Chapter 7
Effect of Snow Condition on Runoff

7-1. Overview

This chapter is primarily about the state of the snowpack during the winter accumulation period and into the early spring and the effect that the snowpack has on delaying runoff from rainwater and melt during this time. The techniques that will be described are generally applicable to rain-on-snow conditions frequently experienced in basins of the eastern and western United States that are subject to winter maritime rainstorms. Hydrological analysis or forecasting under these conditions requires a particular awareness of the ability of the snowpack to store water, thus delaying runoff to some extent. The magnitude of this effect will be discussed, and methods for determining and simulating the storage effect of the snowpack for practical forecasting and design will be presented.

a. Chapter 2 has described the changes in the character of the snowpack as it is transformed from a fresh, low-density, crystalline state to a dense, coarse-grained condition that is isothermal at 0 °C and ready for melt. In a rain-on-snow environment, these conditions are particularly dynamic, continually changing as the basin is subjected throughout the winter to a succession of storms—bringing precipitation either in the form of rain or snow—interspersed by dry periods that are often below freezing at higher elevations. This changing environment must be considered in analysis and modeling, and the changing character of the snowpack as it affects runoff must be a part of continuous simulation models. The following phenomena must be considered in one way or another.

(1) As rainwater or melt enters a subfreezing snowpack, it must first give up energy to raising the temperature of the snow before it can be available for runoff.

(2) In addition to the rainwater and melt that is frozen in the snowpack, an additional amount is lost in satisfying a liquid-water capacity that is inherent in fresh snow.

(3) In the process of traveling through the snowpack, the rainwater and melt may follow a circuitous route as it encounters ice lenses and "cold" pockets within the snowpack, thus delaying the delivery of water to the ground surface.

b. A wide spectrum of alternatives is currently employed in practice in dealing with the above factors, ranging from detailed physical modeling of the snowpack's internal characteristics to simply considering these effects to be small enough that they can be ignored. Fortunately, for some engineering applications the snowpack's condition can be ignored. In design flood derivations, for instance, the snowpack can be assumed to be fully ripe before the flood begins; in many forecasting settings, the uncertainty of many other factors often outweighs the relatively small magnitude of snow-condition effects. In this chapter an overview will be given on the approaches to modeling the condition of the snowpack, and a discussion on the relative magnitude of the phenomena will be presented.

7-2. Cold Content

For practical applications, the concept of cold content is used in quantifying the effect of the snowpack temperature on rain and melt. Cold content defines the amount of energy needed to raise a "cold" snowpack to 0 °C, expressed in terms of the amount of water needed to be produced at the surface to release energy by freezing. This can be calculated by:

$$W_c = \frac{0.5\,\rho_s\,d\,T_s'}{80} \tag{7-1}$$

where

W_c = cold content, in.

0.5 = specific heat of ice, cal/g °C

ρ_s = average density of the snowpack, g/cc

d = depth of pack, in.

T'_s = average temperature deficit of snowpack below 0 °C, °C

80 = latent heat of fusion of water, cal/cc

For practical applications, the average snowpack temperature can be estimated on the basis of the air temperature for 1 to 3 days before the forecast time. Typically, the temperature will be close to that of the air at the snowpack surface, but will approach 0 °C at the ground. For deep snowpacks, a further assumption can be made that only the top 61 cm (24 in.) or so of snow is subject to the influence of air temperature and that the deeper pack is only 1 to 2 degrees or so below freezing. The density of this layer of snow can also be assumed to be greater than the top layer. Examples of computation are presented later in this chapter.

7-3. Liquid-Water-Holding Capacity

As summarized above, the liquid-water-holding capacity of the snow is a second factor that can be considered an "initial loss" in practical applications in snow hydrology and forecasting. Unfortunately, there is very little experimental evidence leading to the quantification of this. It varies, depending upon the depth and density of the snow, the mass of ice layers, and the channelization and honeycombing of the snowpack. At 0 °C this factor is approximately 2 to 5 percent of the SWE (USACE 1956). For most practical applications, a fixed percentage of the SWE is used as an initial loss, in addition to the cold-content loss. Note that this magnitude of loss assumes the free drainage of the water. Therefore, in flat areas the snowpack may hold liquid water far in excess of the amount that is found in mountainous areas.

