A COMPARISON OF SNOWMELT HYDROGRAPHS [1]

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INTRODUCTION

Three snow runoff events are compared with a runoff event without snow. The three snow runoff events represent reasonably good examples of three basic types that frequently occur during the snowmelt period. These are: (1) runoff from rain falling on snow with the air temperature near 32°; (2) runoff from snow melting on clear, warm days; and (3) runoff from a combination of rain and snowmelt. The runoff event without snow is typical of one occurring during the dormant season.

These snow runoff events were observed during the spring of 1962 on the Sleepers River experimental watershed near Danville, Vermont. The storm and snow characteristics for each event are discussed in relation to the corresponding hydrograph characteristics of five gaged watersheds located in series along the same stream.

DESCRIPTION OF RESEARCH AREA

One of the principal streams within this upland watershed rises in the wooded hills on the western boundary at an elevation of 2220 feet and flows southeast for 8.6 miles through agricultural land to its outlet at an elevation of 640 feet. The attached map, Fig. 1, shows this stream, which rises near the weather station designated R-1 and outlets at stream gaging station W-5. The uppermost subwatershed on this stream consists of 0.14 square mile of forested land gaged at station W-1. From there the stream flows about 2 miles to stream gaging station W-2 with 3.21 square miles of drainage area. About 2 miles further downstream is stream gage W-3 with 6.04 square miles of drainage area, and located another 1 3/4 miles further down the stream is gage W-4 which has 16.58 square miles of drainage area. The outlet at W-5, located 2 miles below W-4, gages the runoff from the entire research watershed of 42.91 square miles. Table 1 provides further information on these five watersheds which are located in series along the principal stream, and Table 2 shows some of the characteristics of the stream channel between the gaging stations for these watersheds.

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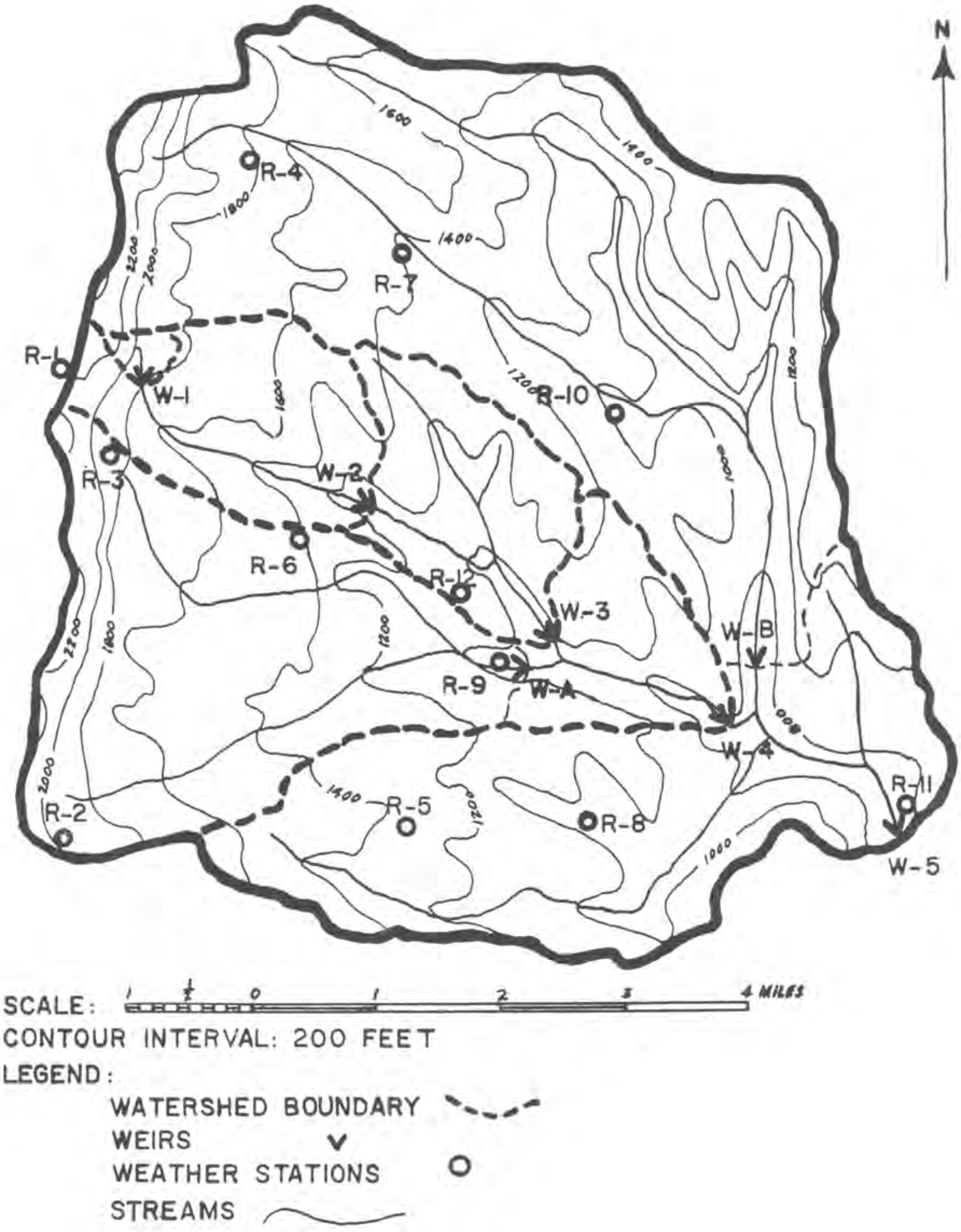


FIGURE NO. 1:
MAP OF FIVE CONSECUTIVE WATERSHEDS ON THE SLEEPERS RIVER, DANVILLE, VERMONT.

