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SUSTAINED WINTER STREAMFLOW FROM GROUNDMELT

The watersheds of the Hubbard Brook Experimental Forest in the White Mountains of New Hampshire are among the few small gaged watersheds for which continuous winter streamflow records are obtained while deep snow covers the area. Records show that a remarkably steady flow of between 0.006 and 0.025 area-inch of water per day leaves the watershed in spite of snow depths up to 6 feet and air temperatures often continuously below 10°F. Wisler and Brater (1959) stated that streamflow of about 0.01 area-inches/day (0.025 cm/day) arises from groundmelt, which is defined as melt of snow by heat transferred from the soil to the bottom surface of the snowpack. Gold (1957) gave measured soil-heat flux data corresponding to a groundmelt of 0.071 cm/day under about 12 inches of snow for February and March 1955 at Ottawa, Ontario. Calculations from soil temperature gradients and thermal conductivity led to groundmelt estimates of 0.01 to 0.02 inches/day at the Central Sierra Snow Laboratory (Corps Engineers, 1956). This note presents data verifying the groundmelt theory for Hubbard Brook.

Sustained Winter Streamflow

The gaged Hubbard Brook watersheds range in size from 30 to 200 acres and have a forest cover of second-growth northern hardwoods. Winter hydrographs show a steady, low-volume streamflow through even the coldest, snowiest winters. Table 1 shows daily streamflow in area-inches for Hubbard Brook watersheds 1 and 3 for the winters of 1961 and 1963, in which no midwinter thaw occurred. Streamflow on the two watersheds is consistent on a unit-area basis even though watershed 1 is 29.2 acres and watershed 3 is 104.7 acres in size. Snow depth was about 20 inches

Table 1. — Measured streamflow on Hubbard Brook watersheds 1 and 3, in inches/day

Date	1961		1963	
	Watershed 1	Watershed 3	Watershed 1	Watershed 3
Jan. 5	0.015	0.015	0.015	0.015
Jan. 15	.012	.011	.015	.015
Jan. 25	.010	.008	.012	.015
Feb. 5	.006	.007	.012	.013
Feb. 15	.007	.008	.012	.013
Feb. 25	.188*	.204*	.012	.015
Mar. 10	—	—	.012	.013
Mar. 20	—	—	.023*	.022*

* Beginning of snowmelt period.

throughout January and early February 1961 and ranged from 15 inches in early January 1963 to 50 inches by mid-March.

The steep watersheds, shallow soils, and tight bedrock preclude the existence of extensive groundwater bodies, so it is not likely that this sustained flow arises from groundwater (Hewlett and Hibbert, 1963).

It is logical that this water originates as groundmelt of the snow pack. Because the soil is warmer at increasing depths in the winter, heat is conducted up to the soil surface, where it is used to melt snow. Since these soils are nearly always saturated by autumn rain, the snowmelt water passes through the soil and reaches the stream. Flow of water in the soil is not impeded by concrete frost formation because this type of frost is practically non-existent (Hart, Leonard, and Pierce, 1962).

If the groundmelt theory is correct, the measured streamflow should be equal to the heat flux from the ground minus the heat flux up through the snow, all divided by the heat of fusion of water. The heat fluxes are the products of the respective temperature gradients and thermal conductivities.

Soil Temperature Profiles

Soil-temperature profiles have been obtained near the foot of watersheds 1 and 3 at weekly intervals throughout the year for several years. These temperatures have been measured with thermistors to the nearest Fahrenheit degree at seven depths and at two separate locations.

Figure 1 presents profiles (average of both locations) obtained in 1961 and in 1963. A straight line has been drawn through the points (except 36 inches) for each date. The slopes of these lines represent the average temperature gradient, which does not change too much in the winter months with depth or with time. The February 11, 1963, gradient of about 0.25° F./inch or 0.05° C./cm can be chosen as typical of this data.

