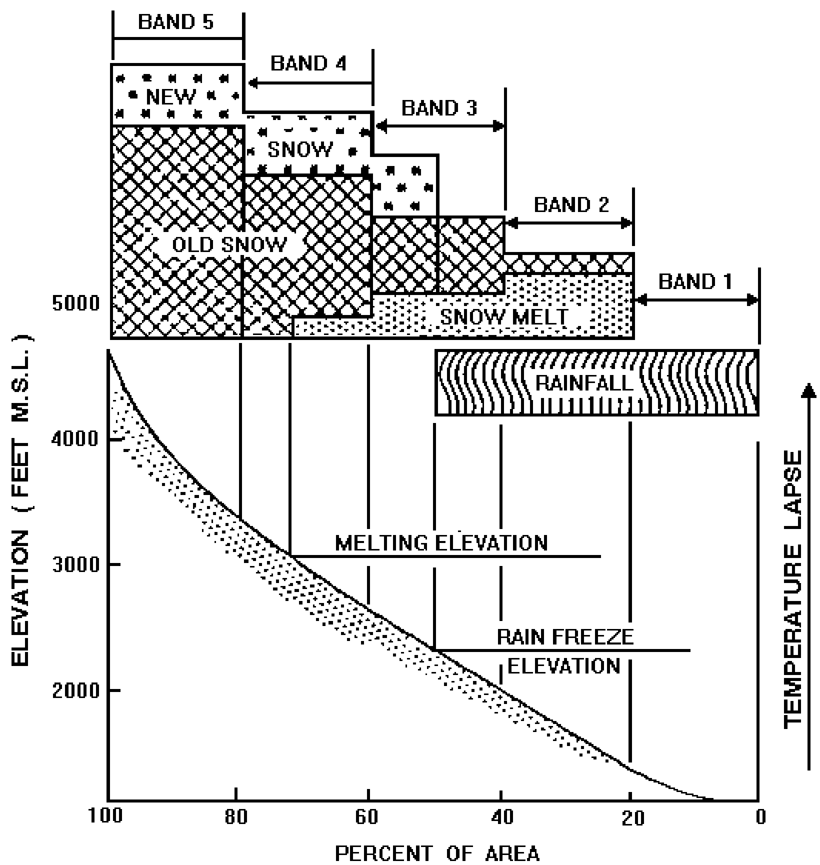

Figure 5-1. Illustration of distributed formulation of a watershed model using elevation bands