TABLE 1

DESCRIPTIONS OF FIVE WATERSHEDS ON THE SLEEPERS RIVER, DANVILLE, VT.

Watershed Number (see Fig. 1	Total Drainage Area Sq Mi	Land Use %	Average Land Slope %	Length Feet	Width	Aspect	Range in Elevation Feet
W-1	0.14	100 woods	*30	3000	2000	ESE	2220 1720
W-2	3.21	67 woods 33 open	10.90	15500	9000	ESE	2300 1140
W-3	6.04	59 woods 41 open	10.23	25500	9000	ESE	2300 920
W-4	16.58	64 woods 36 open	9.33	34500	17500	ESE	2430 730
W-5	42.91	*65 woods *35 open	10.22	45500	35500	ESE	2592 640

* Estimated from partially tabulated field data.

TABLE 2

DESCRIPTIONS OF STREAM CHANNELS BETWEEN FIVE SUCCESSIVE STREAM-GAGING STATIONS ON THE SLEEPERS RIVER, DANVILLE, VT.

Location (Fig 1)	Length of Channel Feet	Change in Elevation Feet	Average Channel Slope Feet/Foot*	Increment of Drainage Area, Sq Mi	Accumulative Drainage Area, Sq Mi
Above W-1	3000	500	0.0909	0.14	0.14
W-1 to W-2	12500	580	0.0461	3.07	3.21
W-2 to W-3	10000	220	0.0189	2.83	6.04
W-3 to W-4	9000	190	0.0186	10.54	16.58
W-4 to W-5	11000	90	0.0041	26.33	42.91

* Slope of a line drawn superimposed on the channel profile curve so that the areas under both line and curve are equal.

DATA AND INSTRUMENTATION

Air and dewpoint temperature data are from hygrothermographs exposed in standard shelters 5 feet above the ground surface. Snow surface and ground surface temperature data are from a two-pen thermograph.

Precipitation data are from recording-weighing-type rain-snow gages. Snow depth, specific gravity, and water equivalent are from fourteen snow courses taken weekly or in some cases twice weekly.

Runoff data are from continuous recording stage recorders at V-notch weir controls except for W-5, which is a natural control. Daily runoff totals for this watershed are given in Table 3, and are based upon an incomplete rating curve.

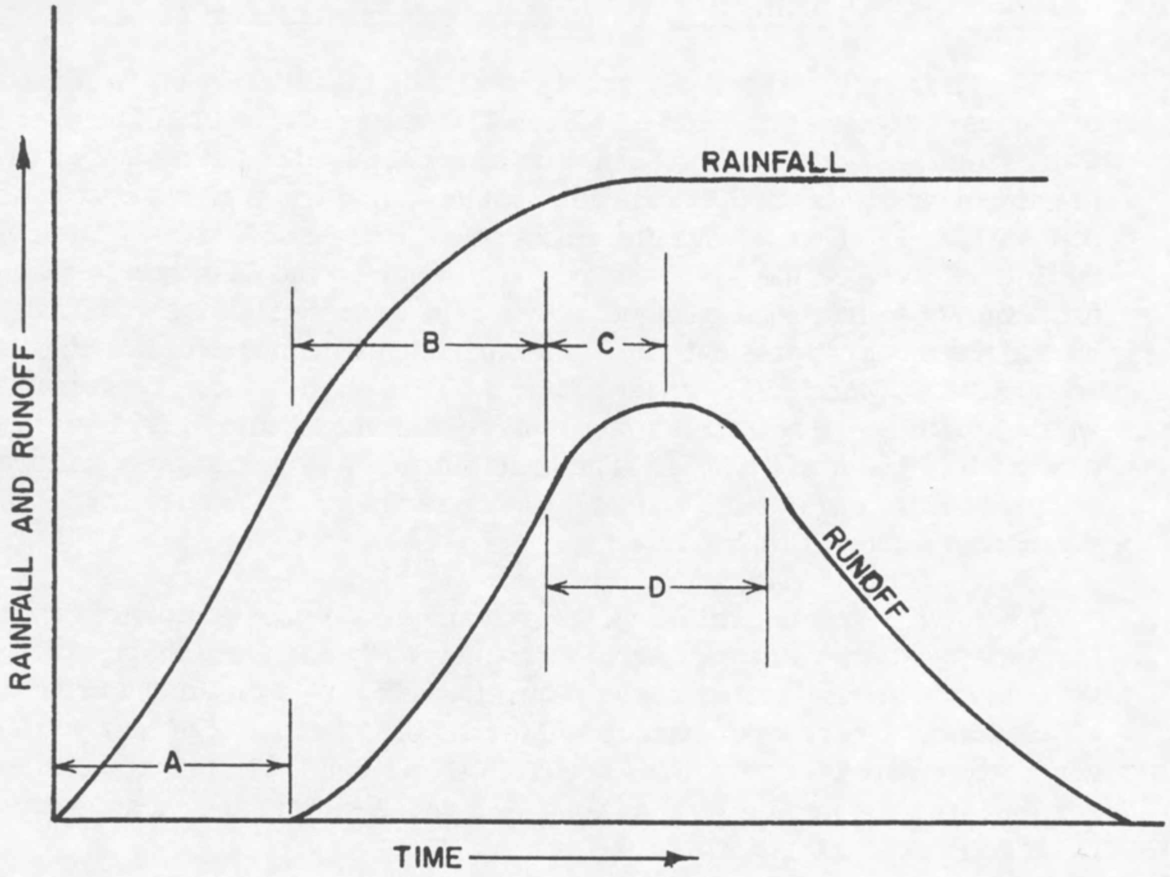
The groundwater measurement reported is from a continuous recorder in an abandoned dug well near station R-3. Anemometer data are from an instrument set 8 feet above the ground at R-12.

