Runoff Processes during Snowmelt

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Abstract. During the snowmelt period of 1967, snowmelt runoff from three pastured plots was measured as it moved to the stream channel over the ground surface, through the topsoil, and through the phreatic zone. Because of the presence of a thin layer of concrete frost in the normally porous topsoil, the infiltration capacity of the soil was reduced to a very low value. Almost one half of the meltwater left the plots as overland flow. Discharge rates, total volumes, and timing of this portion of the runoff were strongly controlled by incoming shortwave radiation. The response of subsurface flow to melting was heavily damped by storage and transmission of water in the soil. Combined daily hydrographs of runoff were dominated by overland flow. Comparison of the timing of such hydrographs with concurrent stream channel hydrographs from basins of the Sleepers River Experimental Watershed suggests that overland flow was a major control of the diurnal fluctuations of streamflow. Previous studies in the same area have demonstrated that much of the overland flow contributing to the responsive stream hydrographs of these basins originates on saturated areas of the watershed.

During 1967 and 1968, an experimental study of the production of storm runoff was conducted in a small basin of the Sleepers River Experimental Watershed near Danville in northeastern Vermont [*Dunne and Black,* 1970*a*, *b*]. Although the experiment was not specifically designed to study snowmelt runoff, the runoff was measured during the spring of 1967. To the writers' knowledge, snowmelt runoff at various levels in the soil, and the relationship of such runoff to certain environmental parameters such as solar radiation, temperature, frost and topography, have not been measured in such detail before. The melting of snow was extremely sensitive to solar radiation as modified by topography. Frost conditions largely determined the response of runoff to melt, because of the marked differences in the characteristics of surface and subsurface flow. Air temperature was not a sensitive predictor of snowmelt runoff.

EXPERIMENTAL AREA

The 0.6-acre study area has a general southerly slope that varies from 16°–49° and has a relief of 60 feet (Figure 1). A small stream drains the toe of the slope, but the hillside has no drainage from above as it is separated by a narrow, flat-topped divide from a steep slope on its northerly side. The hillside has a relatively simple longitudinal profile, and consists of three sections that differ in plan form. The west section has convex contours (plot 1), the center section is concave (plot 2), and the east section has straight contours (plot 3).

The geology and soils of the experimental area have been described elsewhere [*Dunne,* 1969; *Dunne and Black* 1970*a*]. The surficial soil of the hillside is sandy and in summer has an infiltration capacity greater than 3.15 inches per hour. Throughout the study the site was pastured.

INSTRUMENTATION

Runoff from the hillside was intercepted by drains installed in a 275-foot-long trench (Figures 1 and 2). The depth of the trench varied from 5–9 feet depending on the depth of the dense, silty-clay till shown in Figure 2. The interceptors were divided into five sections: a 25-foot-long ungaged buffer zone at each end to reduce edge effects, a 125-foot-long section of the trench that drains the convex hillside, and two 50-foot-long sections that drain the con-

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cave slope and the straight slope. In each section of trench, runoff was collected at three levels: the soil surface, the base of the root zone, and the zone of perennial groundwater seepage (Figure 2). The flow from each interceptor was measured in gage houses at the easterly end of each section. Discharge was determined from continuous records of stage on calibrated weir slots. The numbering system used to refer to the various flow collectors and the area of each plot is shown in Table 1. A roof was built over the trench and surface drain to prevent the direct entrance of precipitation.

Precipitation was measured by a shielded rain gage 400 yards northeast of the experimental site. The depth and water content of the snowpack were measured throughout the winter and the melt period at two snow courses (Figure 1). Photographs of the snow cover were taken at noon each day so that maps of the snow cover depletion could be drawn.

A nuclear depth probe was used to measure soil moisture. Three access tubes, 7 feet in depth, were located in each plot at locations shown in Figure 1. Readings were taken daily during and after the snowmelt period. Measurements of piezometric head were made at the same nine locations at depths of 10, 8, 6, and 4 feet.

Temperature, precipitation, and humidity were measured continuously at the experimental site. Shortwave and net radiation measurements were made 4.5 miles northwest of the site.

DATA

The 1967 snowmelt period on this slope lasted from March 23 to April 2. The weather during this time was warm and sunny. Clouds were rare, high insolation rates were recorded, and only 0.25 inches of rain fell while the melt was underway.

Antecedent conditions. During the three months preceding the snowmelt period, 4.34 inches of precipitation were measured at the rain gage. Snow-course data collected on the slope showed that drifting, melting, and evaporation modified the accumulation. At least 4.60 inches of water were deposited as snow on the eastern end of the experimental area,

