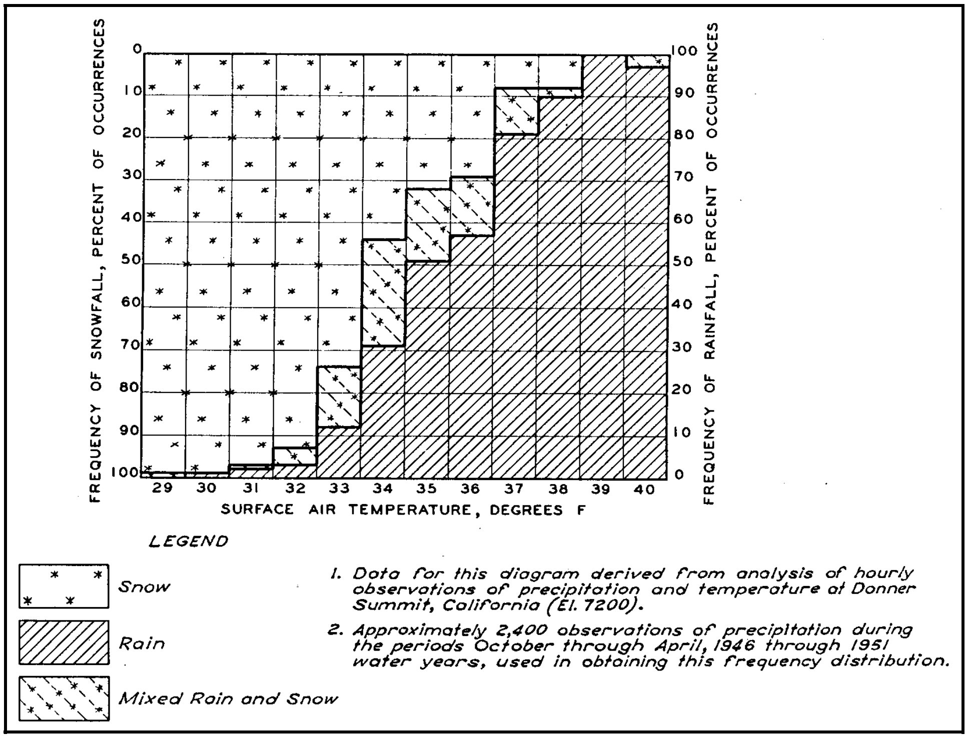
Chapter 4
Snow Accumulation and Distribution

4-1. General

A necessary ingredient in snow runoff analysis is determining the quantity and distribution of snow—more specifically the SWE—that exists in the basin prior to the onset of runoff. The SWE will be the primary determinant governing the magnitude of the snowmelt runoff volume; and the distribution of the snowpack in the basin (whether it be at low or high elevations) will be a factor in determining the rate of melt during the melt season. The SWE estimate must either directly or indirectly consider the process of snow accumulation and distribution, which involves a variety of meteorological and topographical interactions in the basin during the winter accumulation period. This process is much more complex than a rain-only situation, since temperature and elevation play such a prominent role in determining whether precipitation falls as rain or snow. The choice of methodology to determine snow accumulation depends upon data availability, the amount of effort to be expended, and the type of application involved. This chapter will describe alternative approaches for both analysis and forecasting, ranging from simple estimates of a single basinwide average to the detailed simulation of snow accumulation using a continuous model.

4-2. Precipitation, Snowfall, and Snow Accumulation

In the middle latitudes, precipitation usually falls as a result of the colloidal instability of a mixed water-ice cloud at temperatures below 0 °C (32 °F). Snow and rain forms in the atmosphere through a dynamic process. Winter precipitation begins as 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 melting level air temperature for snowflakes falling through the atmosphere varies from 0 to 4 °C (32 to 39 °F), but it is usually about 1-2 °C (34-35 °F). Accordingly, on the Earth's surface, snow falls at elevations higher than the melting level, while rain falls at elevations lower than the melting level. Figure 4-1 shows the frequency of observed forms of precipitation at



1. Data for this diagram derived from analysis of hourly observations of precipitation and temperature at Donner Summit, California (El. 7200).
2. Approximately 2,400 observations of precipitation during the periods October through April, 1946 through 1951 water years, used in obtaining this frequency distribution.

Figure 4-1. Forms of precipitation versus temperature (Figure 1, Plate 3-1, *Snow Hydrology*)

Donner Summit, California. The most significant thing that determines rain or snow is the elevation of the melting level. This is particularly important in mountainous regions. Factors influencing the amount and distribution of precipitation in the form of snow and the SWE may be classified as being meteorological and topographical. Meteorological factors include air temperature, wind, precipitable water, atmospheric circulation patterns, frontal activity, lapse rate, and stability of the air mass. Topographical factors include elevation, slope, aspect, exposure, and vegetation cover.