Soil-Heat Flux

The thermal conductivity of a soil can be calculated by the method given by DeVries (1963). If we assume a soil temperature of 2° C. and volume percentages appropriate to Hubbard Brook as follows: quartz 20%, other minerals 25%, water 15%, air 40%, then the thermal conductivity will be 1.97×10^{-3} cal cm^{-1} sec^{-1} $°C^{-1}$. If we use a temperature gradient of 0.05° C./cm, a heat of fusion of 80 cal/g — and with 86,400 sec/day — we have an equivalent melt by soil conduction $= 0.05 \times 1.97 \times 10^{-3} \times 86{,}400/80 = 0.106$ cm of water/day. The melt contribution of stored heat resulting from gradual lowering of soil temperature can be estimated using a heat capacity of 0.38 cal cm^{-3} $°C^{-1}$ (DeVries) and a temperature drop of 1° F. in the top 20 inches in 30 days, or 0.55° C. in 50 cm in 30 days. Thus the equivalent melt is $0.55 \times 50 \times 0.38/(30 \times 80) = 0.004$ cm/day, which is a small but significant contribution.

The heat lost upward through the snowpack when the air temperature is less than 32° F. can be calculated for a typical condition by using a

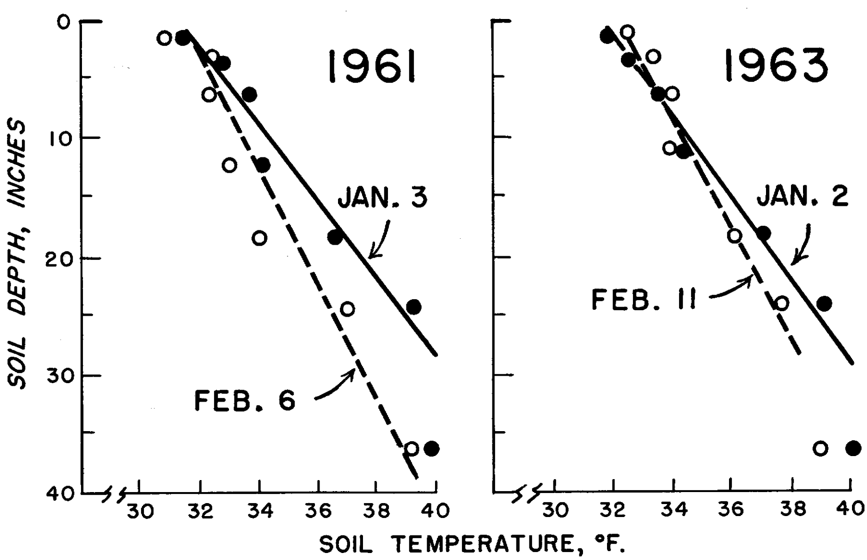

Figure 1. — Soil temperatures at various depths under snow.

thermal conductivity of 0.00032 cal cm^{-1} sec^{-1} $°C^{-1}$ for a snow density of 0.2 (DeVries). An air temperature of 14° F. (10° C. temperature difference) above 30 inches (75 cm) of snow gives an amount of melt which does not occur, since the heat is lost by conduction through the snow, of $0.32 \times 10^{-3} \times 10 \times 86{,}400/(75 \times 80) = 0.046$ cm/day.

The fraction of the soil-heat flux lost by snow conduction can vary from 0 to 1 with variations in snow depth and density and air temperature. The remainder is used in groundmelt. In normal years the heat flux from the ground decreases as the ground cools and the temperature gradient decreases (fig. 1). In 1963, increasing snow depth reduced the fraction of heat lost to the air and increased the fraction for groundmelt, which tended to maintain a constant amount of groundmelt. In 1961, the unusually shallow snowpack allowed the groundmelt fraction of the heat supply to remain constant instead of increasing; thus, as the total heat supply decreased, groundmelt and streamflow decreased.

Our groundmelt approximation from thermal considerations is $0.106 + 0.004 - 0.046 = 0.066$ cm/day. Measured streamflow of 0.015 inch/day or 0.038 cm/day is comparable. Considering the nature of the estimates made in the temperature-profile method, these values are as close as can be expected. Sustained winter streamflow can here certainly be explained by groundmelt of the snow cover.

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