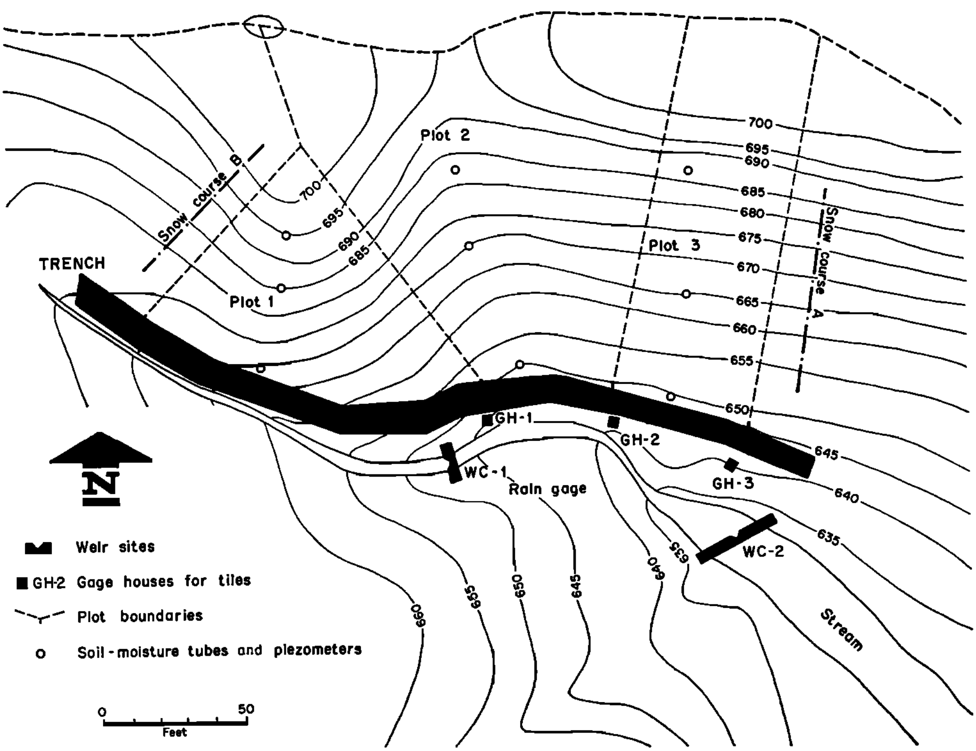

Fig. 1. Map of the experimental area.

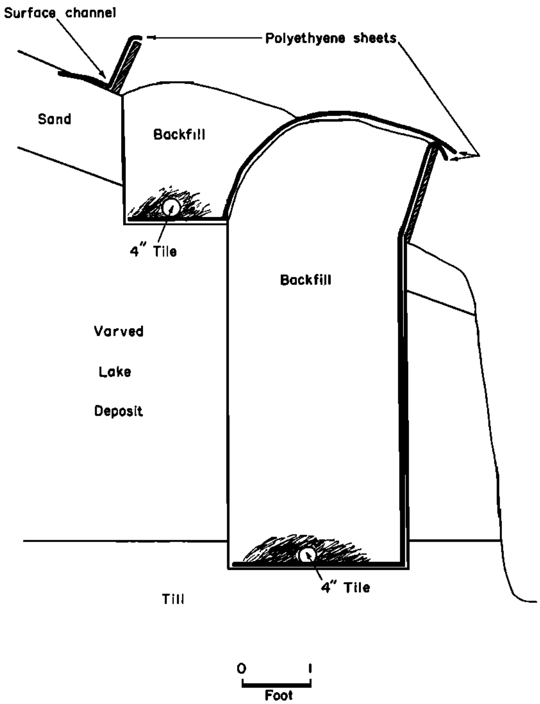

Fig. 2. Cross section of the interceptor trench.

but 2.09 inches of this water were lost by drifting, melting, and evaporation before the snowmelt period began. On the western end of the site, drifting was severe, and at least 6.80 inches of water were deposited as snow. Half this amount was removed, however, before the main snowmelt period began.

In addition to data from the snow courses, a large number of random measurements of snow depth and density were made on the study area 1 day before the snowmelt began. The random measurements showed that the averages of depth and density from the western snow course would give a good estimate of the snow covering plot 1. Similarly, the cover on plot 3 was well represented by the eastern snow course. Averages of data from the two snow courses closely approximated the depth and density of the snow cover on plot 2, except for a 10-foot-square area at the upper end of the concavity, where a drift with a maximum depth of 34 inches stored up to 10 inches of water. The averages of depth, density, and water equivalent of the snowpack at the beginning of the snowmelt period are given in Table 2.

During the preceding winter months several short periods of melting occurred, but the melting did not produce any significant runoff from the slope. The meltwater was, however, extremely important for the hydrology of the hillside during the main period of melting that occurred several weeks later. Percolation of meltwater during the winter melts had at least one important consequence in addition to the transformation of the snow from powder to granules. Some of the meltwater percolated to the ground and refroze at the soil surface and within the upper foot of soil. A discontinuous ice layer at the soil surface and several inches of 'concrete frost' within the upper soil horizon were produced. *Post and Dreibelbis* [1942] characterized concrete frost as an extremely dense structure consisting of many thin ice lenses and small crystals. *Trimble et al.* [1958] reported almost complete impermeability of concrete frost in ring-infiltrometer tests. On March 24, the second day of the main melt period, a survey of frost conditions was made in five pits at the eastern end of the site. Frost depths varied from 0.20–0.83 feet. An ice layer

TABLE 1. Areas of Experimental Plots and Numbering System Used in Referring to the Various Flow Collectors in the Interceptor Trench

	Plot 1 Convex	Plot 2 Concave	Plot 3 Straight
Area of plot	0.13	0.30	0.17
Level of collector			
Surface	1–1	2–1	3–1
Base of root zone	1–2	2–2	3–2
Zone of perennial groundwater seepage	1–3	2–3	3–3

Area of plot is given in acres.

TABLE 2. Average Snow Depth, Density, and Water Equivalent for the Three Plots on the Trenched Slope at 0800 Hours on March 23, 1967

Plot No.	Average Depth, inches	Average Density	Average Water Equivalent, inches
1	8	0.41	3.27
2	7.8	0.37	2.89
3	7.6	0.33	2.51

TABLE 3. Incoming Shortwave Radiation and Albedo of the Snowpack for the Hour of Maximum Insolation during the First Three Days of the Snowmelt Period at Station R-12, Sleepers River Experimental Watershed

Date	Maximum Hourly Incoming Shortwave Radiation, ly/hr	Albedo, %
March 23, 1967	49.5	61
March 24, 1967	58.7	54
March 25, 1967	66.7	47

was present at the soil surface at three of the locations. The soil was not completely impervious, however; in two pits worm holes were found from which water was issuing, and beneath the 34-inch-deep drift at the upper end of plot 2 the soil was not frozen. At the top of the slope, where snow cover had been absent or less than 9 inches for most of the winter, frost had penetrated to a depth of 0.83 feet. However, when the pit was opened below 0.67 feet, water, which had run into the hole during the few minutes of digging, suddenly drained out.