4-3. Watershed Definition

a. Overview. There are two basic approaches for defining a computer model of a watershed and, therefore, the distribution of snow in that model. A lumped model assumes that the progression of each variable through time (e.g., rain, snow, and soil moisture) can be reduced to a single computational algorithm that represents the entire basin. This is a considerably simplifying assumption in basins that have a wide variety of physical features, but such a model may produce satisfactory results for many applications. In a distributed model, the watershed is divided into subunits with variables being computed separately for each. The output from each subunit is combined to produce total basin output. Lumped models are generally limited to event-type modeling, where the model does not operate beyond a single runoff event. The distributed model formulation is required for continuous simulation, in which the model operates through low-flow periods by simulating the effects of evapotranspiration losses, groundwater, and other variables not normally of importance over short periods of flood runoff. Distributed, continuous simulation is being used more in recent years for both analysis and forecasting because of improved computer and data technology.

b. Lumped formulation. In this approach the basin's precipitation and snowmelt input is a single basin-mean quantity that is transformed to runoff by use of a unit hydrograph or similar methodology. Since this approach is normally limited to modeling runoff events only, the SWE prior to runoff must be determined indirectly and a single basin-average value provided as input to the transformation model. The SWE can be determined before the transformation model is executed, either with a separate computer program or perhaps by a manual estimate. Examples of using a lumped formulation in a snow environment might be as follows.

(1) A design flood derivation, in which the initial SWE is calculated in a relatively detailed but entirely independent analysis, using regression and frequency techniques. During melt, a single, basin-average value is acted upon by a depletion curve method discussed in Chapter 8.

(2) A rain-on-snow forecasting situation, in which rain dominates, but snowmelt can nevertheless add significantly to runoff. A single SWE value and snowline elevation is estimated by the forecaster, based upon a snow gauge located in the basin. With the rainstorm lasting only a few hours, the snowcover can be assumed constant during the melt computation.

c. Distributed formulation. For more detailed modeling of snow, a distributed definition of the basin is needed. This enables the snow accumulation process to be modeled directly, using continuous simulation, and it permits a more detailed accounting of snow during snowmelt. The oldest and currently most common approach in the distributed basin formulation is to subdivide the basin into zones or bands based upon elevation. (Technically, this type of formulation would still be lumped spatially.) On each elevation band, precipitation, snow, soil moisture, etc., are simulated independently; then moisture output from each band is totaled to obtain input into the runoff transformation routine. This method of subdividing the basin is a logical one, since in mountainous areas geographical, hydrological, and meteorological conditions are typically related to elevation. The snowband formulation is shown in Figure 4-2. The snowband method is available in several existing models. Setting up and configuring a basin model with these programs typically employs simplifying assumptions and generalized relationships, making the watershed definition a relatively easy process considering the amount of detail in the basic methodology. The snowband formulation is available in hydrologic models such as Hydrologic Engineering Center-1 (HEC-1) (USACE 1990) and Streamflow Simulation and Reservoir Regulation (SSARR) (USACE 1991).

