Chapter 8
Snowmelt—Accounting for Changes in Snow and Snow Cover

8-1. Overview

This chapter describes the requirements needed and techniques used to track the state of the snowpack in a basin once the accumulation of snow has ended and ablation has begun. It follows logically in sequence after Chapter 7, which has covered the internal changes in the snowpack, primarily in winter in rain-on-snow situations or early spring and how they affect snowmelt. This discussion is oriented primarily to spring-summer snowmelt in the large interior basins of the western United States, where snowmelt is a 2- to 3-month-long process. The following is a summary of the changes that take place in the snowpack and its watershed during snowmelt for spring-summer:

- The snowpack, now internally isothermal and at 0 °C, yields meltwater to the soil surface as heat energy is applied at its surface and ground.

- The snow surface albedo continues to decline as surface snow crystals become rounded. This allows greater amounts of shortwave radiation to be absorbed as heat energy.

- As snow melts, first at lower elevations, the snowline begins to climb to higher elevations. This shifts the melting level in the basin to higher and higher elevations as the season progresses.

- As the snowpack recedes, the snow-covered area of the basin decreases, while the snow-free area increases. The soil moisture in the snow-free area decreases, thereby leaving the basin with two distinctly different runoff characteristics.

- Any precipitation falling during the melt season will encounter a variety of potential situations: it will fall as fresh snow at higher elevations, as rain-on-snow at lower elevations, and as rain on bare ground (with reduced soil moisture) at low elevations.

- As the melt season progresses to its later stages, the active melt zone may shift from a forest-covered area to one that is free from forest cover, above the timberline. This results in new energy sources dominating the snowmelt process.

a. The problem for forecasting and analysis is not only to account for the above phenomena if they are important in a particular application but also to accurately as possible assess the residual SWE or volume of runoff anticipated. An initial volume of SWE is determined at the beginning of the snowmelt period, as discussed in Chapter 4. As the melt season progresses, calculated melt is subtracted from the initial values to yield a residual, and any additional precipitation is added. Any error in the initial estimate is carried into the residual; as the residual decreases, the error becomes more and more significant. This calls for the ability to update the residual snow-runoff estimate carried in the model by checking with observations in the basin.

b. In rain-on-snow situations, the meteorological conditions are such that most of the phenomena described above have little relevance. Here, the freezing level is continually shifting with the passage of storms, and the watershed's soil moisture may be saturated by rainfall, whether on snow or not. A snow-covered area may change in a matter of hours, rather than weeks, during a significant storm. The magnitude of the snowpack volume may be relatively small compared with the rainfall runoff involved. Solar radiation is often of little consequence. Despite the differences, however, modeling in this environment still requires the accounting of the snowpack during melt. Often, short-cuts and subjective methods are employed in operational applications.

8-2. Simplified Methods, Lumped Models

a. *Simple estimates.* The simplest approach in dealing with changes in the snowpack during melt is to assume that the changes are insignificant. This may be a reasonable assumption for rain on snow. If, for instance, the rainstorm is relatively short and the snowpack large, there may literally not be any change in the snowpack's areal extent during the storm. Chapter 10 discusses this further in conjunction with design flood analysis. For river forecasting during rain on snow, manual updates, based upon real-time observations, will help determine the status of the snowpack. A further check in forecasting is to see how well the model is tracking observed streamflow.

b. Snow cover depletion curve. An approach that has been used in lumped models for spring-summer melt settings is to employ a snow cover depletion curve that describes the basin's snow-covered area as a function of accumulated snow runoff. Used in conjunction with an area-elevation curve, the snowline elevation for the basin can also be determined. An example of a generalized depletion curve as used in the SSARR model is shown on Figure 8-1. The "theoretical depletion curve" is derived using historical field and remote-sensing records together with runoff data. Studies have shown that this generalized relationship is relatively uniform for a basin. Observed conditions of snow cover and runoff, however, may yield a point that is not on the theoretical curve. In this case a proportionally adjusted curve is followed, as shown in Figure 8-1.

(1) While the snow cover depletion curve yields an accounting of the snow cover, this method still needs to independently estimate expected total basin SWE. The typical approach is to use multiple-regression procedures as described in Chapter 9 to determine an initial estimate of the total SWE (actually, expected total basin seasonal runoff). The accounting of currently remaining SWE during the melting of the snowpack is simply a process of subtraction. Adjustments in expected residual runoff and snow-covered area are periodically made during the snowmelt season using satellite data and fixed-wing reconnaissance flights and by verifying model performance by comparing observed and computed streamflow. This methodology is used in the Snowmelt Runoff Model (SRM) (Chapter 11).