Measurements of piezometric head and soil moisture before the melt began indicated that, apart from the upper foot of soil, the profile was drier than at any other time except late summer. The water table lay 9 feet below the surface of the ground at the base of plot 1, 4–5 feet below the surface of the concavity in plot 2, and 7–8 feet below the surface in plot 3. Discharge from the lower tiles in each plot had declined steadily throughout the winter and at midnight on March 22, all discharges were less than 0.005 cubic feet per minute (cfm) (or less than 0.0002 inches per hour). The other tiles draining the slope had no flow prior to the melt.

Patterns of radiation and air temperature. Table 3 shows the albedo of the snowpack during the hour of maximum insolation on the first 3 days of the melt period, when a complete cover was beneath the radiometer. The steepness and southerly aspect of the trenched slope caused an increase in the effectiveness of incoming radiation. The elevation of the sun with respect to various parts of the slope at midday during the snowmelt period ranged from 61°–90°.

The relationship between the patterns of air temperature and incoming shortwave radiation is shown in Figure 3. During the snowmelt period, sunrise and sunset occurred at approximately 0545 and 1815, respectively. Air temperatures were above 32°F from about 0800 to 2000. Predawn minimum temperatures were close to 20°F, except after the cloudy nights of March 27 and 28. Daily totals of shortwave radiation and degree-hours above 32°F are given in Table 4.

Runoff. Table 5 is a summary of the disposition of meltwater from the snowpack on this steep, south-facing slope. The relatively large amounts of surface runoff resulted from

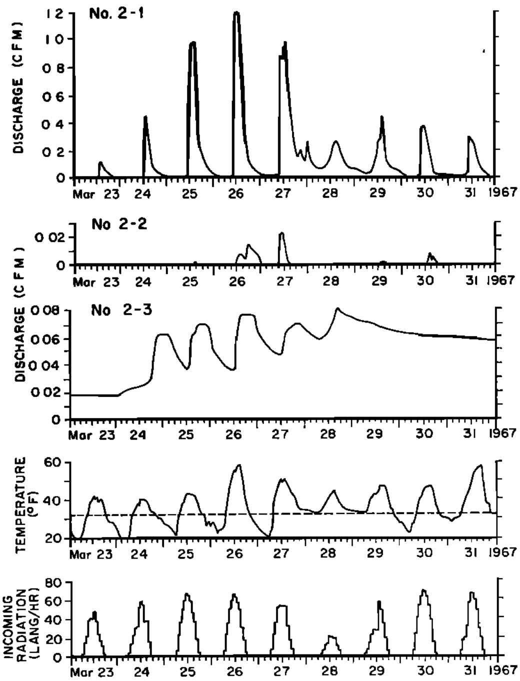

Fig. 3. Air temperature, incoming shortwave radiation, and runoff from plot 2 (concave) during the snowmelt period of March 1967.

TABLE 4. Daily Summaries of Air Temperature, Incoming Shortwave Radiation, and Flow from the Surface Channels and Lower Tiles of the Three Hillside Plots during the Snowmelt Period of March 1967

				Surface Channel				Lower Tiles			
				Total Outflow		Peak Discharge		Total Outflow		Peak Discharge	
Date	Degree Hours above 32°F	Radiation, langleys	Snow Cover	ft^3	inches	cfm	in./hr	ft^3	inches	cfm	in./hr
Plot 1 (convex)											
March 23	66	314	98	6	0.013	0.047	0.006	1	0.002		
March 24	51	374	98	37	0.078	0.173	0.022	1	0.002	0.001	
March 25	79	477	94	105	0.223	0.473	0.050	3	0.006	0.003	
March 26	188	466	89	159	0.337	0.620	0.079	18	0.038	0.029	0.003
March 27	153	387	71	207	0.439	0.673	0.085	39	0.083	0.059	0.006
March 28	98	137	59	54	0.114	0.113	0.014	42	0.090	0.031	0.003
March 29	126	295	46	50	0.106	0.213	0.027	34	0.072	0.026	0.003
March 30	104	495	28	54	0.114	0.113	0.014	48	0.102	0.034	0.003
March 31	197	421	3	26	0.055	0.081	0.011	55	0.117	0.040	0.004
April 1–2	338	709	0	30	0.064	0.070	0.009	144	0.305	0.066	0.006
Total	1400	4075		728	1.543			385	0.817		
Plot 2 (concave)											
March 23	66	314	88	24	0.024	0.120	0.007	18	0.016	0.019	0.001
March 24	51	374	75	83	0.075	0.453	0.025	43	0.039	0.059	0.003
March 25	79	477	67	267	0.242	0.973	0.054	79	0.072	0.066	0.004
March 26	188	466	51	329	0.299	1.187	0.065	79	0.072	0.072	0.004
March 27	153	387	42	366	0.333	0.853	0.047	81	0.073	0.066	0.004
March 28	98	137	32	180	0.163	0.253	0.014	93	0.084	0.076	0.004
March 29	126	295	25	154	0.140	0.427	0.024	94	0.086	0.069	0.004
March 30	104	495	17	116	0.105	0.376	0.021	83	0.076	0.060	0.003
March 31	197	421	9	91	0.083	0.323	0.018	86	0.079	0.056	0.003
April 1–2	338	709	1	79	0.073	0.115	0.006	169	0.155	0.076	0.004
Total	1400	4075		1689	1.537			825	0.752		