7-4. Movement of Water Through the Snowpack

The final effect of a snowpack on rainwater and melt is the time delay as liquid water moves downward to the ground surface. This process has been explored in laboratory experiments, as discussed in Chapter 2, and theoretical equations have been developed to explained the phenomenon. Anderson (1973) has developed empirical relationships using time lag and attenuation to represent drainage through a snowpack. However, in practical applications, this seldom is considered a significant enough delay to warrant a detailed evaluation. The snow investigations studies noted that the net storage effect on water draining through a moderately deep snowpack resulted in a time delay on the order of 3 to 4 hr.

7-5. Simulating Change in Snow Condition

Simulation of the above phenomena involves the following considerations:

- Calculating the gain or loss of heat from the air, liquid water, and ground sources.

- Maintaining a continuous accounting of negative heat storage in the snowpack, including diurnal.

- Maintaining an estimate of the snowpack thermal conductivity, a function of snowpack density.

- Accounting for the variation in snowpack character in the vertical dimension.

- Keeping an accounting of the liquid water currently in the snowpack, in both the retained and gravitational phases.

- Estimating the attenuation and time lag of gravitational water movement through the snowpack.

Many of these processes are obviously complex and therefore are computed explicitly in only detailed physical models. In a physically based simulation, an internal mass balance is continuously computed as a part of the basic energy balance of the snowpack (Equation 2-1). Snowpack settling and density may be continuously estimated, with the snowpack definition being accounted for in more than one vertical layer.

a. An empirical approach that is currently used widely is that of Anderson (1973). Here, an accounting is maintained of the relative temperature of the snowpack below freezing as a function of time. In effect, the snowpack is simulated as an energy reservoir; once the reservoir is full (snowpack isothermal and at 0 °C) meltwater moves to the ground. This can be done through an index relation such as:

$$T_s(2) = T_s(1) + F_p(T_a(2) - T_s(1)) \qquad (7\text{-}2)$$

where

T_s = index of the snowpack surface temperature at times (1) and (2)

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

T_a = air temperature

b. If F_p is close to 1.0, the snow temperature will remain close to that of the air; thus, values close to 1.0 would be appropriate for shallow snowpacks. For a deep snowpack, a low value of F_p will result in a slow cooling or warming of the snow. The variable T_s is limited to a maximum of 0 °C (32 °F) in the simulation process.

c. Once a snow-surface temperature index is established for a computation period, the cold content can be calculated through an equation such as:

$$W_c(2) \quad = W_c(1) + C_r\,(T_a(2) - T_s(1)) \tag{7-3}$$

where

W_c = cold content, in. (mm)

T_a = air temperature

T_s = index of the snowpack surface temperature

C_r = conversion factor, in. (mm)/degree-day

The value of C_r can be made a variable in simulation models by relating it to calendar periods or to a cumulative temperature index function. Figure 4-1 is an example of a computer printout made during a winter-snow accumulation period. In this model, snow conditioning is simulated using the above technique. Note that for several periods following a cold period, snowmelt is limited by satisfying cold content and liquid-water deficiency requirements.

7-6. Impact on Runoff

The magnitude of cold content can be illustrated by calculating this factor for various assumed conditions using Equation 7-1. This is shown in Table 7-1. For the deep snowpack example, the calculation is subdivided into two layers, above and below a 61-cm (24-in.) depth. As can be seen, the cold content is a relatively small factor compared with the potential magnitude of rainfall and snowmelt. It varies from 3 percent or more of the SWE for "cold" snow, to 1 percent or less of the SWE for deeper snow that is closer to 0 °C.

a. A second illustration, based upon observations made at the Willamette Basin Snow Laboratory, is shown on Figure 7-1. Illustrated is the storage and transmission of water in the snowpack for an observed rain-on-snow situation. Here, a snowpack having a water equivalent of 67.8 cm (26.7 in.) receives input from a 2-day rainstorm. Since the snowpack was colder than 0 °C (at -6 °F), some rain and condensation was taken up in raising the temperature of the snow to 0 °C through the process of freezing; this amounted to 0.76 cm (0.3 in.) of water. An additional amount of liquid water, 1.27 cm (0.5 in.) was permanently retained in the snowpack, making the total quantity of stored water 2 cm (0.8 in.) Finally, the snowpack also temporarily stored some water input as it progressed through the pack. In this case, given the rate of input involved, there was a time delay of 12 hr between the beginning of rain and melt and the beginning of runoff. The hydrograph resulting from the input summarized in Figure 7-1 is shown in Figure 7-2. The loss of 2 cm (0.8 in.) is displayed.

b. For practical applications in a rain-on-snow situation, snow-condition effects can be thought of as an "initial loss" that is subtracted from input, much in the same way as initial losses in dry-soil conditions are simulated in rain-runoff situations. For the engineer, the problem is to be able recognize this potential and to be able to incorporate this time lag in the snow hydrology analysis, where appropriate. Practically speaking, this may not a major factor in design analysis since the snow can usually be assumed to be fully primed prior to the beginning of significant runoff producing melt. In certain forecasting situations, however, the effect of snow conditioning can be noticeable, and it is definitely a factor that needs to be considered in continuous simulation models that operate through periods antecedent to active snowmelt periods.