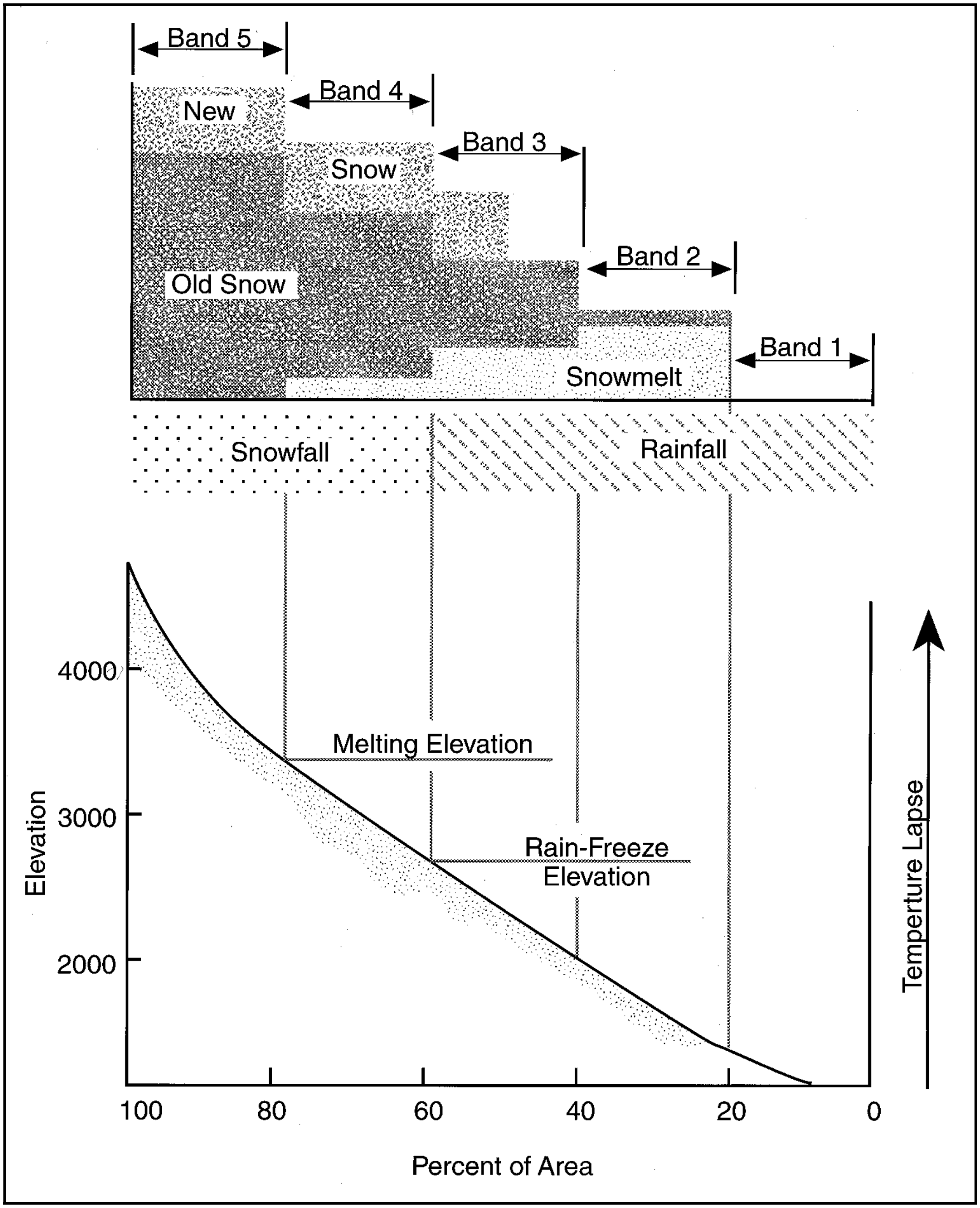


Figure 4-2. Schematic of an elevation band watershed model

(1) With the advent of digital terrain models and geographic information systems (GIS), there has been a move to define a watershed model with a fixed grid, most likely in a rectangular coordinate system. With this type of definition, such characteristics as topographic features, soil types, land-use development, and stream patterns can be specified from a GIS database. Model characteristics, including those pertaining to snow, can also be specified so that

each grid cell functions independently of the others in the simulation.

(2) Figure 4-3 is a schematic of a grid-cell basin formulation. It can be seen that the spatial, grid-cell approach can indirectly consider elevation effects. For applications in steep, mountainous terrain, the challenge for this approach is adequately defining the vertical relief. Wigmosta, Vail, and Lettenmaier (1994) employed a spatially distributed, physical model on a 2900-km^2 watershed in northwestern Montana, using a 180-m grid spacing. This requires over 220 000 cells to define the watershed.

(3) Another technique of defining a watershed is that employed by the U.S. Geological Survey and others (Leavesley et al. 1983, Kite and Kouwen 1992), where the basin is divided into relatively homogeneous HRUs based on elevation, slope, aspect, and vegetation. The Precipitation-Runoff Modeling System (PRMS) program uses this technique (see Chapter 11 and Appendix F regarding computer programs).

4-4. Design Floods—SWE Estimates from Historical Records

a. General. Certain hydrological engineering analyses require the determination of a design flood by way of applying precipitation of a specified magnitude to a rainfall-runoff model. If a snowpack is involved, the magnitude and distribution of the SWE is needed as input to the snowmelt portion of the runoff model. The SWE might best be determined by continuous simulation as described in Paragraph 4-5; however, if a continuous model is not being used, then the SWE has to be determined by an independent analysis of historical data. The SWE might either be a single basin-average value for input into a lumped model, or SWE values might be distributed into a spatial grid or elevation bands for use in a distributed melt model. The former approach, for example, would be appropriate for a relatively flat Midwest basin, while the latter method would be needed for a mountainous western basin. The values typically needed are a seasonal accumulation of winter snow, for example:

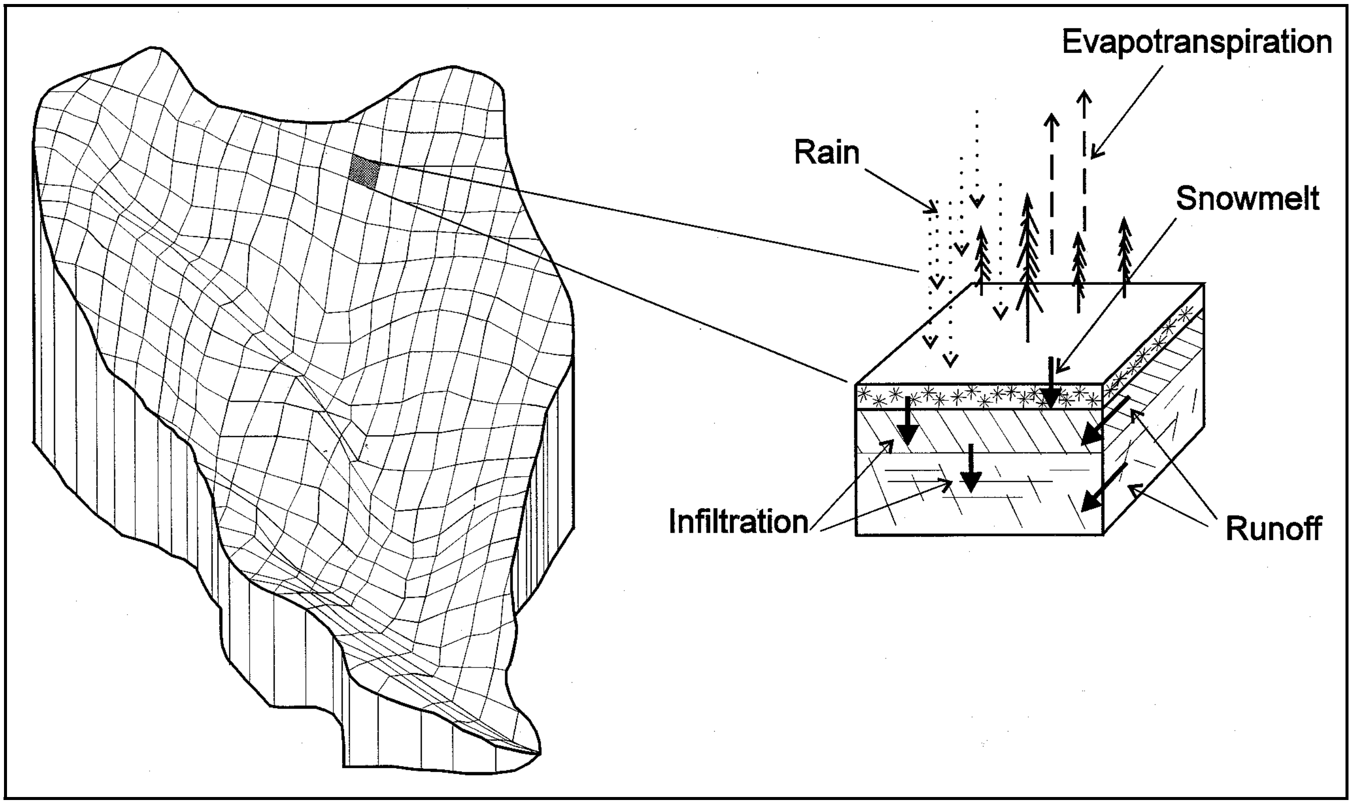


Figure 4-3. Schematic of grid cell formulation

(1) A winter (November-March) accumulation of snow as input into a spring runoff derivation.

(2) A representative midwinter accumulation (November-December) to be a factor in a December (rain-on-snow flood derivation).

b. Analysis process. The process for developing an SWE quantity is much the same as in rainfall analysis leading to input to a rainfall-runoff model. For rain analysis, the steps are as follows:

(1) Develop depth-duration-frequency curves for stations in the basin and determine the values of precipitation appropriate for the flood magnitude being analyzed.

(2) Using techniques such as the Thiesson polygon or isohyetal analysis, develop mean basin (or subbasin increment) values.

(3) Based upon historical records or design flood guidance, develop temporal distributions of the rainfall totals.

(1) For estimates of initial SWE, the first step above could involve long-term (e.g., 1-6 months) durations representing snow accumulation over all or part of a winter season. This would use available SWE records in and near the basin and would also employ precipitation data where feasible. The second step, developing areal quantities, requires more judgment and care than in rain-only cases, and most always would require an isohyetal analysis in mountainous areas. The third step above is not necessary since all that is required is an accumulated value for an initial value. Temporal distribution is determined later during snowmelt by the temperature and precipitation pattern employed as input.

(2) The difficulty in making point-to-areal SWE conversions in a mountainous winter rain-on-snow environment is illustrated in Figure 4-4. This shows the basin divided into three zones, each needing to be considered differently in the analysis. The highest parts of the basin are essentially always snow-covered in the winter, and in fact might accumulate more snow during even a relatively warm frontal passage. In this zone, the SWE determination is not particularly sensitive since there might likely be more snow present than can be melted in a 2- or 3-day rain. The lowest zone, by contrast, is essentially always snow-free, except in rare cases. It also is not critical in the analysis since any snow that would be there in some years would be shallow and assumed to be quickly melted before the peak of the flood.

(3) It is in the middle zone of Figure 4-4 that an SWE determination requires particular care. The historical records might say that in some years this is snow-free by midwinter, while in other years there is partial or complete snow cover. The analysis must determine the appropriate degree of SWE and cover associated with the given magnitude of event. Interpolation using isohyetal analysis may be difficult if, for instance, available snow gauges are located only at higher elevations, thereby not completely reflecting the conditions in the middle zone. To do a detailed determination of SWE for model input in such a situation, the best type of analysis would be continuous simulation of the period of record throughout the winter, as is described in Paragraph 4-6. For the maximum design floods, conservative estimates of the snow “wedge” could be employed as described in Chapter 10.