(2) A consideration with this type of approach is how to compute runoff from the snow-free portion of the basin during spring or summer rain. One option that has been successful in the Columbia basin is to simply assume that summer rain falling over the snow-free area is negligible, since soil moisture is relatively

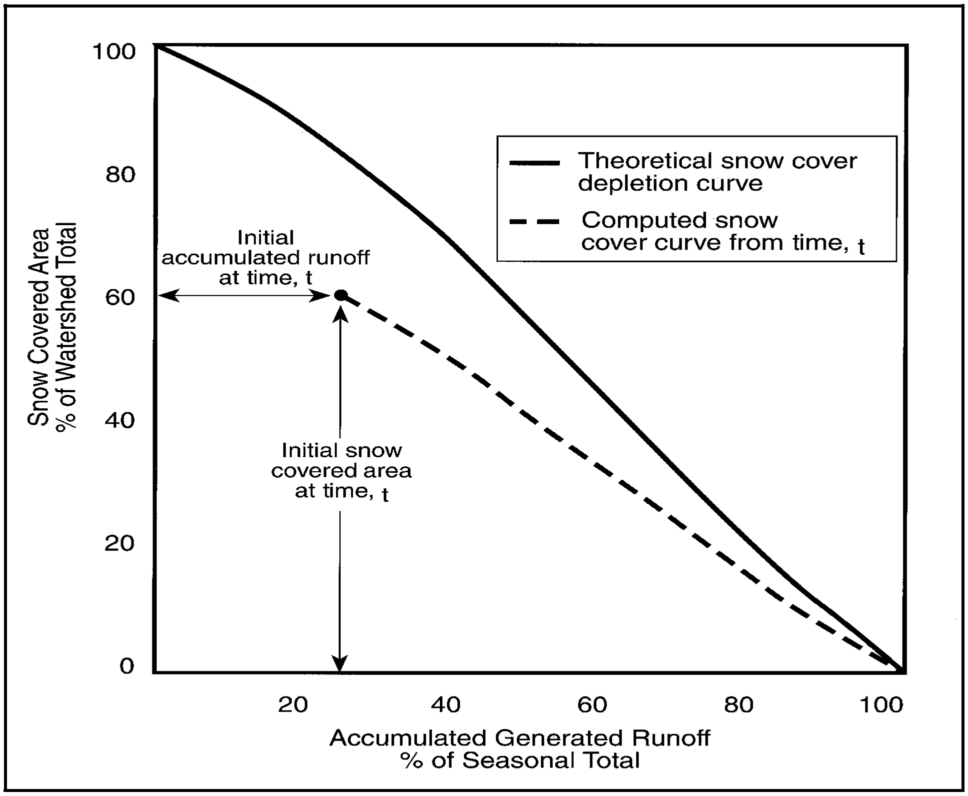

Figure 8-1. Example of snow cover depletion curve

low and rainfall quantities are not normally great. An alternative to this is to split the basin into a snow-covered and a snow-free zone. The snow-covered area is continuously defined with a snow cover depletion curve, and the snow-free component is computed as a complement to that area. With this technique, runoff from the snow-free portion is independently computed and added to the snow-covered runoff. Both of these options are available in the SSARR program under the lumped basin options.

(3) The snow cover depletion curve method is suitable for some design flood derivations in summer snowmelt settings since the depletion curve is based upon historical conditions, and initial SWE can be determined by independent analysis of historical records. This approach may not be valid, however, if the design condition includes a heavy spring rainstorm in addition to snowmelt.

8-3. Detailed Methods, Distributed Models

With all of the changes in the watershed and in a snowpack taking place during snowmelt, simplified approaches are limited in their ability to address many of these changes. A distributed model is required to begin accounting for changes in any detail.

a. Snow-band formulation. This method of defining a basin model, described in Chapter 4, can be employed with reasonable success to account for changes in the snowpack. The accounting of snow quantity, cover, and quality is done zone by zone. There is no reason why this cannot account for all the physical changes that occur during snowmelt. An important consideration, however, is whether each zone is assumed to be either 100-percent snow-covered or snow-free. If so, the basin may require a large number of zones to be adequately represented. Even with a large number of zones, the snowline can abruptly change as a zone transitions from being snow-covered to snow-free, causing unrealistic results in simulated flow. Because of this, a model may allow simulation of a gradual transition in snow cover within a zone. Figure 8-2 is a portion of summary printout from an SSARR model simulation, showing the changes in snow cover on eight bands of elevation. In this model, snow conditions are strictly homogeneous on each band, but a limiting function prevents abrupt transitions as a band becomes depleted of snow. An indicator flag shows when this has happened.

b. Grid-cell-based models. As with the snow-band approach, a horizontally defined grid system can also account for changes in the snowpack, provided the grid is fine enough. The same problems crop up as in the elevation band definition if homogeneous conditions are assumed and abrupt transitions occur.