METHODS OF ANALYSIS

The hydrographs for each runoff event in the five watersheds are discussed in terms of their antecedent conditions, storm rainfall and heating characteristics, and the key times for various rainfall and hydrograph characteristics. These key times and the points of inflection referred to in the following discussion are illustrated in Figure 2.

The variations in the time sequences of the hydrographs produced by these events can be compared according to the following criteria:

1) The time lag between the beginning of rain and the beginning of storm runoff at a stream gage is a function of the initial loss to interception, surface resistance to overland flow, and the channel velocity. Rainfall intensity is a primary factor in the absence of snow but is limited in winter by the permeability and depth of the snowpack. Ice on the streams would increase the elapsed time by nullifying the usual effects of channel precipitation. 2) The time lag between the end of the period of intense rainfall and the associated point of inflection which marks the beginning of the crest segment of the hydrograph is a function of watershed size, surface resistance to overland flow, and channel velocity. 3) The time to peak is a function of the volume of storm runoff in addition to the criteria listed above. 4) Snow retards overland flow physically by absorption, mechanically by friction, and thermodynamically by either freezing or increasing the viscosity of the flowing water. The amount of melt water from remote areas of a watershed that reaches a channel is therefore extremely small at the beginning of a snowmelt period, but increases rapidly as the melt season progresses and a regime is established that permits contributions to the channel from the entire watershed. The melt water that contributes to a day's runoff either begins the day as snow whose melt is within a few hours' travel time from a channel, or as a previous day's melt which has been slowly and intermittantly moving down-slope, either on or below the ground surface, and which arrives at a channel on the day in question.



A. TIME FROM BEGINNING OF RAINFALL TO BEGINNING OF RUNOFF.

B. TIME FROM END OF MOST INTENSE RAINFALL TO INFLECTION AT BEGINNING OF CREST SEGMENT OF HYDROGRAPH.

C. TIME FROM RISING INFLECTION TO HYDROGRAPH PEAK.

D. CREST SEGMENT OF HYDROGRAPH.

FIGURE 2. TIMING CHARACTERISTICS OF RAINFALL MASS CURVE AND RUNOFF HYDROGRAPH.

SNOW RUNOFF EVENT #1; MARCH 31-APRIL 1, 1962

The first event described, runoff from rain falling on snow with air temperatures near freezing occurred on March 31 and April 1, 1962. The precipitation was associated with a cold front which crossed the area from west to east during the afternoon of March 30, and had become stationary over the east coast by 1:00 AM April 1. Wet snow began to fall during the night of March 30 and continued until about dawn on the 31st. Shortly after noon on the 31st rain began, continued for about 29 hours, then changed to wet snow at most stations and finally stopped during the morning of April 2. Air temperatures dropped from a high of about 65° at 2:00 PM on March 30 to about 33° at 2:00 PM on the 31st. Temperatures and heating factors are indicated for a typical station in Table 3. A history of the precipitation is given in Table 4. The precipitation was remarkably uniform throughout the basin, both in time and amount of precipitation, particularly for the most significant intense rainfall fraction.

When the March storm began the stream was almost completely frozen over from the headwaters to the gaging station at W-2, and from there to W-3 the ice remained on about one half of the channel. Below W-3 the ice had been largely cleared away by snowmelt runoff on March 30. The runoff of March 31 and April 1 gradually cleared all remaining ice from the channel, but unfortunately deposited some of it in ice jams above stations W-3 and W-5, making these hydrographs difficult to interpret for parts of the event.

The 0.10 to 0.15 inch of wet snow that fell during the night of March 30 did not produce a discernible change in stage at any of the gaging stations. This moisture was added to that already stored in the snowpack.

The rain that began about noon on March 31 produced runoff from all watersheds. Figure 3 and Table 5 show comparative data for this event and a similar storm which occurred in October, 1962. The March storm consisted of three distinct periods of relatively intense precipitation which produced corresponding runoff peaks from each of the five watersheds. For the first 18 hours of rain the March and October storms produced mass curves of about the same shape and magnitude, but after this time they diverged widely, and further comparison of the hydrographs produced is not warranted.