4-5. Forecasting Applications—SWE Estimates from Real-Time Data

Determining SWE accumulation in forecasting models theoretically employs the same process as used for design floods described above, except that the source of data is a real-time gauging network. However, given the typical uncertainties with data in a forecasting situation and the need for a quick response in making the forecast, it is quite likely that any detailed analysis will be minimal and the estimate of SWE will be relatively rough. The degree of accuracy depends heavily on the thoroughness of the real-time gauging network, and that in turn relates to the network design and the perceived need for SWE data in the forecasts. If snowmelt figures significantly in the streamflow forecasts, then the network should include strategically placed snow pillows or precipitation gauges to provide data for the model input. It would be best in such situations to have gauges in the transitory zone rather than at higher elevations where snow is always present (refer again

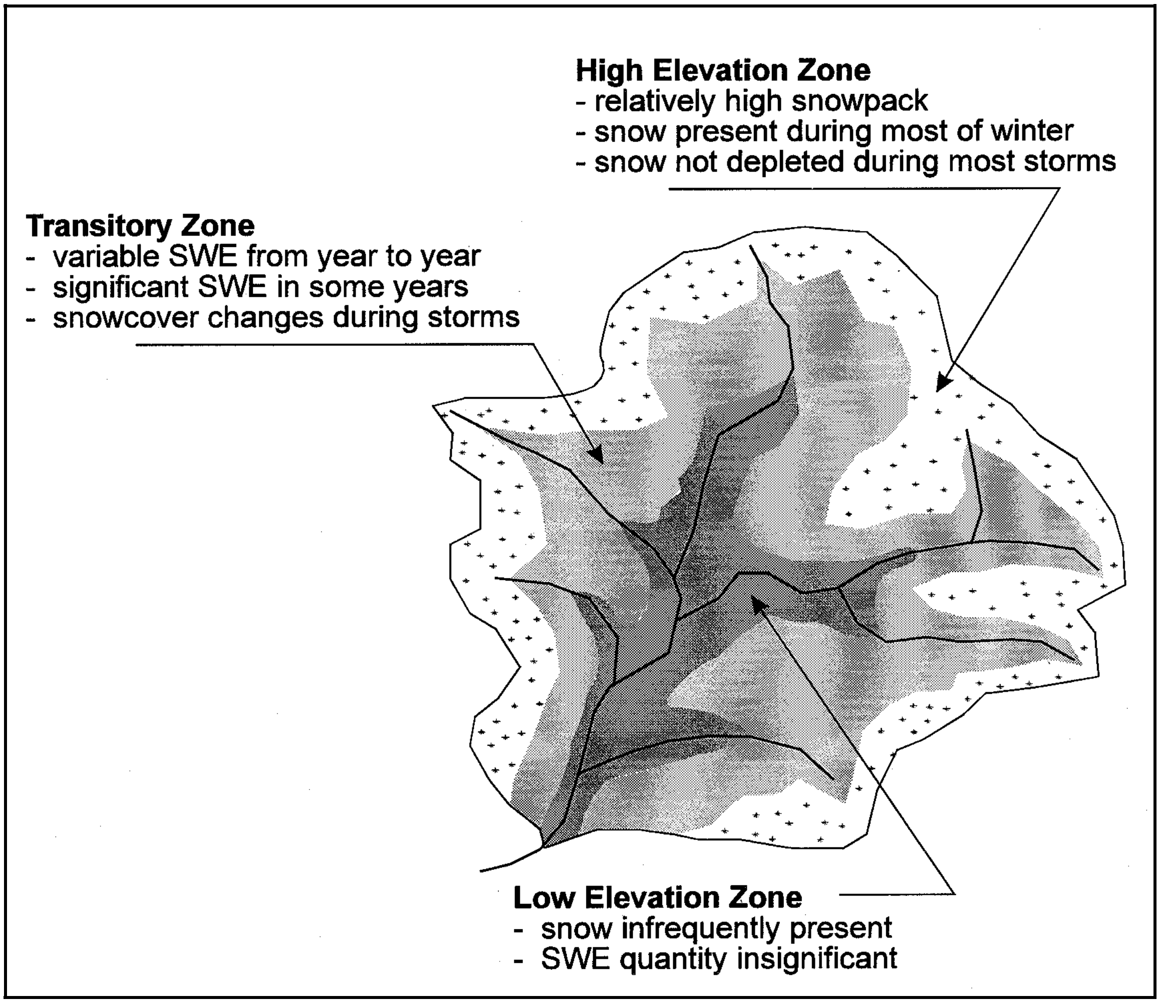


Figure 4-4. Illustration of SWE variation in a mountainous basin with rain on snow

to Figure 4-4). On the other hand, if snowmelt is a relatively small quantity compared with rainfall, the installation of snow pillows may not be warranted. Of course, only rough estimates of SWE would be possible in this case.

