METHODS OF ESTIMATING LIQUID WATER STORAGE IN SNOW

by

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Water retention by snowpacks remains an poorly understood process in snow hydrology. Although less important than basin-wide snow water equivalent or daily snowmelt, the ability of snowpacks to store liquid water is known to influence runoff production, particularly during rain-on-snow events. Few rigorous studies have been directed toward improving our ability to forecast the response of a snowcover to sudden inputs of water. Nevertheless, a variety of methods have been developed to provide estimates of snowpack water retention. This paper examines some of these techniques, focusing on theory and observations of snowpack behavior in the mid-elevation Sierra Nevada.

THEORETICAL CONSIDERATIONS

Although water storage in snow has been only a small part of recent work on water relations in snow (e.g., Colbeck 1978, Wankiewicz 1979, Dozier 1987), some fundamental concepts are available. When water is introduced into dry snow, both thermal and capillary storages are filled before water can move beyond some point. Freezing of water releases latent heat to warm the surrounding volume of snow to 0°C. The volume of water required by a unit volume of snow may be calculated as:

$$T(C/L)(p_s/p_w)$$

where T = initial temperature (°C),
C = specific heat of ice (2.09×10^3 J Kg^{-1} deg^{-1} at 0^oC),
L = latent heat of fusion of ice (3.34×10^5 J Kg^{-1}),
p_s = snow density, and
p_w = water density.

Using typical temperatures and densities of Sierra Nevada snowpacks, "cold content" values calculated with the equation above are usually less than 0.01 cm^3 water/cm^3 snow.

After some volume of snow has warmed to 0°C, additional water is held by capillary forces between grains. This requirement may be best considered as a proportion of the pore volume. This irreducible water saturation has been measured as 0.07 cm^3 liquid/cm^3 pore space in a few experiments (Colbeck 1974, 1978). Model studies in the high Arctic found that this widely-accepted value of 0.07 was "reasonable" (Marsh 1982), but two measurements in British Columbia (Wankiewicz 1979, p. 225) were considerably higher. Multiplication of the 0.07 value by snow porosity yields volumetric water retention values of 0.05 to 0.03 cm^3 water/cm^3 snow for snow densities of 0.2 to 0.5 g/cm^3. All water retention values for semi-homogeneous snow layers measured at the USDA-Forest Service's Central Sierra Snow Laboratory (CSSL) over a 3-year period were in or below this range (Kattelmann 1986). Liquid water measurements in partially drained snowpacks ranged up to 0.12 cm^3 water/cm^3 snow (Davis *et al*. 1985). Water was once thought to be retained as surface films around grains as well as in pore spaces (e.g., Gerdel 1954, U.S. Army 1956), but capillary theory suggests that water cannot exist as films around grains due to the lower pressure of water in the void space (Colbeck 1979a).

"REAL WORLD" CONSIDERATIONS

Use of the values cited above to assess water storage potential in snowcover would seem straightforward, if not for the complex structure of snowpacks and its effects on water routing. The Sierra Nevada snowcover has been observed to exhibit a wide range of responses to rainfall. Water delivery to streams has been delayed by the snowpack for up to two days (U.S. Army 1956) or just a few hours (Hall and Hannaford 1983). Several potential influences may account for the great variability in response. The wetting history of the snowpack may be the easiest effect to identify. Snowpacks that have previously transmitted water throughout their depth offer little storage or delay to subsequent inputs of water.

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Up to about 2000 m in the Sierra, mid-winter melt usually satisfies storages in any given layer within a week or so if there is no additional snowfall. Rainfall intensity may also alter the snowpack response. Even with the same total precipitation, intense rainfall flows more efficiently through the snowpack than low-intensity rainfall, due to increasing permeability to the liquid with increasing water contents at higher fluxes (Colbeck 1978). More intense rainfall also appears to flow through a smaller proportion of the snowpack volume (Kattelmann 1986).

Other external influences include attributes of the physical location of the snowpack. Elevation partly determines the exposure to rainfall or snowfall and the development of the snowpack. Aspect influences the snowpack's melt history and depth, with north slopes probably having the greatest potential storage. Increasing slope angle probably decreases storage and increases water delivery to streams, but the slope effect is really unknown because almost all field studies have been conducted on flat ground. Forest cover appears to result in wetter snowpacks with less available storage than in the open because of the drip from the melting of canopy-intercepted snow.

The internal structure and drainage system of the snowpack may well be the primary determinant of the snowpack's response to rain. Hydrologists cannot continue to assume that the snowpack acts as a homogeneous unit because reality is clearly otherwise. The layered structure of the snowpack has long been recognized to redirect the flow of water from strictly vertical (e.g., Gerdel 1954, U.S. Army 1956). Ice layers tend to increase water storage by inhibiting free drainage. Pore size differences between fine-grain snow overlying coarse grain snow also inhibit drainage, since water accumulates at the boundary until the capillary pressure difference is relieved (Wankiewicz 1979). Ponding of water in snow above the soil surface and blockage of rills and small streams by snow causes additional delay to runoff.