The hydrologic condition of the watershed was very similar at the beginning of both of these events except for the presence of snow and higher channel stages in March. In both March and October, losses to evapotranspiration are assumed to be negligible for short periods. The moisture content of the soil was very nearly the same (an average of approximately 32 percent moisture by weight for the A horizon) and there was no frost. Groundwater levels were slightly higher at the beginning of the March storm and rose at the rate of 0.10 foot per hour throughout both storms compared. Losses in interception were somewhat higher in October because of the dead leaves remaining on the trees or piled loosely on the ground.

TABLE 3

ANTECEDENT CONDITIONS FOR WATERSHED W-5

42.91 SQUARE MILES, MARCH-APRIL, 1962

Date	Precipitation		Snow on Ground			Runoff 1/	Heating, From R-12			
1962	Rain Inches	Snow Inches Melted	Depth Inches	Water Equiv Inches	Specific Gravity	Daily Totals Inches	Mean Temp °F	Degree Days Above 20°F	Degree Days Above 32°F	Degree Hours Above 32°F
3-12		0.35	26.8	6.7	0.250	0.0233	27	7	0	0
13		0.40				.0247	28	8	0	0
14						.0233	26	6	0	16
15						.0226	32	12	0	10
16						.0226	34	14	2	40
17						.0240	32	12	0	24
18						.0240	24	4	0	0
19			25.0	7.4	0.296	.0240	20	0	0	0
20						.0221	22	2	0	50
21			25.0			.0240	32	12	0	72
22						.0538	36	16	4	154
23			24.0			.0780	30	10	0	18
24						.0979	34	14	2	126
25		0.02	22.0			.0979	36	16	4	88
26		0.02				.1080	37	17	5	100
27			20.7	6.4	0.324	.2218	38	18	6	104
28						.2774	34	14	2	132
29			15.0	5.0	0.333	.3466	40	20	8	208
30		0.02				.3965	48	28	16	364
3-31	0.80	0.08	12.5			.3954	32	12	0	28
4-1	0.80					.4779	31	11	0	2
2		0.02	10.6	3.6	0.340	.2846	24	4	0	0
3						.1343	20	0	0	0
4			9.8			.1223	22	2	0	26
5						.1853	32	12	0	114
6			9.0			.2203	38	18	6	240
7	0.77					.4537	40	20	8	222
8	0.02					.5352	43	23	11	266
9			3.4	1.0	0.294		43	23	11	240

1/ Rating curve has not been fully established.

TABLE 4

PRECIPITATION AT FIVE WEATHER STATIONS

FOR THE STORM OF MARCH 30-APRIL 2, 1962

Weather* Station No. and Elevation	WET SNOW		RELATIVELY INTENSE RAIN		TOTAL STORM 6		Snov Dept on Apri Inch
	Time of Beginning and Ending	Amount Inches	Time of Beginning and Ending	Amount Inches	Time of Beginning and Ending	Amount Inches	
R-1 2200	11:40pm 3/30 5:00am 3/31	0.14	12:20pm 3/31 5:30pm 4/1	1.52	11:40pm 3/30 10:00am 4/2	1.79	21.
R-3 1830	11:40pm 3/30 5:00am 3/31	0.15	12:30pm 3/31 5:10pm 4/1	1.53	11:40pm 3/30 6:00am 4/2	1.79	18.
R-6 1360	11:40pm 3/30 5:00am 3/31	0.14	12:20pm 3/31 5:00pm 4/1	1.54	11:40pm 3/30 6:00am 4/2	1.80	6.
R-12 1150	11:00pm 3/30 4:00am 3/31	0.10	12:00n 3/31 6:00pm 4/1	1.55	11:00pm 3/30 4:00am 4/2	1.72	9.
R-11 600	1:00am 3/31 4:20am 3/31	0.10	12:30pm 3/31 6:00pm 4/1	1.57	1:00am 3/31 4:00am 4/2	1.74	0.

* Refer to Fig. 1 for location of these stations in relation to the five watersheds.

TABLE 5

A TIME COMPARISON OF HYDROGRAPH COMPONENTS FOR THE STORMS OF MARCH 31-APRIL 1 AND OCTOBER 5-6, 1962

Watershed Number	Elapsed Time From Beginning of Rain to Beginning of Runoff Hours & Minutes		Elapsed Time from Rainfall Intensity Inflection To Hydrograph Inflection Hours & Minutes		Elapsed Time From Hydrograph Inflection To Initial Peak of Hydrograph Hours & Minutes	
	March	October	March	October	March	October
1	1:55	0:35	2:10	1:05	3:40	4:20
2	1:10	0:20	1:50	1:35	2:15	4:15
3	1:00	0:20	1:35	1:50	3:15	4:15
4	0:40	0:20	1:35	3:05	3:45	4:45
5	0:30	0:20	1:10	3:45	5:10	5:35

From Figure 3 and Table 5 it is apparent that the time lapse between the beginning of rain and the beginning of runoff was relatively long for the March storm as compared with the one in October. The relative magnitude of this time lapse in winter is largely attributed to the snowpack which, depending upon its degree of ripening, would dampen the usual effects of rainfall. If the degree of ripening is assumed to be a function of increasing specific gravity the snowpack above approximately the 1400-foot contour was continuing to ripen during the storm and the snow below this elevation was overripe and decreasing in specific gravity over the same period. This generalized condition was reflected in the crystalline structure of the snow during this period, as the heavy wet snow still present at higher elevations had been previously metamorphosed to large cup crystals at lower elevations.