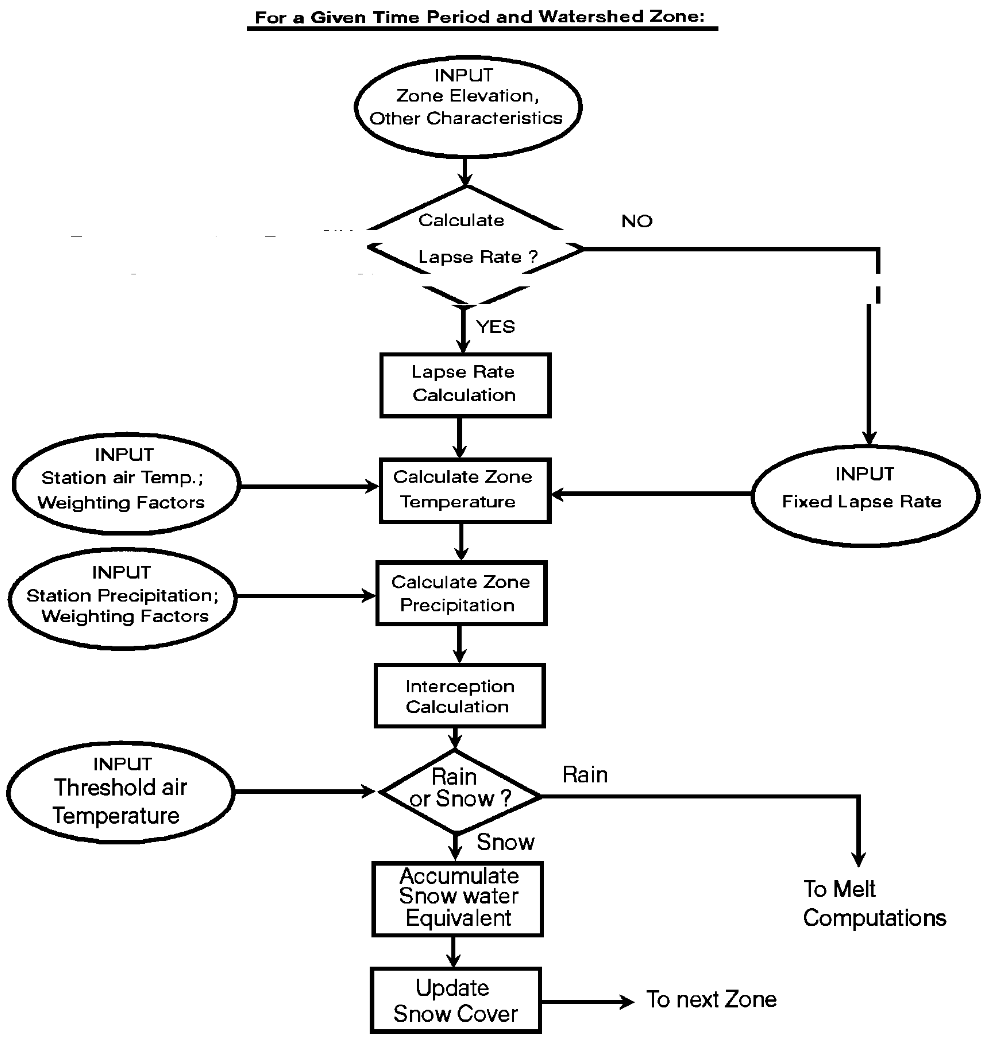

Figure 5-2. Illustration of snow accumulation simulation

calculated variable. The rain-freeze temperature is likewise usually a fixed value, usually around 34 °F.

d. Alternatives to simulation of snow accumulation. Various alternatives exist to a detailed accounting of snow accumulation, depending on the hydrologic regime involved and the application desired. For analyzing discrete rain-on-snow storm events, such as in design flood analysis, a simple estimate of snow water quantity at the (beginning) of the storm may be sufficient, particularly if the snowmelt contribution is relatively small compared to rain runoff. This may be based upon historical records of snow. In the Columbia basin, operational forecasting of spring snowmelt runoff employs simplifying assumptions of snow accumulation for most basins. In this case, the seasonal accumulation of snow is estimated through the use of multiple regression models using winter precipitation and snow as independent variables. Errors in this estimate are accounted for during the simulation of snowmelt by adjusting the model's estimate of snow based upon model performance and observed areal distribution of snow.

5-5. Simulating Snowmelt

a. Overview of applications and approaches. Numerous alternatives present themselves in determining the best approach for simulating snowmelt in flood-runoff analysis. These approaches range from simplified assumptions on discrete storm events to detailed simulation using energy budget principles and distributed definition of the watershed. The choice of methods is dependent upon the application involved, resources available, and data availability. Table 5-2 summarizes the options that are possible and how they tend to relate to given types of applications. A typical situation that might be encountered is that of calculating a hypothetical flood from specified rainfall, either of specified frequency or from a National Weather Station (NWS) hydrometeorological report. If the meteorological conditions are such that rainfall dominates and the duration of the storm is relatively short, it may be quite satisfactory to use a simple approach to estimating snowmelt (e.g., by establishing an antecedent water content by historical analysis then using an assumed rate of melt or a temperature index applied with a melt rate factor). The simulation of snow conditioning would not be required, since the assumption of a "ripe" snowpack prior to the storm could be assumed. On the other hand, the derivation of a design flood or the forecasting of flood runoff in a basin that is predominately snow would likely require a more detailed simulation of snow conditioning and snowmelt, perhaps through the use of theoretical or empirical equations as described below.

b. Simulation of energy input. As discussed in paragraph 5-2*d*, the sources of heat energy that cause snowmelt involve several factors that can be difficult, if not impossible, to quantify and measure. In actual practice then, the theoretical relationships involved are reduced to empirically derived equations that have worked satisfactorily in simulation models. Two basic approaches are commonly used: the "energy budget" solution which employs simplified equations that represent key causal factors such as solar radiation, wind, heat from condensation of water vapor, etc.; and the "temperature index" solution which uses air temperature as the primary independent variable through the use of a fixed or variable "melt-rate factor." The latter solution is almost exclusively used in practical applications of forecasting and analysis.

(1) Energy budget solution. Although variations exist in the equations that have been developed to simulate snowmelt, those developed in the 1950's by the U.S. Army Corps of Engineers remain sound and serve to easily illustrate the basic principles involved. These were based on extensive field experiments coupled with theoretical principles, as discussed in the summary report, "Snow Hydrology" (USACE 1956). The several equations that were derived are also presented in EM 1110-2-1406, Runoff From Snowmelt, and have been used in several applications. The equations presented with abbreviated explanation below are described in detail in both of these documents.