The existence of drains or channels (zones of preferential flow with above-average permeability) has been well known for decades. Effects of these features however, have been included in modeling of water movement through snow only recently (Colbeck 1979b, Marsh 1982). Drains minimize water storage because the water bypasses much of the snow volume. Excavation of snow dyed during artificial and natural rain at CSSL indicated that less than 20 percent of the snow conducted water (Kattelmann 1986). Zones of dry snow were found to be subfreezing for up to two days after water began draining out of the snowpack. Other studies (e.g., U.S. Army 1956, Sulahria 1972, Marsh 1982) have also found residual cold regions bypassed by percolating water. Thus, we must conclude that cold content and capillary water storage are not always fully satisfied before water is released from the snowpack. Eventually, these dry zones become wetted, and losses from water inputs must occur to satisfy these storages. However, these losses can occur as water is freely draining from other parts of the snowpack.

ESTIMATION TECHNIQUES

Most operational streamflow forecasting models with a snowmelt component include a means of estimating the water storage capacity of the snowpack. The basic premise that water is not yielded from the snowpack until this storage is satisfied has been employed for some 30 years (U.S. Army 1956, Morris 1985). A sensitivity test of snowmelt runoff model subcomponents found that inclusion of a liquid water subroutine improved model performance significantly (Kuusisto 1979). The most common method of calculating the available storage is as a constant proportion of the snowpack water equivalent. The constant is best determined by optimization (e.g., Bergstrom 1975). Some representative water holding capacities used in models appear in Table 1. Other models estimate the storage value as some function of density and/or temperature or other parameters (Table 2). The equations of Kuzmin (1948), Sulahria (1972), and Anderson (1976) show an inverse relationship between density and water holding capacity, but that of Ebaugh and DeWalle (1977) shows water holding capacity increasing with increasing density.

Two other methods (Bertle 1965, Kovacs 1982) do not evaluate water holding capacity directly but estimate a threshold density above which the snowpack begins to yield water. The USBR procedure (Bertle 1965) which estimates density by compaction was used by a large utility in a legal defense regarding cloud seeding activities (Riesboll, et al. 1965). These authors calculated that the snowpack retained 24 and 33 percent liquid water by weight at the 1800 m and 2100 m levels, respectively. They acknowledged without comment that these values were 5 to 10 times greater than other studies indicated. Previously, a threshold density method had been found to greatly overestimate storage (Boyer and Merrill 1954). The other threshold density method (Kovacs 1982) estimates the density as an increasing function of the number of snow layers. The success of this method may be related to water storage at layer interfaces.

Table 1. Water holding capacity (WHC) values used in snowmelt runoff models

WHC by Weight	Region	Source
0.02 - 0.05	Sierra-Cascades	U.S. Army (1956)
0.04	Rocky Mountains	Leavesley and Striffler (1979)
0.05 + 1cm at base	Sweden	Bergstrom (1975)
0.08 - 0.1	Norway	Saelthun (1979)
0.11	Finland	Kuusisto (1979)
0.13	Soviet Union	Glazyrin and Lifanov (1968)

Table 2. Equations used to estimate water holding capacity by weight[1/]

Equation	Source
$WHC = (0.11/p_s) - 0.11$	Kuzmin (1948)
$WHC = 0.00625T + 0.02$	Boyer and Merrill (1954)
$WHC = 1.2 - 2.8\ (p_s)$ + other terms (for old snow)	Sulahria (1972)
$WHC = 0.8 - 2.0\ (p_s)$ + other terms (for fresh snow)	
$WHC = (0.24(p_s) - 0.0291)/p_s$	Ebaugh and DeWalle (1977)
$WHC = 0.03$ if $p_s \geq 0.2$, otherwise $WHC = 0.07\ [(0.2 - p_s)(0.2)] + 0.03$	Anderson (1976)

[1/] WHC = water holding capacity by weight, p_s = snow density (g/cm^3), T = absolute value of temperature (°C)

A few other snowmelt runoff models ignore water holding capacity altogether (e.g., Martinec 1975, Obled and Rosse 1977) and still produce good results. In a few Sierra Nevada rain-on-snow events, the best fit with observed streamflow was obtained by routing rainfall through subfreezing snow with no delay (Hall and Hannaford 1983).

SUMMARY AND CONCLUSIONS

Although layers and channels appear to control water movement through snow, their distribution and physical influences are not well understood. In general, layers and channels permit water enroute through the snowpack to bypass large volumes of snow. With the exclusion of much of the snowpack from interaction with initial inputs of water, snowpack outflow can occur long before all storages are satisfied under traditional considerations. Similarly, losses can continue after the beginning of water release from the snowpack base as the wetted volume expands. As understanding and quantification of these processes grows, this information should be incorporated into physically-based snowmelt runoff models.

Meanwhile, the traditional notion of complete storage fulfillment prior to water release can be continued wherever it seems to work. Empirical calibration of the water retention values provides adequate results and can compensate for other obscure processes.

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