Because of the greater permeability and shallower depth of snow on the lower watersheds, the rainfall penetrated to the soil surface in less time than at the higher elevations. Once the soil was reached the usual requirements of wetting and infiltration had to be satisfied before storm runoff to the streams could begin.

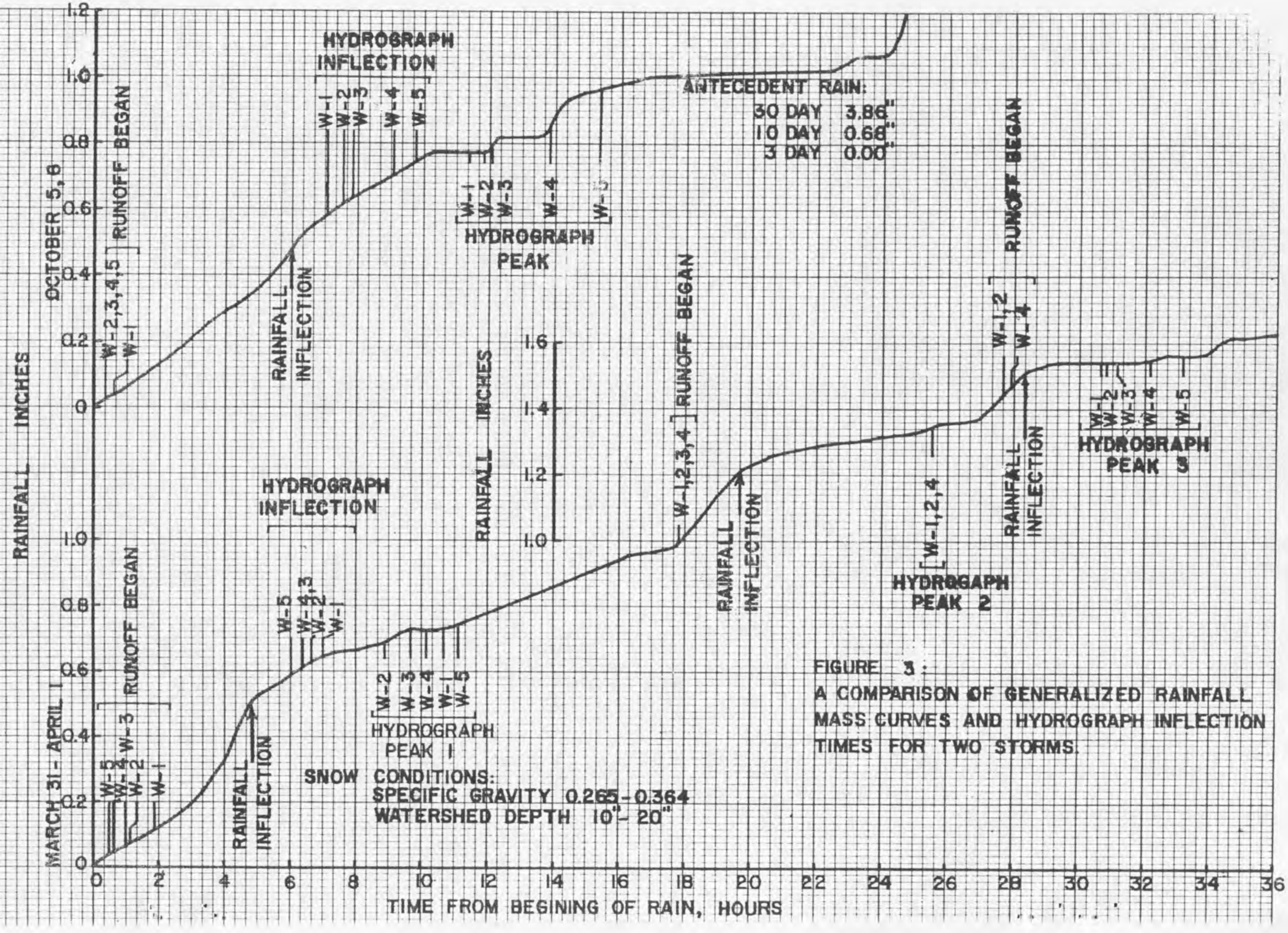


FIGURE 3:
A COMPARISON OF GENERALIZED RAINFALL MASS CURVES AND HYDROGRAPH INFLECTION TIMES FOR TWO STORMS.

In the March storm, watershed W-5 reacted 30 minutes after the rain began, followed in order by W-4, W-3, W-2, and W-1. The inflection was caused by channel precipitation reinforced by watershed runoff, except for W-1, where the iced-over stream prevented precipitation from falling directly into the channel. The variation in reaction time for each watershed is approximately proportional to the logarithm of the snow depth in the vicinity of each stream gage, indicating a relationship between snow permeability, depth, and beginning time of watershed runoff.