Table 7-1
Variation in Cold Content

	Assumed Factors			Calculated Factors		
Descriptive Condition	***d*, in.**	**ρ**	**T'_s, °C**	**SWE, in.**	***Wc*, in.**	***Wc*/SWE, %**
Shallow, relatively fresh snowpack. Several days of 8 °C temperatures prior to application	16	0.20	6.0	3.2	0.12	3.8
Same, but warm snowpack	16	0.20	1.0	3.2	0.02	0.6
Deep snowpack, top 61-cm (24-in.) layer cold	24 36 60	0.20 0.30	5.0 1.0	4.8 10.8 15.6	0.15 0.07 0.22	1.4
Deep, ripe snowpack. Warmer antecedent conditions	24 56 80	0.35 0.45	1.0 0.5	8.4 25.2 33.6	0.05 0.08 0.13	0.4

Note: d = snow depth, in.; ρ_s = snow density, g/cc; T'_s = average temperature of snow layer, °C below freezing; SWE = beginning snow-water equivalent, in.; W_c = cold content from Equation 7-1, in.

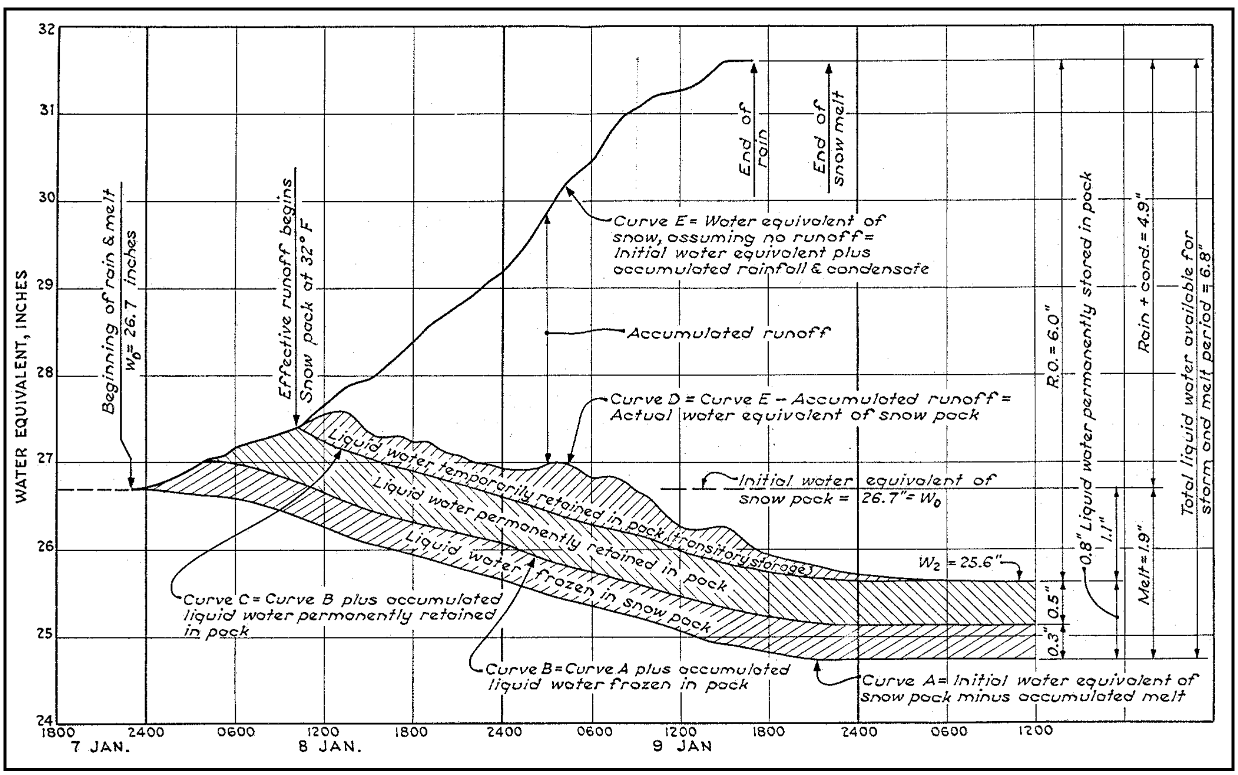

Figure 7-1. Snowpack water balance during rain on snow (Figure 4, Plate 8-9, *Snow Hydrology*)