(a) For snowmelt during rain, in which shortwave solar radiation is relatively unimportant and condensation melt is relatively high, the following equation (Eq 20, EM 1110-2-1406) applies:

$$M = (0.029 + 0.0084kv + 0.007P_r)(T_a - 32) + 0.09 \tag{5-1}$$

where

M = total daily snowmelt, in inches

k = factor representing the relative exposure of the basin to wind (for unforested areas, k = 1)

Table 5-2
Snowmelt Options[1]

Application	Example	Basin Configuration: Lumped	Basin Configuration: Distributed	Snow Conditioning	Melt Calculation: Simplified[2]	Melt Calculation: Temperature Index	Melt Calculation: Energy Budget
Single-event analysis-Rain-on-snow	Design floods in coastal mountains	Yes	Possibly	Assumed "ripe"	Possibly	Possibly	Possibly
Single-event analysis-Snow (plus rain)	Design floods in interior basins	Yes	Yes	Assumed "ripe"	No	Yes	Yes[3]
Single-event forecasting-Rain-on-snow	Short-term flood forecasting	Yes	Yes	Optional	Possibly[4]	Yes	No
Single-event forecasting-Snow (+ rain)	Short-term flood forecasting	Yes	Yes	Optional	No	Yes	No
Continuous simulation, any environment	Long-term flood/drought forecasting; Detailed analysis for design	No	Required	Required	No	Yes	Possibly
Macro simulation in small watersheds	R&D applications; analysis for detailed design; special applications	No	Required	Required	No	No	Yes

[1] Qualitative indicator shown for type of option that might typically be used for application. This is a guideline only. "Yes" or "No" indicates suggested option.

[2] Simplified approach might be to assume a constant or variable moisture input due to snowmelt.

[3] Has been used for probable maximum flood (PMF) calculations in the Columbia basin.

[4] Would be appropriate only in situations where snowmelt is small compared with rain.

v = wind velocity at the 50-ft height, in miles per hour

P_r = daily rainfall, in inches

T_a = mean temperature of the saturated air, in degrees Fahrenheit

The constants in the equation are based on field investigations. The factor 0.029 relates snowmelt due to longwave radiation to temperature, and the term 0.0084kv represents the effects of convection-condensation melt. The factor 0.09 accounts for melt from ground heat. If, for example, on a given day the average air temperature is 50 °F, rainfall is 3 in., and wind velocity is 20 mph in an unforested environment, then the melt components would be:

Solar radiation (long wave)	- 0.5 in.
Convection-condensation	- 3.0 in.
Rain	- 0.4 in.
Ground heat	- 0.1 in.
Total	- 4.0 in.

This example illustrates the importance of the convection-condensation melt component, and the corresponding importance of wind, in a rain-on-snow situation. The importance of rain itself in producing melt is relatively small.

(b) For the case of snowmelt during rain-free periods, direct (short-wave) solar radiation must be accounted for. Several equations are developed in Snow Hydrology (USACE 1956) depending upon the degree of forest canopy involved. One, for partly forested areas (Eq 24, EM 1110-2-1406) is as follows:

$$M = k'(1 - F)(0.0040 I_i)(1 - a) + k(0.0084 v)$$
$$(0.22 T_a + 0.78 T_d) + F(0.029 T_a) \tag{5-2}$$

where

M = snowmelt, in inches per period

k' = basin shortwave radiation melt factor. It depends on the average exposure of the open areas to shortwave radiation melt factor. It depends on the average exposure of the open areas to shortwave radiation in comparison with an unshielded horizontal surface

I_i = observed or estimated insolation (solar radiation on horizontal surface), in langleys

a = observed or estimated average snow surface albedo

k = basin convection-condensation melt factor, as defined above. It depends on the relative exposure of the area to wind

T'_a = difference between the air temperature measured at 10 ft and the snow surface temperature, in degrees Fahrenheit. (Snow surface temperature can be assumed to be 32 °F)

T'_d = difference between the dewpoint temperature measured at 10 ft and the snow surface temperature, in degrees Fahrenheit

F = estimated average basin forest canopy cover, effective in shading the area from solar radiation, expressed as a decimal fraction

The energy budget equation requires considerably more data than those previous so that its usage becomes limited in practical applications. One possibility, however, is in PMF derivations where variables such as insolation, albedo, etc. can be maximized through analysis of historical data (USACE 1956) and EM 1110-2-1406. Both of the equations presented are available in the HEC-1 (USACE 1990a) and SSARR (USACE 1987) computer programs. The generalized snowmelt equations also provide a useful method of estimating relative magnitudes of melt components. Table 5-3 presents melt quantities calculated from these equations for six hypothetical situations--three with rain, three without.