8-4. Snow Observations During Snowmelt Forecasting

Regardless of the simulation technique used during snowmelt, an essential operational practice for runoff and streamflow forecasting is to make use of field observations to verify the model's state variables. This can range from simple subjective checks, based upon a limited amount of data, to complex systematic procedures. Three methods of employing field data are summarized below. This subject is discussed in more detail in EM 1110-2-9038.

a. Areal snowcover. This is a parameter that is fairly easily obtained, either from satellite imagery or by special aerial reconnaissance flights. Rango and Itten (1976) have effectively employed satellite observations in accounting for snow during snowmelt. The National Weather Service's Remote Sensing Center in Minneapolis has an ongoing program of providing processed snow-cover data to cooperating agencies during the spring-summer snowmelt period in the western States.

(1) An older approach still used by some USACE offices is flying fixed-wing aircraft into the basin at or near the snowline elevation and reporting the status of the snowline at fixed reference points. These data are converted to snow cover using an area-elevation curve. Snow-flight data are now used where satellite data are not yet satisfactory, or to simply to augment the remotely sensed data.

(2) Both the satellite observations and aerial reconnaissance can be obscured by a cloud cover. With satellite passes being at fixed intervals, it is possible to miss having snow cover information for an extended period. Partial cloud cover can be

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                                        SSARR SNOWBAND MODEL (METRIC) -
        COMPUTED FLOW, ILLECILLEWAET R., CANADA
             AREA      BASE-TEMP        ZONES
APR 1982     1155         0                 8                                                           FLAGS BY ZONE
DA  HR  PCPN  INT SNOWL  WE  LR TA    MR   RG   ET  SMI ROP BFP   SURF  SUBSF BASEF  LOWERZ   TOTAL     OBS   1******8
27 240              709 124                        4.9       0  5.000 13.800 4.000   4.800  27.600  27.550
28 240  0.29 0.19   709 124 7.3 10 0.242 0.30 0.06 5.0  44  81  5.221 16.041 4.185   4.785  30.232  30.200   DDSSSAAA
29 240  0.08 0.05   709 124 7.3  9 0.303 0.13 0.06 4.9  44  80  3.600 15.230 4.365   4.770  27.965  28.800   DDSSSAAA
30 240     0    0   709 123 7.3 12 0.245 0.27 0.08 5.0  44  81  3.393 13.776 4.540   4.755  26.465  27.400   DDDSSSSS
                           V O L U M E  -  C E N T I M E T E R S
        0.37                             0.71                    0.09          0.1            0.63
             0.25                              0.2                      0.34          0.11            0.65
MAY 1982
 1 240  0.00 0.00   709 123 7.3 12 0.254 0.28 0.08 5.0  44  81  4.115 14.365 4.726   4.741  27.946  28.250   DDDSSSSS
 2 240  1.14 0.30   709 123 7.3 12 0.263 0.40 0.08 5.1  45  80  5.232 16.246 4.934   4.727  31.139  28.150   DDDAAAAA
 3 240  0.70 0.07   709 124 7.3  9 0.311 0.13 0.06 5.1  45  78  4.034 15.994 5.144   4.713  29.885  25.750   DAAAAAAA
 4 240  0.43 0.05   709 124 7.3  9 0.311 0.12 0.06 5.1  45  81  2.360 12.629 5.324   4.699  25.013  24.550   DAAAAAAA
 5 240  0.00 0.00   709 124 7.3 10 0.240 0.18 0.07 5.1  45  83  2.175 10.479 5.487   4.685  22.826  24.900   DDCSSSSS
 6 240  1.41 0.11   709 124 7.3 12 0.247 0.50 0.07 5.2  45  83  4.281 12.318 5.684   4.672  26.956  31.050   DDDAAAAA
 7 240  1.13 0.07   709 125 7.3 12 0.192 0.54 0.08 5.4  46  77  7.222 18.154 5.944   4.659  35.979  36.550   DDDCAAAA
 8 240  0.00 0.00   709 124 7.3 13 0.202 0.39 0.09 5.4  47  74  7.825 22.853 6.226   4.647  41.550  37.000   DDDCSSSS
 9 240  0.00 0.00   709 124 7.3 13 0.211 0.37 0.08 5.4  47  75  7.084 24.008 6.503   4.635  42.230  40.450   DDDCSSSS
10 240  0.00 0.00   709 123 7.3 14 0.180 0.53 0.11 5.5  48  76  8.098 25.551 6.791   4.623  45.063  45.400   DDDQCSSS
11 240  0.01 0.01   709 122 7.3 16 0.164 0.66 0.13 5.6  48  74 11.069 29.932 7.111   4.612  52.723  51.250   DDDQCCAA
12 240  0.70 0.32   709 122 7.3 15 0.167 0.68 0.12 5.6  48  72 13.392 35.360 7.464   4.601  60.816  56.650   DDDQQCAA
13 240  0.14 0.08   709 121 7.3 16 0.176 0.68 0.13 5.7  49  71 14.317 39.818 7.835   4.591  66.562  63.500   LDDQQCAA
14 240  0.03 0.02   709 120 7.3 18 0.175 0.69 0.16 5.7  49  70 14.325 42.876 8.221   4.581  70.004  74.200   LDDQQCCA
15 240  0.11 0.08  1050 119 7.3 19 0.198 0.79 0.19 5.8  50  69 15.741 46.186 8.624   4.572  75.123  82.300   DDDQQCCA
16 240  0.10 0.06  1050 117 7.3 21 0.205 1.07 0.23 6.0  50  69 21.152 52.401 9.069   4.564  87.186  92.250    DDDQQQC
17 240  1.09 0.33  1050 116 7.3 21 0.230 1.39 0.24 6.3  51  66 29.731 63.251 9.594   4.556 107.132 109.000    DDDDQQQ
                            V O L U M E  -  C E N T I M E T E R S
        6.99                             9.39                    1.29         0.86            6.34
             1.50                             1.97                      3.61          0.59            6.37
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EXPLANATION OF CODES