Plot 3 (straight)											
March 23	66	314	78	2	0.003	0.010	0.001	1	0.002		
March 24	51	374	67	36	0.058	0.153	0.015	1	0.002	0.002	
March 25	79	477	63	76	0.123	0.300	0.029	19	0.031	0.027	0.003
March 26	188	466	44	111	0.180	0.327	0.032	44	0.071	0.046	0.004
March 27	153	387	31	88	0.143	0.233	0.023	58	0.094	0.046	0.004
March 28	98	137	29	35	0.057	0.053	0.005	61	0.167	0.046	0.004
March 29	126	295	26	36	0.058	0.153	0.015	41	0.066	0.018	0.002
March 30	104	495	12	33	0.053	0.100	0.010	31	0.050	0.021	0.002
March 31	197	421	3	34	0.055	0.081	0.008	28	0.045	0.019	0.002
April 1–2	338	709	0	43	0.070	0.046	0.004	46	0.074	0.016	0.002
Total	1400	4075		494	0.800			330	0.602		

Snow cover is given as a percentage of the plot area covered by snow at midday.

the great reduction in the infiltration capacity of the soil caused by concrete frost. The findings of the present study confirm the very low permeability of the soil when concrete frost is present. During the snowmelt period a weighted average of 2.87 inches of water were available for infiltration, but only 1.53 inches of water infiltrated the soil during the 180 hours in which free water was known to be draining from the snowpack. For the first several days of the snowmelt, water that had melted from the thin snow cover on the flat, upper portion of plot 3 stood in pools on the ground surface. The soil at that location is a very coarse sand with a saturated conductivity of approximately 18 inches per hour when frost free.

In the remainder of this section the amounts and timing of flow from the concave slope (plot 2) are described in detail. Data from the other two plots are also presented in the tables and figures of this section and any important contrasts between the plots are noted.

Runoff from the Surface Channels

On the 3 days preceding March 23, temperatures rose above 32°F for a total of 19 hours (38 degree–hours). Runoff began in channel 2-1 at 1330 on March 23. Figures 3, 4, and 5 show the dramatic fluctuation of discharge each day. Surface runoff showed a strong diurnal fluctuation, the magnitude of which correlated roughly with the daily pattern of air temperature and incoming shortwave radiation (Figure 3). Table 4 summarizes the total daily flow volumes, together with the daily peak outflow rates from the surface channel in each plot. Daily totals of incoming shortwave radiation and of degree–hours above 32°F are also included in the Table. Table 4 and Figure 3 show the general increase of peak discharge and the total daily outflow with radiation and temperature totals during the first few days of the snowmelt. After the 27th, the reduction in areal extent of snow cover (Figure 6), followed by low amounts of radiation on the 28th, caused a reduction of runoff. A 0.25-inch rainstorm on the night of March 27th produced two small, sharp rises in the hydrographs of the surface channels, and yielded only 0.03 inches of runoff.

Each day, runoff from the surface channels began several hours after the onset of melting

TABLE 5. Disposition of Meltwater on the Three Hillside Plots during the Snowmelt Period of March 1967

Plot No.	Initial Water Content of Snowpack, inches	Surface Runoff, inches	Runoff from Root Zone, inches	Runoff from Lower Tiles, inches	Additions to Groundwater Storage, inches
1	3.27	1.54	0.02	0.82	0.89
2	2.89	1.54	0.01	0.75	0.59
3	2.51	0.80	0	0.60	1.11

temperatures (Figures 3, 4, and 5). The lag decreased from 4.5 hours on the first day to 2.5 hours on the fifth day. Each night, the snowpack drained until it was at a free-moisture content analogous to the field capacity of a soil. Absorption of shortwave radiation and sensible heat after sunrise began to melt snow at the surface of the pack. The meltwater was probably subject to some refreezing on percolating into the pack as the upper few inches of snow cooled considerably each night when air temperatures fell to near 20°F. After slow, unsaturated percolation through the granular snow and displacement of stored water, some water reached the ground surface. The larger portion of this meltwater flowed downhill as surface runoff because of the low infiltration capacity of the frozen soil. The first meltwater measured in channel 2-1 must have originated in the immediate vicinity of the channel, where travel time along the ground would be small. It is therefore reasonable to conclude that the 2.5–4.5-hour lag between the onset of melting temperatures and the first response of runoff was caused largely by the time taken for water to be displaced from the base of the snowpack. If melting began before air temperatures exceeded 32°F because of the absorption of shortwave radiation, the lag was even longer.

Although the duration of the time lag between the onset of melting temperatures and the beginning of runoff must have been influenced by the rate at which temperature and radiation increased, the major control of the lag seems to have been the depth of the snowpack. There was an approximately linear relationship (through the range of the data) between the depth and water content of the snow on plot 2 and the lag between the onset of melting temperatures and runoff from channel 2-1. There was an even stronger correlation between the snowpack depth and the lag between sunrise and runoff. Each day meltwater had less distance to percolate before reaching the ground surface. As the moisture-tension curve of granular snow is like that of a sand [*Gerdel*, 1945], the moisture gradient and therefore the gradient of hydraulic conductivity, is large near the ground surface. As the snow depth decreased, the average hydraulic conductivity of the pack increased each morning. The effect was similar to that of a decrease in the depth to a water table on the responsiveness of a groundwater body during rainfall.