(2) Temperature index solution. Because of the practical difficulties of obtaining data needed for the energy budget equations, common practice is to simulate snowmelt by the "temperature index" solution, utilizing the basic equation

$$M = C\,(T_a - T_b) \tag{5-3}$$

where

M = snowmelt, in inches per period

C = melt rate coefficient that is often variable (discussion follows)

T_a = air temperature, in degrees Fahrenheit

T_b = fixed base temperature, near 32 °F

Given the numerous variables contained in the energy budget equations above, it can be seen that the employment of temperature only as an index to snowmelt results in further approximation and inaccuracy; yet, considering the other uncertainties involved - particularly in forecasting applications - this does not usually preclude its use.

(a) The melt-rate factor, C, is of course an important key in the successful application of the temperature index equation. Assuming daily melt computation interval, this factor would be on the order of 0.02 to 0.04 in./degree per day when used with maximum air temperature and 0.04 to 0.10 in./degree per day when used with average air temperature. In clear-weather melt situations, this factor would typically increase as the snowmelt season progressed because of factors such as the decrease in albedo, increased short-wave radiation, etc. Because of

Table 5-3
Relative Magnitude of Snowmelt Factors

a. Assumed Conditions

Case	Description	Assumed Meteorological Conditions				
		T_a	T_d	I	R	V
1.	Clear, hot, summer day. No forest cover. Albedo = 40%	70	45	700	0.0	3
2.	Same as Case 1, 50% cloud cover	65	50	500	0.0	3
3.	Same as Case 1, fresh snow. Albedo = 70%	70	45	700	0.0	3
- -	- -	- -	- -	- -	- -	- -
4.	Heavy wind and rain, warm. No forest cover	50	50	0	3.0"	15
5.	Same as Case 4, but light rain, windy	50	50	0	0.5"	15
6.	Same as Case 5, but light wind	50	50	0	0.5"	3

T_a = Air Temperature, °F
T_d = Dewpoint Temperature, °F
I = Solar Insulation, langleys
R = Daily rainfall, in.
V = Mean wind velocity, mph

b. Daily Melt Quantities

Case	Snowmelt Components, in.					Total Melt in.	Rain + Melt in.
	M_{sw}	M_{lw}	M_{ce}	M_r	M_g		
1.	1.68	0.00	0.46	0.00	0.02	2.16	2.16
2.	1.20	0.00	0.46	0.00	0.02	1.69	1.69
3.	0.84	0.00	0.46	0.00	0.02	1.32	1.32
- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - -
4.	0.07	0.52	2.26	0.38	0.02	3.25	6.25
5.	0.07	0.52	2.26	0.06	0.02	2.93	3.44
6.	0.07	0.52	0.45	0.06	0.02	1.12	1.62

M_s = Short-wave radiation melt
M_{lw} = Long-wave radiation melt
M_{ce} = Convection/condensation melt
M_r = Rain melt
M_g = Ground heat melt

this, provision is usually made in simulation models to calculate this as a variable, perhaps as a function of accumulated runoff or accumulated degree-days of air temperature.

(b) The choice of base temperature depends upon the computation interval involved and the form of the temperature data. If maximum daily temperature is the input variable, then this factor would be higher than 32 °F, perhaps 40 °F. For a more frequent time interval, the factor would be at or near 32 °F.

(c) The possible range of the melt-rate factor can be illustrated by referring to the hypothetical cases presented in Table 5-3. Using the daily melt quantity calculated by the empirical energy budget equations and the temperatures assumed, the melt-rate coefficients calculated through Equations 5-1 and 5-2 would be as shown on Table 5-4. Table 5-4 generally confirms field experience regarding the range in variation of the temperature index melt-rate factor. For clear-melt conditions, the factor varies between 0.03 and 0.06 in./°F and increases as the snowmelt season progresses. For rain-melt conditions, the factor can exhibit wide ranging variations from 0.06 to 0.20, depending upon wind velocity and, to a lesser extent, the precipitation quantity. These factors would be higher if the temperature index used is the maximum daily temperature. In forecasting practice, the melt-rate factors are estimated through the process of calibrating a hydrologic model. Once established for known historic conditions, the factor can be modified by judgment to be applied to the design condition or forecast situation under consideration. Use of Equations 5-1 and 5-2 can be useful guides in this process. Additional discussion of the magnitude of the temperature index melt-rate factor can be found in the summary report (USACE 1956) and "Handbook of Snow" (Gray and Male 1981).