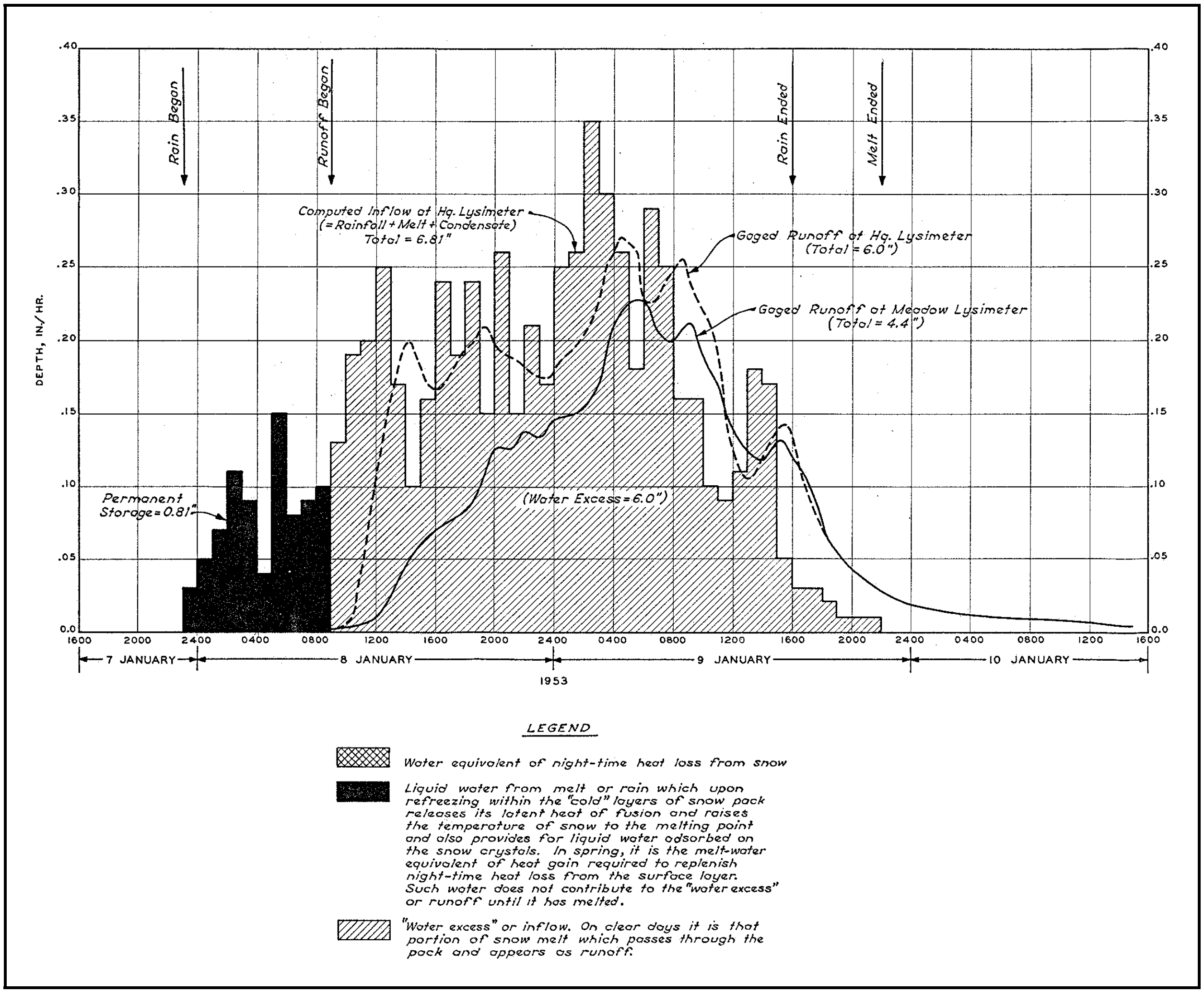

Figure 7-2. Hydrograph resulting from Figure 7-1 rain-on-snow event (Plate 8-8, *Snow Hydrology*)