Once surface runoff began, the discharge rate increased rapidly (Figure 3) to a peak at the

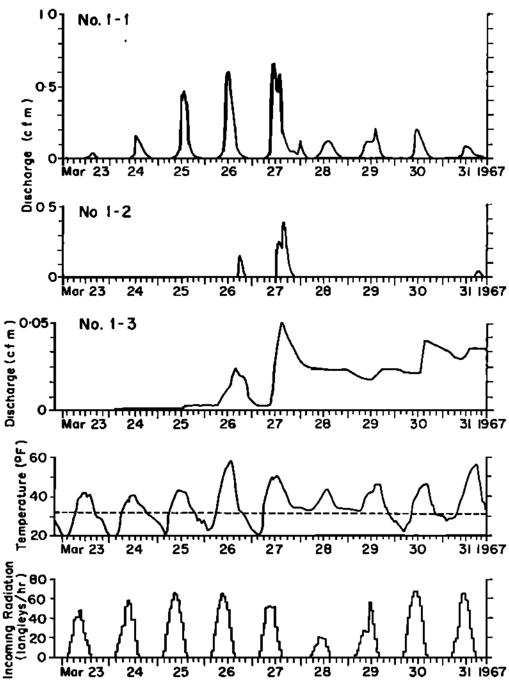

Fig. 4. Air temperature, incoming shortwave radiation, and runoff from plot 1 during the snowmelt period of March 1967.

time of maximum incoming radiation. Thereafter, flow rates declined rapidly even though air temperatures continued to rise for another 2–3 hours. By the time air temperatures had fallen back to 32°F, the surface of the snowpack had begun to refreeze and runoff rates had fallen to less than 0.133 cfm. There was strong hysteresis in the relationship between surface runoff and air temperature. For example, by the time the air temperature had reached 54°F on the morning of March 26, the discharge rate from channel 2-1 was 1.080 cfm. In the afternoon, when the declining air temperature was again 54°F, surface runoff was contributing only 0.367 cfm. Refreezing of the snow surface was usually well underway by the time air temperatures had fallen back to 37°–38°F. Surface runoff was extremely sensitive to changes of insolation rather than to air temperature fluctuations, as Figures 3, 4, and 5 show.

The response of surface runoff to short-term fluctuation of incoming shortwave radiation also demonstrated the strong control of runoff exercised by insolation. On both March 27 and March 29 (Figure 3) the hydrographs from channel 2-1 reacted quickly to changes in insolation produced by the passage of a few scattered clouds. Figure 7 shows the hydrograph of flow from channel 2-1 and the instantaneous pattern of incoming shortwave radiation for March 27. Although there are numerous rapid fluctuations in the insolation graph, four strong peaks can be associated with the four peaks of the hydrograph. Each hydrograph peak lagged its respective pulse of radiation by approximately 30 minutes. A 15-minute moving average of incoming radiation (Figure 7) filtered out most of the short-term fluctuations and produced three major peaks, which preceded the hydrograph maxima by 20–30 minutes. Air temperatures for the same period did not show the same rapid fluctuations. The graphs in Figure 7 demonstrate that snowmelt and surface runoff were more sensitive to changes of shortwave radiation than to additions of sensible heat by conduction and convection. The general shapes of the daily temperature graphs, however, were reflected in the general shape and size of the surface runoff hydrographs (Figure 3).

Slight differences in the timing of flows from

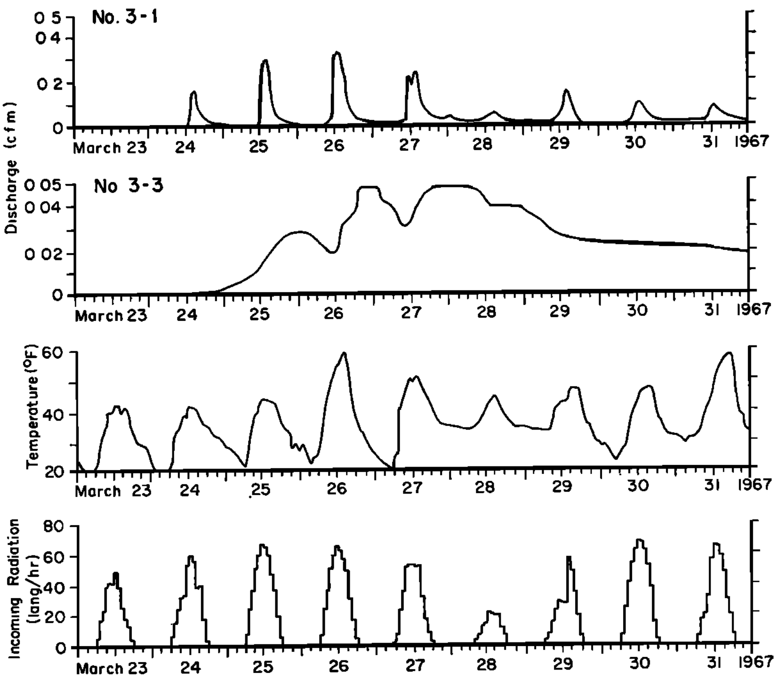

Fig. 5. Air temperature, incoming shortwave radiation, and runoff from plot 3 during the snowmelt period of March 1967.