c. Snow conditioning. As discussed in paragraph 5-2*c*, snow conditioning or metamorphosis involves the warming of the snow pack to 32 °F, along with changes in density and character of the snow and the satisfying of liquid water deficiency. The first step in simulating this process is maintaining an accounting of the relative temperature of the snowpack below freezing as a function of time. This can be done through an index relation such as proposed by Anderson (1975):

$$T_s(2) = T_s(1) + F_p\,(T_a - T_s(1)) \tag{5-4}$$

where

T_s = index of the temperature of the snow pack

T_a = temperature of the air

F_p = factor, varying from 0 to 1, representing the relative penetration of the air temperature into the snowpack

If F_p is close to 1.0, the snow temperature will remain close to that of the air; thus, high values would be appropriate for a shallow snowpack. For a deep snowpack, a low value of F_p will result in a slow cooling or warming of the snow. The factor T_s is limited to a value of 32 °F.

(1) Once a snow temperature index is established for a computation period, the cold content (inches of water required to raise the snowpack to 32 °F) can be calculated through an equation such as:

$$CC(2) = CC(1) + C_r(T_a - T_s(2)) \tag{5-5}$$

Table 5-4
Relative Magnitude of Melt-Rate Factors
(Refer to Table 5-3 and Equations 5-1 and 5-2)

Case	T_a	T_b	Melt	C in./°F	Comment
1	70	32	2.16	0.057	Low albedo, high SWE
2	65	32	1.69	0.051	Case 1, cloud cover
3	70	32	1.32	0.035	Case 1, fresh snow
4	50	32	3.25	0.181	Heavy rain, windy
5	50	32	2.93	0.163	Light rain, windy
6	50	32	1.16	0.064	Light rain, light wind

where

CC = cold content (inches of water required to raise the snowpack to 32 °F).

C_r = factor which converts the increment of temperature differential T_a - T_s to an increment of cold content differential

The value of C_r might typically range from 0.01 to 0.05 with higher values associated with late winter or early spring season. This factor is typically made a variable in simulation models by relating it to calendar periods or to a cumulative temperature index function.

(2) The other factor important in simulating snowmelt is the liquid water deficiency of the snow. This is usually taken as a constant percentage of the water equivalent of the snowpack on the order of 3 percent. When melt occurs, or rain falls upon the snowpack, the water generated must first be applied to satisfying the cold content and liquid water deficiency before water is available to enter the ground.

d. Snow accounting. As snowmelt progresses, the elevation of the snowline moves upward and the areal snowcover of the basin decreases. An accounting of this is necessary to be able to differentiate between snow-free and snow-covered areas which have different hydrologic characteristics; and determine the elevation, of the snowpack, for calculating air temperature for indexing melt. A second computation, either associated with snow cover or independent, is the accounting of the remaining snow water equivalent of the snowpack.

(1) If the basin has been configured into zones of equal elevation as described in paragraph 5-4*b*, the accounting of snow cover and quantity can be done on a zone-by-zone basis. One assumption that can be made is to make the zone homogeneous with respect to elevation and either 100 percent snow-covered or snow-free. This assumption may require a large number of zones for adequate basin representation. Even with a large number of zones, the abrupt changes in the snowline can occur as a zone changes from snow-covered to snow-free. Because of this, some models provide an ability to simulate a gradual transition within the zone.

(2) An alternative to the distributed approach in accounting for snow during melt is to employ a snow-cover depletion curve in conjunction with a "lumped" watershed configuration. A snow-cover depletion curve describes the basin's snow-covered area as a function of accumulated snow runoff as a percent of seasonal total. Studies have shown this relationship to be of relatively uniform shape for a basin. Using historic field and satellite information, a pattern curve can be developed for a basin. This does not have to be followed precisely in actual application if flexibility exists in the program to make adjustments, for instance based upon real-time satellite observations of snow cover. While the snow-cover depletion curve yields an accounting of snow cover, this method still needs to employ an independently derived estimate of expected total basin snow water equivalent (SWE). The typical approach is to use multiple regression procedures as noted in paragraph 5-4*d*. The accounting of current remaining SWE during the melting of the snowpack is simply a process of subtraction. Adjustments to the estimates of SWE will likely be required, based upon model performance in simulating runoff.

e. Simulation elements. Figure 5-3 illustrates the process of simulating snowmelt in a simulation model. For a given time period and subbasin element, these include: (1) rain: is this a dry or wet melt calculation? (2) temperature, lapse rate, elevation of zone, etc.; (3) elevation of snow; (4) calculate temperature at zone pertinent to indexing; (5) melt; (6) type of melt computation; (7) other melt factors as necessary; (8) updated snow condition status; (9) water available for melt; and (10) updated snowline and SWE.