DA	Day
HR	Hour
PCPN	Precipitation, cm
INT	Interception, cm
SNOWL	Elevation of snowline, meters
WE	Snow water equivalent, cm
LR	Lapse rate, degrees C / 1000 m
TA	Air temperature at sea level, degrees C
MR	Melt rate, cm/degrees C-day
RG	Runoff generated, melt+precip-int-soil loss
ET	Evapotranspiration, cm/day
SMI	Soil moisture index, cm
ROP	Computed runoff percent
BFP	Computed baseflow percent

SURF	Surface flowrate, cms
SUBSF	Subsurface flowrate, cms
BASF	Baseflow flowrate, cms
LOWERZ	Lower zone flowrate, cms
TOTAL	Total computed discharge, cms
OBS	Observed discharge, cms
FLAGS	Indicators of snow activity on each elevation band
D	Dry weather melt occurring
R	Rain melt occurring
S	Snow on band, no accumulation nor melt
A	Snow being accumulated
L	Dry melt restricted by band transition
Q	Melt, but no RO because of liquid water deficiency
C	Melt, but no RO because of cold content

Figure 8-2. Example of elevation band output during snowmelt

accommodated to a large degree in satellite observations through the skillful use of image processing. In both types of observations, a heavy forest cover can also obscure the snowline. Again, this can be at least partially accounted for by experienced observers and skilled use of processing techniques.

(3) When an observation of snow cover is obtained, it is compared with the model's current calculation of snow cover or snowline elevation, whether it be the lumped or distributed models described above. A significant difference would suggest a change in the model, particularly if it is confirmed by other indicators described below.

b. Snow-water equivalent. A second field indicator used to verify forecast models is SWE data from snow courses or snow pillows. If automated reporting is available, such as through the SCS SNOTEL network, these data are readily available for operational use. When used in conjunction with a distributed model, they can help to determine the current SWE state being computed by an element in the model. These measurements can also be used to help estimate the snowline in a basin. An example of a simple approach in using SWE data is shown in Figure 8-3. Here, historical SWE readings for a specific date have been correlated with computed-model SWE for a given elevation band in the basin. The model data are taken from simulation runs made for the basin. Several bands were checked against the observed data to see which had the best correlation and which would be most useful in adjusting the model. Once the model is in the forecast mode, the real-time data are compared against this correlation. If outliers are found, the model should probably be adjusted. The National Weather Service has developed a sophisticated technique using a geographical information system and optimal interpolation (kriging) in which mean areal SWE is calculated from snow measurements. These values are used to update model-simulated SWE via Kalman filtering (Day, Schaake, and Ellis 1989; Day 1990).