The problem is far more complex than that, however. In addition to the more obvious variables there is the contribution from channel precipitation. At periods of low flow this may be very small during the first few minutes of a storm. For watershed W-5, for example, this contribution amounted to 0.01 acre-inches for the October storm, and 0.16 acre-inches for the March storm, or 16 times as much water. This variation was caused by differences in the width and velocity of the channel surface, which are functions of stage only. The amount of precipitation which fell before an inflection could be detected, is a function of intensity and time. For conditions such as those that prevailed during the two storms described here, channel precipitation is of more consequence during the snowmelt season than at other seasons of the year.

The more important watershed runoff contribution also developed differently during the first few minutes of these individual storms. At W-5, because of the longer time lapse and higher channel velocity on March 31, 4100 feet of channel and associated river bank was contributing runoff to the gage at the time of inflection. At the corresponding time of the October storm, only 240 feet of channel and associated river bank was contributing to the gage. Quantitatively, the river bank contribution must have been disproportionately large for the October storm, and very small in March owing to the time lost in infiltrating the snowpack.

In the October storm, all gaging stations except W-1 reacted 20 minutes after the rain began. (Times are plotted to the nearest 5 minutes on Figure 3 and Table 4, and the time sequence has been preserved in relation to the generalized rainfall mass curve.) The first water from the storm to reach the gaging stations was from precipitation that fell on the channel surface. The inflection in the hydrograph that heralded the beginning of runoff was apparently caused by channel precipitation reinforced by the commencement of watershed runoff. The hydrograph for watershed W-1 lagged 15 minutes behind the other four because of the initial loss to interception.

After the initial rise, which marked the beginning of runoff at the gaging stations, the hydrographs continued to rise until after the most intense period of rainfall. At a time after the high-intensity rain had ended, an inflection occurred, marking the beginning of the crest segment of the hydrograph (Fig. 2). In the October storm the period of most intense rain was not well defined, and each watershed hydrograph attained a peak value a short time afterwards in a time sequence which was in order of watershed size. In the March storm the inflections marking the beginning of the crest segment of the hydrographs occurred in the same time sequence as the initial inflections marking the beginning of runoff, again indicating that the runoff from rain falling on a snow-covered watershed is delayed in proportion to the snow permeability and depth.

Once runoff from this intense rain reached the stream it moved rapidly, and because of the high stages which existed in March as compared with October, the March hydrographs attained peak values in a shorter time after their inflections, as shown in Table 5 and Figure 3. These peaks occurred in order of ascending amounts of watershed inches of runoff, with W-2 contributing the least.

A very gradual recession began at all stations after the initial peak of the March storm. This trend was interrupted by another period of relatively intense rain which apparently produced an inflection in all hydrographs about 15 minutes after it began. The end of the intense rain was followed by nearly simultaneous peaks at all stations. The hydrographic records for the period of the second peak was confused by ice jams, so that the actual times were difficult to evaluate. In addition, this peak was very broad with no distinct crest and an almost imperceptible recession. During this period there was considerable ice movement. In the upper parts of the stream the ice was breaking up and small jams formed above several of the gaging stations. A large jam formed about one mile above station W-5. From the evidence available it appear that the occurrence of simultaneous peaks was a combination of coincidence and confused record rather than a logical sequence of events. This situation lasted into the next period of relatively intense rain, which swept away most of the remaining ice and stabilized conditions within the channel except for the large jam above W-5. For the third and last rise the time lapse from the end of intense rain to the hydrograph peaks was much shorter than it had been previously, and the pattern of these peaks resemble those of the October storm.

Table 6 compares these elapsed times and gives the ratio of October to March, which varies from 2.5 for the steepest watershed with the most snow to 2.0 for the flattest watershed with the least snow. If the peak at each successive gaging station is assumed to coincide with the passage of a translatory wave, it appears that this wave traveled from 2.5 to 1.5 times faster in March than in October because of the relationship which increases average channel velocity, and hence wave celerity, with an increase in stage. Such a comparison would not be valid for the other March peaks because of the presence of ice on the streams, and perhaps the question mark in Table 6 can be attributed to some remaining ice.

It is assumed that the 1.5 inches that fell in the 29 hours of continuous rain preceding the third and last rise of the March storm had completely ripened the snowpack below 1800 feet. The moisture retained by the snow had undoubtedly increased to a maximum along with the permeability and porosity. Throughout this long rain the intensity equalled or exceeded 0.10 inch per hour three times (Fig. 3) and the maximum hour produced only 0.20 inch. Temperatures remained nearly constant at all stations and within a few degrees of freezing.

TABLE 6

A COMPARISON OF TIMES FOR THE FIRST PEAK OF THE OCTOBER STORM AND THE THIRD PEAK OF THE MARCH STORM

Watershed or Stream Gaging Station	Elapsed Time from Rainfall Intensity Inflection To Hydrograph Peak			Travel Time of Translatory Wave Between Successive Stream Gaging Stations*		
	October Minutes	March Minutes	Ratio Oct/Mar	October Minutes	March Minutes	Ratio Oct/Mar
W-1	325	130	2.50			
W-2	350	140	2.50	25	10	2.50
W-3	365	160	2.28	15	20	?
W-4	470	220	2.14	105	60	1.75
W-5	560	280	2.00	90	60	1.50

* Refer to Table 2 for a description of the channels between successive gaging stations.