a. Basin-average SWE or SWE distribution can be estimated using the concept of a real-time observation acting as an index to the objective SWE variable. This requires analysis of historical data, typically using single or multiple regression. Independent variables would be the station observations available, conceivably including snow pillow, precipitation, and perhaps temperature data. The dependent variable would be basin-mean or subbasin quantity; for instance, the average SWE on a certain elevation zone in the forecast model. This technique is discussed further in conjunction with continuous model forecasting. Even if the accuracy of such relationships is relatively low, they do give a forecaster quick guidance in what may be a stressful forecast situation. In spring/summer snowmelt settings, where an extensive snow-covered area exists, the index concept can be carried to more rigorous levels by employing the advanced statistical techniques described in Chapter 9. Here, several index stations, including precipitation and SWE sensors, can be used to produce a mean basin SWE estimate for input into a snowmelt model.

b. For rough estimates of SWE where real-time SWE data are not available, the forecaster might employ SWE observations outside of the basin and manual observations of snowline elevation and snow depth from dam tenders, weather stations, ski areas, etc. Precipitation and temperature gauge data could also be employed to keep a running estimate of snow accumulation in certain critical elevation zones—this would be a manual or spreadsheet calculation that amounts to a simple version of modeling snow accumulation with continuous simulation.

4-6. Simulation of Snow Accumulation Using Continuous Modeling

The most thorough procedure for estimating snow accumulation is to employ a continuous simulation model that operates through the winter accumulation season. The model typically uses temperature and precipitation as input and, operating on a relatively short time-step, keeps a running accounting of SWE for each of the distribution elements in the model configuration. Other phenomena that also need to be accounted for are interception and sublimation. The advantage of this approach is that the basin's SWE distribution is relatively accurately defined for the snow runoff determination involved. The disadvantage is that it requires more effort to set up and run the model and may represent "overkill" for the application involved. Figure 4-5 illustrates the steps involved in such a simulation, this case being for a snow-band model. Figure 4-6 shows the basin summary output from the SSARR model for a period of simulation during the winter. The status of each of 10 bands is shown on the right side of the output. If desired, the modeler can request a detailed listing of the computation for each of the bands.

a. For applications in hydrological engineering analysis, it is common to simulate snow accumulation and melt for a continuous period of several years, perhaps the period of record. If a long period of record is available, the statistical reliability of the SWE distribution may be relatively good. For example, in a design flood determination, the simulation results for each distribution element could be extrapolated as desired to a desired frequency level for input into a hypothetical design flood. For operational studies involving water supply and multiple-year droughts, a continuous simulation approach is almost essential if runoff modeling is required. An example of modeling for a reservoir operations study is described in Chapter 10.

b. In forecasting applications, continuous simulation can be usefully employed to obtain a distributed portrayal of SWE in the basin. It is an essential part of long-range Extended Streamflow Prediction forecasting described briefly in Chapter 10. In rain-on-snow settings, where a quick forecast response is required and snowmelt is not a key factor, the more time-consuming effort involved in running the model may limit its use in real-time in favor of the more approximate procedures described above. A continuous model could conceivably be operated as a background analyzer between forecasts, to provide an update on SWE and other variables for the forecaster, and then as an event-type model operated to produce the rain and snowmelt-runoff forecast.