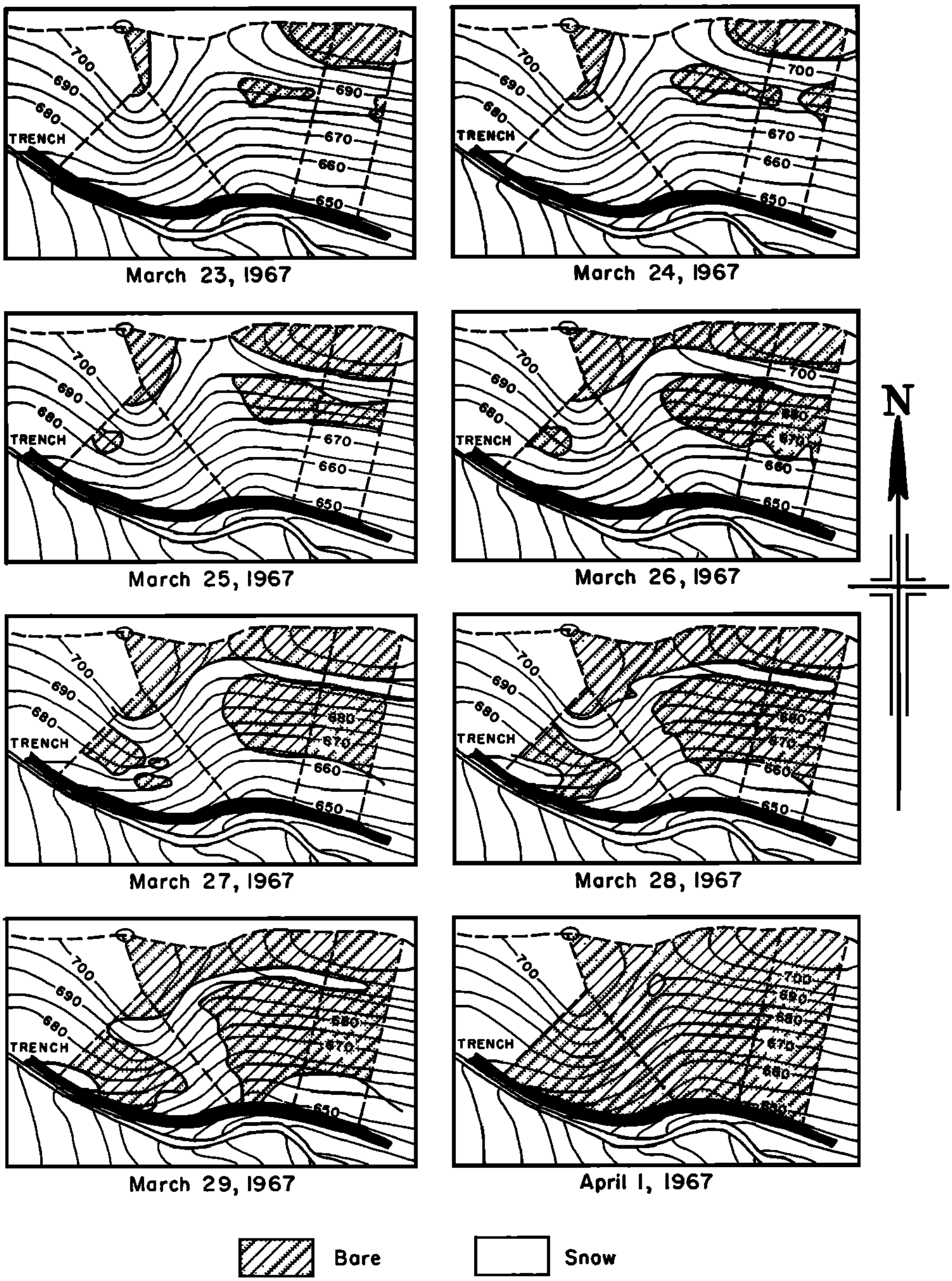

Fig. 6. Distribution of snow cover on the hillside plots at noon each day during the melt period of March 1967.

the three surface channels also reflected the importance of shortwave radiation. Flow from channel 1-1 generally began to increase 0.5–1.5 hours before that from channel 2-1, which in turn preceded flow from channel 3-1 by about another half hour. The timing of peak flows from the three channels followed the same pattern. The lags seemed to be caused by differences in the timing of insolation on the various plots. The aspect and convex shape of plot 1 caused it to receive a maximum amount of radiation earlier than plot 2. Flow rates from the concave plot, therefore, rose and fell somewhat later than those from plot 1. The straight slope of plot 3 faces due south and its lower one-third is shaded by trees so that maximum insolation occurs later than in the other plots. This pattern of insolation was reflected in the timing of surface runoff and in the pattern of depletion of snow cover through the melt period (Figure 6). The great sensitivity of snowmelt runoff to radiation as modified by aspect and slope is demonstrated.

Daily totals of surface flow also demonstrated the close relation between runoff and insolation. As indicated by the decrease in lag between sunrise and the onset of runoff, surface flow became more sensitive to radiation as snowmelt proceeded. Figure 8 shows the relationship between total daily amounts of incoming short-

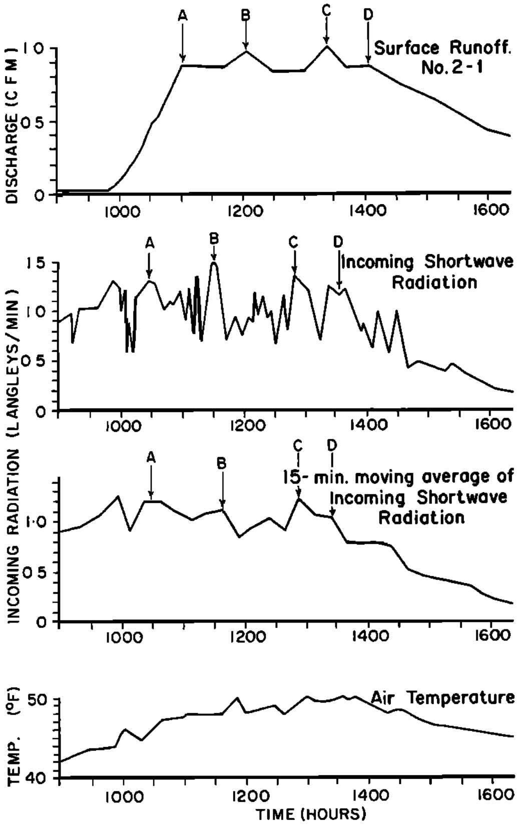

Fig. 7. Air temperature, incoming shortwave radiation, and runoff from channel 2-1 on March 27, 1967.