SNOW RUNOFF EVENT #2, APRIL 5 & 6, 1962

Warm winds associated with a high centered off the Atlantic coast initiated a warming trend which was reinforced by sunshine on April 4, 5, and 6. The wind run at an exposed location was 106 miles on the 4th, 107 miles on the 5th, and 134 miles on the 6th. The fastest mile was 12 mph for each of these three days. Throughout this period the wind was slowly shifting from west through south to southeast.

The temperatures and heating factors for five selected weather stations are given in Tables 7 and 8, which show a variation in heating that, in this type of weather, is probably more closely related to the exposure of the weather stations

TABLE 7

DAILY TEMPERATURE & HEATING FACTORS AT FIVE WEATHER STATIONS

APRIL 4, 5, 6, 7, 1962

* Station	Maximum				Minimum				Deg Hours Above 32°			
R-1	4th	5th	6th	7th	4th	5th	6th	7th	4th	5th	6th	7th
Snow Surface	33	33	33	32	15	24	33	31.5	6	8	10	0
R-1	43	51	57	51	21	31	36	45	92	196	350	380
R-3	39	48	55	46	12	20	26	34	40	132	268	248
R-6	41	48	57	47	11	21	24	34	48	140	264	244
R-12	37	46	53	46	8	19	21	34	26	114	240	222
R-11	46	55	61	51	13	18	20	36	96	172	354	292

* Refer to Fig. 1 for the location of these stations.

TABLE 8

DURATION OF TEMPERATURE ABOVE FREEZING FOR APRIL 4, 5, 6, 7, AND SNOW COURSE DATA FOR APRIL 2 & 9, 1962 AT FIVE WEATHER STATIONS

Station	Time 32° was Reached Temp Rising				Time 32° was Reached Temp Falling				Snow Depth and Specific Gravity	
R-1	4th	5th	6th	7th	4th	5th	6th	7th	2nd	9th
Snow Surface	1030	1100	1000	1000	1930	2000	2400	----		
R-1	0830	0700	----	----	2400	----	----	----	21.3 0.357	20.3 0.374
R-3	0900	0630	0600	----	1730	2030	----	----	18.4 0.364	8.9 0.360
R-6	0930	0700	0645	----	1830	2100	----	----	6.5 0.523	00.0 -----
R-12	0930	0800	0700	----	1800	1930	----	----	9.5 0.316	0.00
R-11	0900	0830	0800	----	1900	1945	----	----	00.0 ----	0.00 ----

* Refer to Fig. 1 for the location of these stations.

than any other factor. Snow surface temperatures at station R-1 are also given, and show a greatly reduced heating trend. The ground surface temperature at this station varied between 30° at night and 31.5° at midday, indicating that a slight heating of the ground surface by radiation did occur through the 21-inch snowpack. No frozen ground was reported at any of the weather stations, but a thin skin of frost undoubtedly formed at night where the snow had been completely melted.

The snow depth and specific gravity for each of these weather stations are also shown in Table 8 for two dates which bracket the runoff events reported. The snow at station R-1 attained a maximum specific gravity of 0.382 on April 16, but at all other stations, including a number not reported here, the maximum specific gravity had been reached during the period between March 27 and April 2.

The two important sources of heat for melting the snow were latent heat condensation from water vapor brought to the snow surface by turbulent exchange, and insolation. Of these two, insolation is considered most important for the period in question.

The highest dewpoint temperature recorded for the period was 37°, which would melt snow by condensation of vapor at the rate of about 0.25 inch of water per day if accompanied by winds of 10 mph. For most of the period, however, the dewpoint was near 32°.