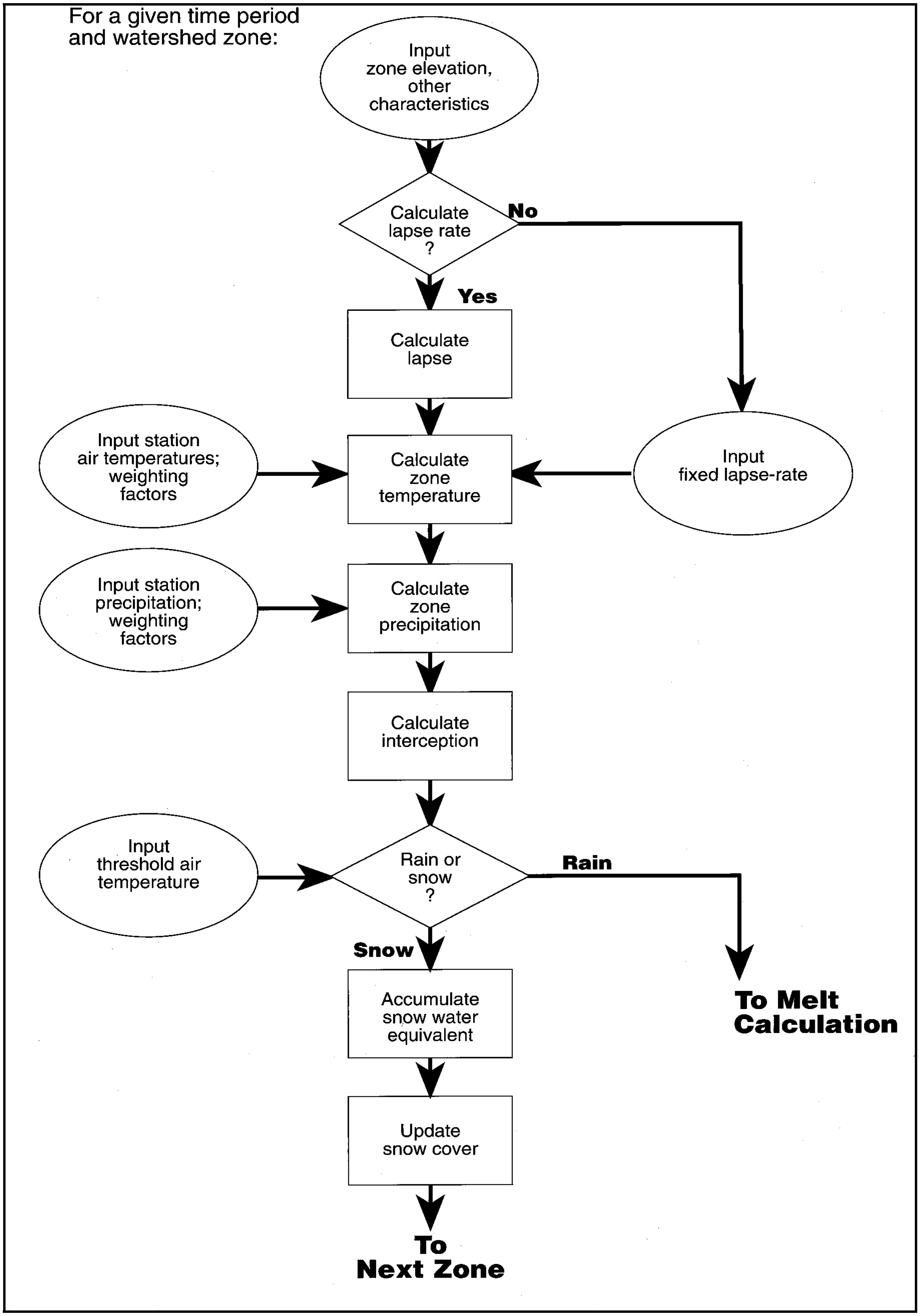


Figure 4-5. Algorithm of snow accumulation variation

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                                    SSARR SNOWBAND MODEL (METRIC) -
         COMPUTED FLOW, ILLECILLEWAET R., CANADA
             AREA      BASE-TEMP       ZONES
OCT 1966     1155          0             6                                                                  FLAGS BY ZONE
DA  HR  PCPN  INT SNOWL  WE  LR TA    MR   RG   ET SMI ROP BFP   SURF  SUBSF BASEF LOWERZ   TOTAL     OBS    1.....6
 1 240  0.02 0.01  2158 420 5.6 13 0.201 0.04 0.05  17  67  90   0.05   5.80 15.91   6.98   28.74   38.94         AA
 2 240     0    0  2158 420 6.4 13 0.198 0.02 0.04  17  67  89   0.12   3.38 15.77   6.97   26.24   34.26          S
 3 240     0    0  2158 420 6.4 12 0.195 0.01 0.04  17  67  89   0.11   2.00 15.59   6.95   24.65   28.86          S
 4 240     0    0  2158 420 4.2 13 0.194 0.08 0.07  17  67  89   0.25   1.34 15.37   6.94   23.90   27.23          D
 5 240  1.67 0.37  2158 420 0.8 11 0.194 1.03 0.14  17  66  88   2.73   2.81 15.34   6.92   27.80   29.52          D
 6 240  2.98 0.11  2158 420 3.0 11 0.372 2.09 0.07  18  68  70  14.19  11.32 15.77   6.91   48.19   40.78          R
 7 240  0.57 0.06  2158 420 6.4 16 0.191 0.35 0.07  18  71  60  18.22  19.32 16.47   6.89   60.90   55.51         DA
 8 240  0.03 0.03  2158 420 6.4 11     0 0.00 0.03  18  71  65   8.74  18.17 17.05   6.88   50.84   48.99         AA
 9 240  0.74 0.06  1902 420 6.4 11     0 0.21 0.03  18  71  71   3.54  14.04 17.52   6.87   41.97   33.70        AAA
10 240  0.25 0.03  1050 420 5.4  6     0 0.02 0.02  18  72  76   1.87  10.23 17.89   6.85   36.84   29.28      AAAAA
11 240  0.87 0.01  1472 420 6.4 10 0.053 0.31 0.03  18  72  82   1.48   7.52 18.19   6.84   34.03   27.02      DDCAA
12 240     0    0  1472 420 6.4  8 0.052 0.03 0.02  18  72  79   1.43   5.80 18.44   6.83   32.49   24.89       SSSS
13 240     0    0  1902 420 6.4  8 0.052 0.01 0.02  18  72  83   0.62   4.01 18.58   6.81   30.02   22.98       SSSS
14 240  0.08 0.05  1472 420 6.4  8     0 0.01 0.02  18  72  86   0.23   2.60 18.62   6.80   28.25   21.90       AAAA
15 240  2.33 0.03  1472 422 6.4 10 0.050 0.21 0.02  18  72  88   0.41   1.91 18.63   6.79   27.73   21.21       AAAA
16 240  0.31 0.02  1050 423 6.4  7     0 0.02 0.02  18  73  85   0.52   1.59 18.59   6.77   27.48   20.84      AAAAA
17 240  1.71 0.01  1050 424 6.4  8 0.049 0.06 0.02  18  73  86   0.41   1.32 18.50   6.76   26.99   20.37      ACAAA
18 240  4.38 0.01  1050 428 6.4  8 0.137 0.47 0.01  19  73  87   2.01   2.21 18.43   6.74   29.39   20.46      RCAAA
19 240  1.41 0.01  1050 429 4.2  5 0.049 0.17 0.02  19  74  84   3.56   3.79 18.40   6.73   32.47   21.01      DQAAA