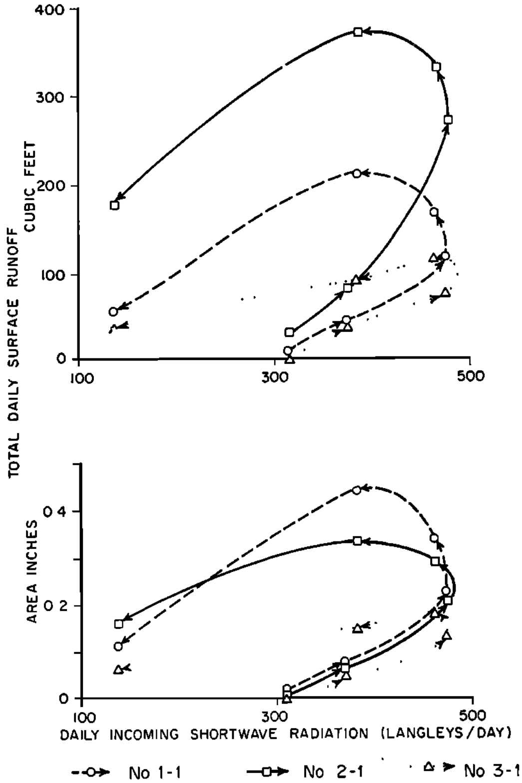

Fig. 8. Relationship between daily totals of incoming shortwave radiation and surface runoff for the three plots on the trenched hillside during the snowmelt period of March 1967.

wave radiation and surface runoff from each plot. Arrows on the curves indicate the progression of days. There was a general increase of surface runoff as radiation increased during the first 3 days of the snowmelt period. On the fourth and fifth days the amounts of runoff increased, in spite of a reduction in radiation. Total incoming shortwave radiation on March 27 was almost exactly equal to that received on March 24. Runoff on the earlier date, however, totalled only 18–40% of that on March 27, in spite of the fact that the snow-covered areas of the plots were smaller on the 27th. The increased flow seems to have been due to the thinning of the snowpack with consequent reduction in albedo. The effect of the reduction of snow cover on runoff during these first 5 days was presumably counteracted by the increased absorption of radiation by the remaining snowpack and frozen ground. No simple relationship existed between total daily surface runoff and total daily degree hours above 32°F.

The generation of surface runoff on the slope was dependent on the occurrence of concrete frost in the top few inches of soil. The distribution and pattern of melting of this frost were of great significance in controlling the area that could contribute to surface runoff at any time. As the snow cover was removed from the slope, important changes began to occur in the distribution of concrete frost. The exposed soil remained frozen for approximately 1 day after the snow had melted from a particular place. Even a 1-inch thick, discontinuous snow cover was capable of shielding the ground sufficiently to keep the soil surface frozen. Once the snow cover was removed, however, the darker ground absorbed large amounts of solar radiation. After approximately 1 day, the concrete frost decayed and the infiltration capacity of the soil increased sufficiently to absorb all meltwater from the snowpack further upslope. A large proportion of the area of plots 1 and 2 remained connected to the channel at their base by snow-covered frozen soil until late in the snowmelt period (Figure 6). A larger proportion of the meltwater from these plots, therefore, reached the channel as surface runoff than was the case on the straight plot (3), where almost one half of the hillside could not supply surface runoff after the third day of the melt period.

Runoff from the Root Zone

Runoff production in the root zone (the top 18–24 inches of the soil profile) was negligible during the snowmelt period. Approximately 11.3 cubic feet (0.02 inches) flowed from tile 1-2 (convex slope) and 8 cubic feet (0.01 inches) flowed from tile 2-2 (concave slope). Plot 3 yielded no flow from this zone. Figures 3 and 4 show the patterns of discharge from tiles 1-2 and 2-2. While a snow cover persisted, the pattern of flow was strongly diurnal and had the same characteristics of rapid rise and fall exhibited by the surface flow. The timing of the subsurface flow relative to that of the surface flow, however, was highly erratic.

The contribution from the topsoil was small because no thick zone of saturation developed in that horizon. The absence of a saturated zone was confirmed by soil moisture profiles. Rates of snowmelt were low (less than 0.6 inches per day) and the rate of infiltration was reduced below this value by the presence of concrete frost. The *B* horizon of the soil could transmit water percolating to it faster than rates of melting could supply. After much of the concrete frost had been removed and insolation rates were high, a thin perched water table was observed in the lower part of plot 1, and the water table in the lower part of plot 2 rose a short distance into the upper soil horizon.

Runoff from the Lower Tiles

The pattern of discharge from the lower tiles during snowmelt consisted of a series of hydrographs associated with each day's melt, superimposed on a general rise in discharge (Figure 3). These hydrographs were quite different from those at the surface. Each groundwater hydrograph had a more gradual rise and recession than the corresponding surface hydrograph. Peak flow rates were small compared with those from the surface channels (Table 4). Groundwater peak flow rates from plot 2 varied from 13% of the surface peak flow on March 24 to 6% on the 26th. Thereafter, the percentage again increased as groundwater discharge continued to rise slowly, while surface peak flow rates declined because of depletion of the snow cover.