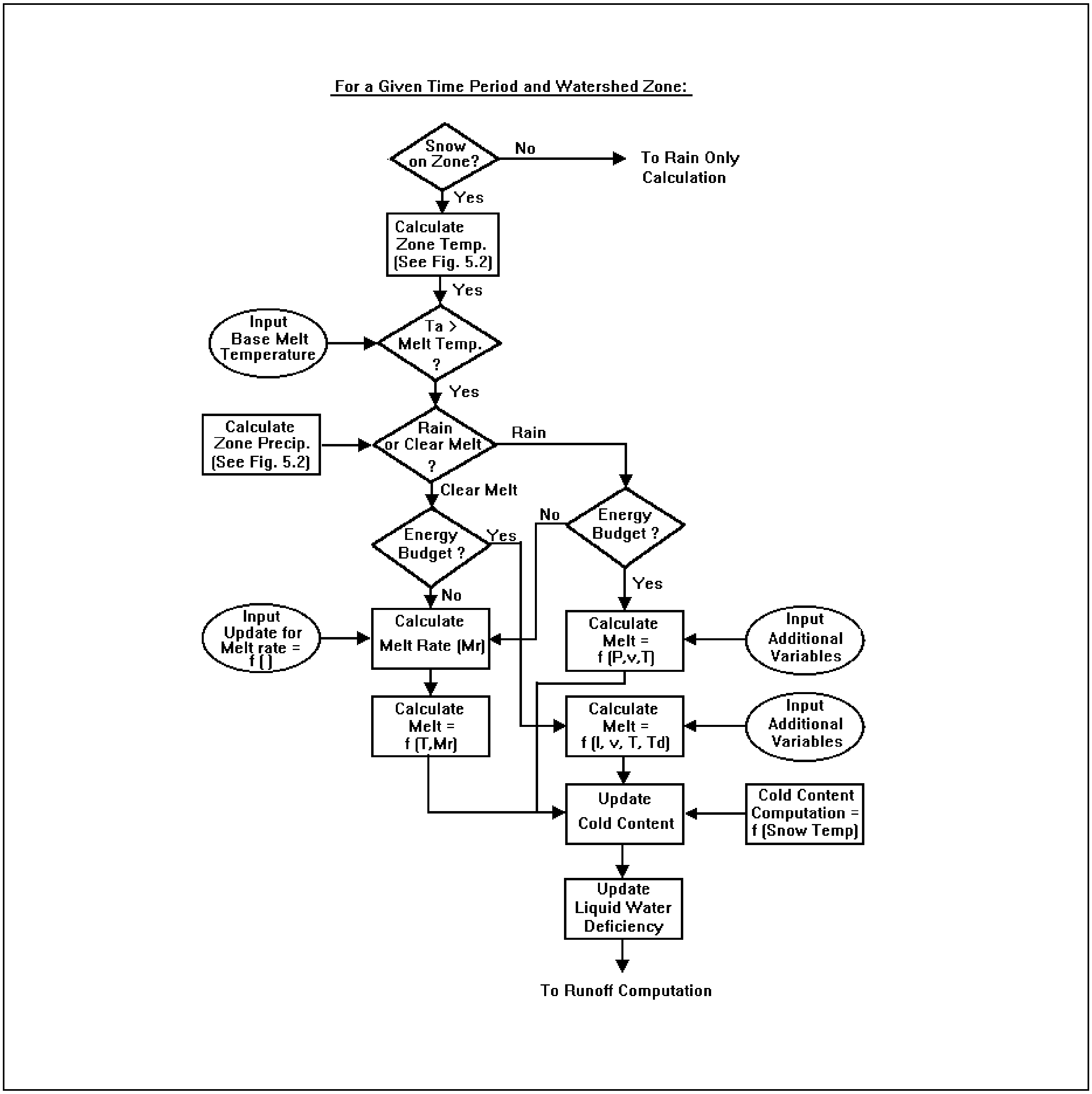

Figure 5-3. Illustration of snowmelt simulation