20 240  1.23 0.02  1050 430 6.4  8 0.049 0.15 0.02  19  74  84   3.32   4.70 18.34   6.72   33.07   20.56      DQAAA
21 240  0.35 0.02  1050 430 6.3  6 0.050 0.03 0.02  19  74  85   2.19   4.54 18.23   6.70   31.66   19.57      AAAAA
22 240  2.84 0.01   709 433 5.4  4 0.049 0.01 0.01  19  74  86   0.88   3.49 18.06   6.69   29.13   19.29     AQAAAA
23 240  0.48 0.01   709 433 2.7  3 0.047 0.02 0.02  19  74  87   0.33   2.41 17.84   6.68   27.26   21.21     AACAAA
24 240  0.14 0.01   709 434 4.5  7 0.046 0.05 0.02  19  74  88   0.24   1.67 17.59   6.66   26.16   28.43     DDCCAA
25 240  0.68 0.02   709 434 4.5  9 0.052 0.18 0.03  19  74  88   0.57   1.51 17.34   6.65   26.06   40.07     DDDCCC
26 240  0.24 0.02   709 434 5.3 10 0.055 0.17 0.03  19  74  85   1.06   1.87 17.10   6.63   26.66   46.16     DDDCCA
27 240  0.12 0.02   709 434 6.4 10 0.052 0.10 0.02  19  75  83   1.18   2.20 16.87   6.62   26.87   40.64     DDAAAA
28 240  0.94 0.02   709 435 6.4  7 0.064 0.07 0.02  19  75  84   0.97   2.22 16.63   6.60   26.42   33.13     DAAAAA
29 240     0    0   709 435 2.6  6 0.053 0.10 0.03  19  75  86   0.82   2.11 16.37   6.59   25.88   30.44     DDDCCC
30 240     0    0  1050 434 3.4  8 0.055 0.11 0.03  19  75  85   0.82   2.04 16.11   6.58   25.55   28.53     DDDCCC
31 240     0    0  1050 434 5.0  7 0.056 0.05 0.02  19  75  85   0.72   1.89 15.85   6.56   25.02   26.47      DSSSS
             V O L U M E -  C E N T I M E T E R S
       24.37                             6.17                    0.55         4.00           7.25
             0.96                             1.00                      1.12         1.57            6.90
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EXPLANATION OF CODES

DA	Day	**SURF**	Surface flowrate, cms
HR	Hour	**SUBSF**	Subsurface flowrate, cms
PCPN	Precipitation, cm	**BASF**	Baseflow flowrate, cms
INT	Interception, cm	**LOWERZ**	Lower zone flowrate, cms
SNOWL	Elevation of snowline, meters	**TOTAL**	Total computed discharge, cms
WE	Snow water equivalent, cm	**OBS**	Observed discharge, cms
LR	Lapse rate, degrees C / 1000 m	**FLAGS**	Indicators of snow activity on each elevation band
TA	Air temperature at sea level, degrees C	**D**	Dry weather melt occurring
MR	Melt rate, cm/degrees C-day	**R**	Rain melt occurring
RG	Runoff generated, melt+precip-int-soil loss	**S**	Snow on band, no accumulation nor melt
ET	Evapotranspiration, cm/day	**A**	Snow being accumulated
SMI	Soil moisture index, cm	**L**	Dry melt restricted by band transition
ROP	Computed runoff percent	**Q**	Melt, but no RO because of liquid water deficiency
BFP	Computed baseflow percent	**C**	Melt, but no RO because of cold content

Figure 4-6. Example of computer printout during snow accumulation