c. Streamflow. The final means of checking a forecast model's computation of snowmelt is to compare computed discharge against streamflow observations. Although not necessarily a sensitive indicator in the early stages of snowmelt runoff, this comparison becomes very important in confirming residual SWE volumes carried by the model in late-season melt. This check is viable for both the lumped and distributed models described above. Two different measures of performance are possible: How well does the model compute recently observed streamflow? How reasonable are the streamflow volumes generated by the model when run through the normal recession period? The latter check involves comparing with historical statistics or plots for the period being sampled.

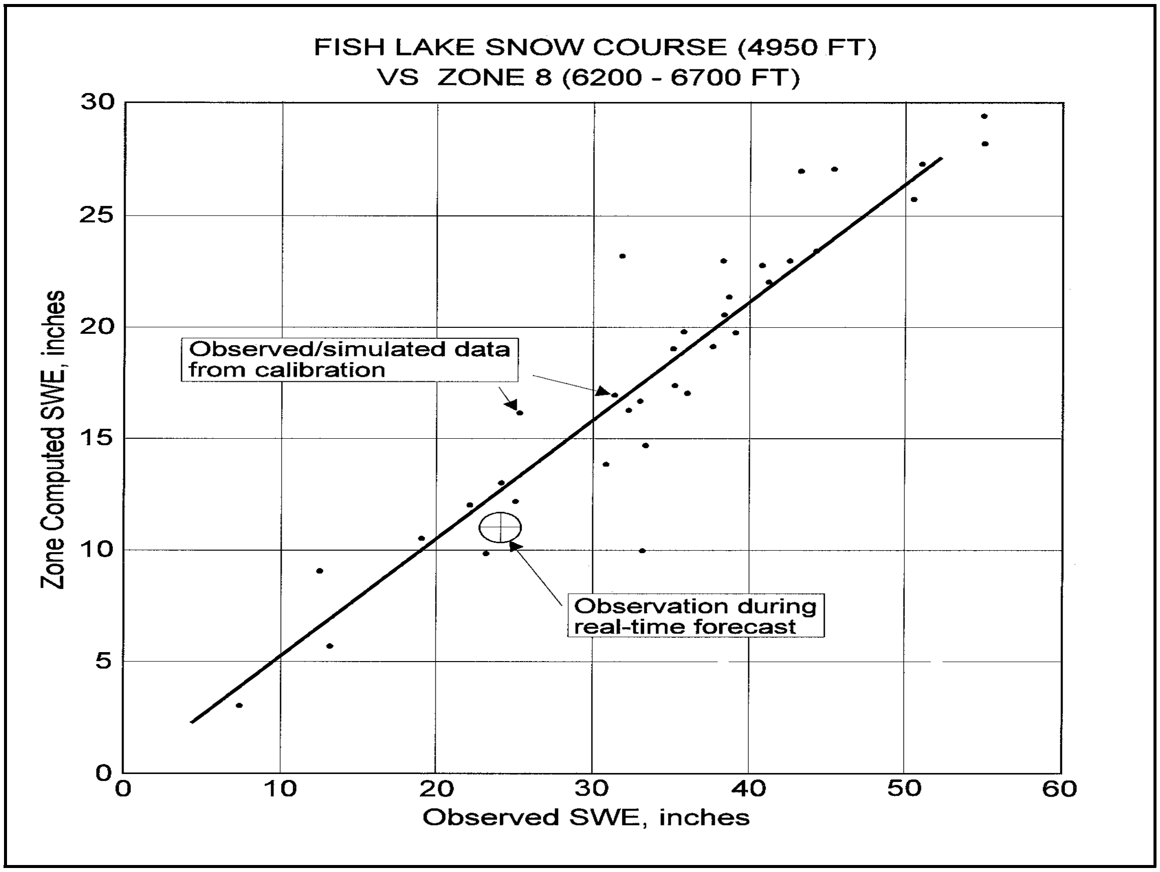

Figure 8-3. Example of correlation—snow band SWE versus snow pillow SWE