Peak flow rates in the lower tiles occurred several hours after those of surface runoff (Figure 3). The time lag between these two maxima decreased through the snowmelt period from approximately 10.5 hours on March 24 to 6 hours on March 26 and 27. The rising limb of the groundwater hydrograph began very close to noon on most days and, therefore, became steeper each day. This pattern was apparently produced by three reinforcing tendencies: melting increased in intensity, infiltration capacity of the soil increased over an expanding area, and sensitivity of the groundwater system increased as the water table approached the ground surface. Even though the responsiveness of the groundwater system increased, however, subsurface flow was subject to so much storage and resistance that peak flows were too small and too late to contribute significantly to the daily peak flows in the stream channel at the base of the slope (Figure 9).

Flow from tiles 1-3 and 3-3 followed the same general pattern as that from tile 2-3 on the concave slope (Figures 4 and 5), but the hydrographs from tiles 1-3 and 3-3 were less regular and less responsive to snowmelt. Table 4 shows the volumes and peak rates of flow from each of the three tiles during the snowmelt period. The largest daily volumes and rates were generally measured in tile 2-3 (concave slope). Daily totals of subsurface flow expressed in area inches of runoff, however, were sometimes greater from plots 1 and 3, particularly late in the snowmelt period, which suggests that the subsurface 'watershed' draining to tile 2–3 was smaller than the surface drainage area of the plot.

SUMMARY AND DISCUSSION

During the snowmelt period of 1967, runoff from three pastured plots in Vermont was dominated by overland flow over a thin layer of concrete frost in the porous topsoil. This runoff was strongly controlled by incoming shortwave radiation. Maximum daily discharges occurred at the time of maximum insolation and were followed by a rapid decline during which discharge rate was highly correlated with radiation. Short-term fluctuations of runoff could be related to rapid variations of insolation during the passage of clouds. Slight differences in the timing of surface runoff occurred between plots with differing aspect. Daily totals of surface runoff and radiation were related in a simple fashion, as long as snow covered most of the plots, but no such simple relationship existed between runoff and air temperature. During the early part of the snowmelt period, runoff became more sensitive to incoming shortwave radiation, mainly as a result of the thinning of the snowpack. Because of large differences in the volumes and timing of flows from various levels within and at the surface of the soil, the proportion of the ground surface covered by concrete frost was an important determinant of the runoff pattern.

The combined hydrograph of runoff from plot 2 is shown in Figure 9. Comparison of such hydrographs with concurrent stream channel hydrographs from basins of the Sleepers River Experimental Watershed suggests that overland flow was also a major control of the diurnal fluctuations of streamflow. At the outlet of a 0.18-square-mile catchment, the daily rise of stream flow began 1 to 3 hours after that from the steep south-facing plot, whereas daily hydrograph peaks in the catchment occurred 0–6 hours after those from the plot. The rise of streamflow began 1–2 hours before that of groundwater outflow and peaked 2–5 hours earlier. At the outlet of a 43-square-mile watershed, hydrographs began to rise 2–3.5 hours after the plot and peaked 2.5–11 hours after the plot.

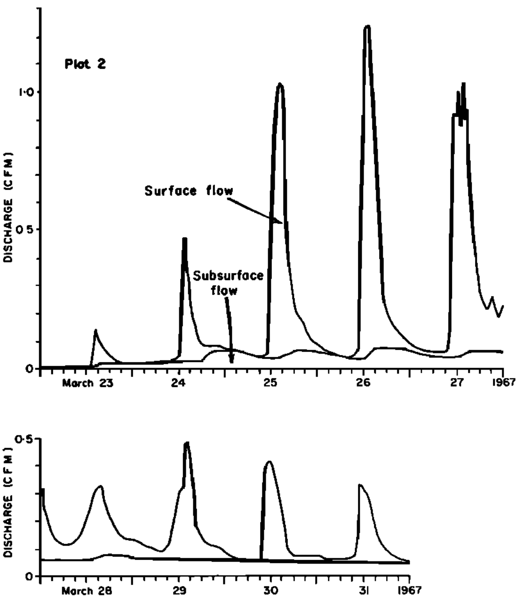

Fig. 9. Combined hydrograph of surface and subsurface flow from plot 2 (concave) during the snowmelt period of March 1967.

Groundwater flow from the plot peaked before or at the same time as flow from the larger watersheds, and was much smaller than surface runoff in total amount and peak rate at the height of the melt period. The larger watersheds had a thicker snow cover, lower average slopes, and a greater variation of aspects than the plots described in this report. These factors, together with storage and transmission in the channel system, may account for the lag between surface runoff from source areas and hydrographs at downstream gaging stations. The results of the present study suggest that groundwater contributes significantly to the overall rise of streamflow, but that overland flow may be the dominant control of diurnal fluctuations in streams of the size mentioned.

Even on parts of the watershed not covered by concrete frost, complete saturation of soils is responsible for overland flow on some areas of river basins in humid areas. This overland flow is extremely sensitive to rapidly changing inputs of water, whether from rainfall or snowmelt [*Dunne and Black*, 1970*a*, *b*]. In the 0.18-square-mile watershed referred to above, saturated, nonfrozen soils subject to overland flow during snowmelt, cover approximately 25% of the total area of the catchment. In other basins of the Sleepers River watershed, seasonally saturated soils cover 25–40% of each drainage basin. Concrete frost and saturated soils are widespread enough to provide ample opportunity for overland flow during snowmelt.

Snowmelt runoff is strongly influenced by nonuniform characteristics of snow accumulation, concrete frost, saturation of soils, and radiation as modified by topography and cover. The combination of these factors causes the area contributing quick runoff to be dynamic in the sense that it varies during and between days. These facts suggest that the 'partial-area' concept of runoff production during rainstorms in Vermont [*Ragan*, 1967; *Dunne and Black*, 1970*a*, *b*] may be a useful conceptual framework within which to view snowmelt runoff production in the same area.

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