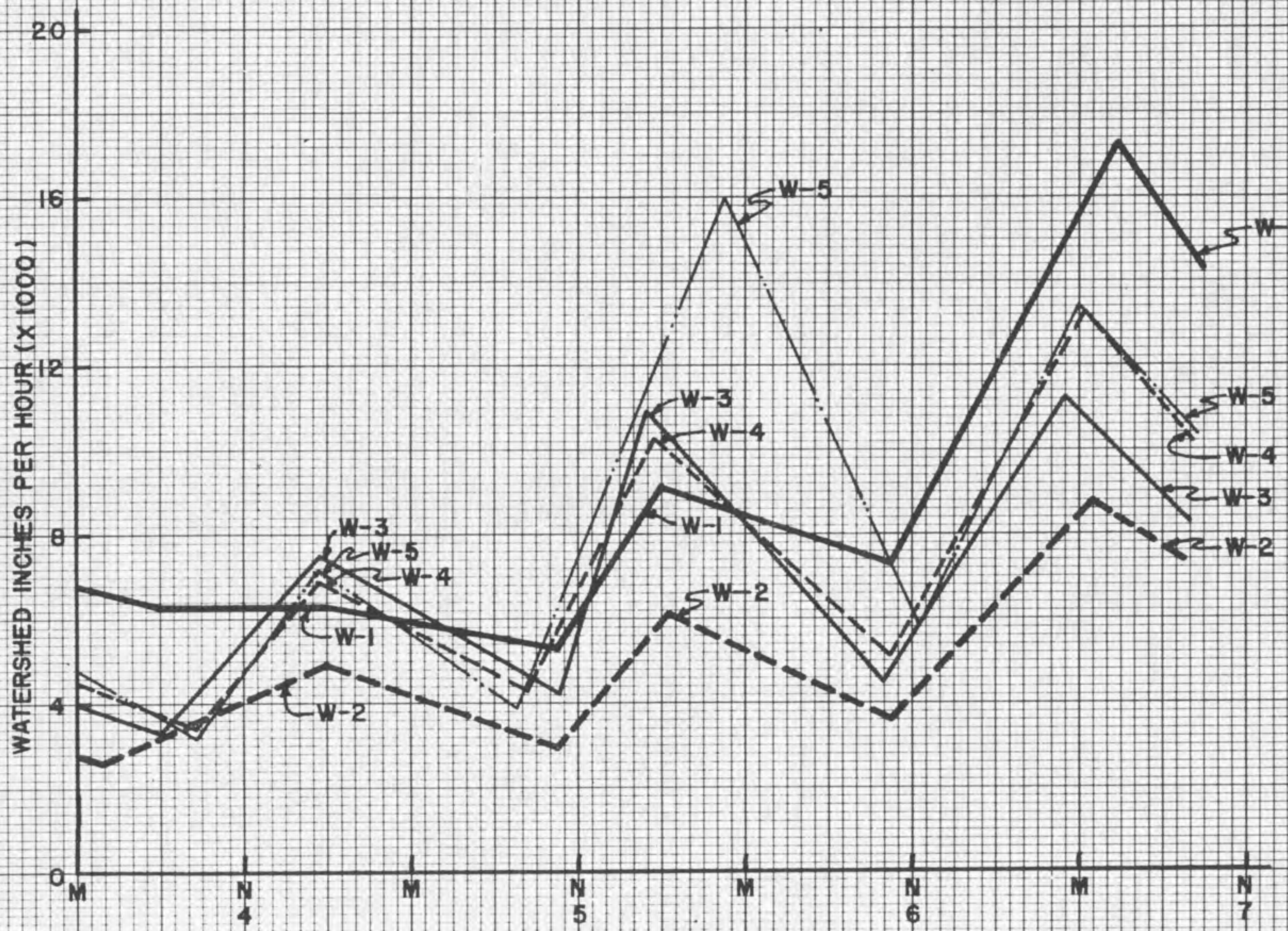
Air temperature in watershed W-1 rose above 32° at about 8:30 AM on April 4 (Table 8), and after a lag of several hours melting began at the snow surface. The melt was barely sufficient to halt the recession which had begun after the peak of April 2, and by 6:00 PM even this slight pause had given way to further recession as the temperatures dropped below freezing (Fig. 4). The warmer temperatures of the 5th and 6th caused considerable melt, and judging by the slope of a line connecting the low points, or troughs, of the hydrograph for the period, this watershed was the most affected.

Watershed W-2 produced a hydrograph for this period similar in shape, but not in magnitude, to that of W-1. Probably the difference in magnitude can be explained by the relative amount of southern exposure in these two watersheds.

Watersheds W-3 and W-4 produced hydrographs similar in both shape and magnitude. The steeper limbs of these hydrographs, as compared to those for the two upper watersheds, resulted from both exposure and the more rapid melting of relatively shallow snow at the lower elevations.

The hydrograph for watershed W-5 is in a class by itself. There was very little snow left below 1000 feet elevation, and runoff at the W-5 stream gaging station was almost entirely water arriving from upstream areas. These arrivals were timed in such a way that there was a partial reinforcing at W-5 on the 5th and 6th. This situation rarely occurs in summer, and it wasn't in evidence during the event of March 31-April 1st.

FIGURE 4. A COMPARISON OF HYDROGRAPHS OF SNOW MELT RUNOFF FROM FIVE WATERSHEDS. APRIL 4,5,6,7, 1962



On April 4th, all hydrographs attained their peaks for the day about 30 minutes after the temperature began to fall. On the 5th, this time had increased to between 30 minutes and 1 hour, except for W-5 which lagged 3 1/2 hours. On the 6th, after three consecutive days of melting, these times varied from 7 1/2 to 9 1/2 hours. The accuracy of these times is limited by the data available, but the trend is apparent. It appears that the shape and timing of these snowmelt hydrographs are dependent upon the interaction of two causal factors. One is the character of the channel, including the stage-discharge relationship, which governs the time of arrival at the gage of melt water which has reached the stream during the day in question. The other is loosely labeled the "watershed characteristics", which governs the time required for melt water from remote areas of the watershed to reach a channel. This second factor, although negligible at first, becomes more important as the melt season progresses and a regime is established that permits contributions to runoff from the entire watershed. This trend is in evidence in Fig. 4 and Table 7. As the period progresses the sequence of the daily peaks becomes less dependent upon the channel velocities and small variations in temperature as the contributing area increases.

SNOW RUNOFF EVENT #3, APRIL 7, 1962

The final event for which data are presented is runoff from a combination of snowmelt and rainfall. The precipitation was associated with a rapidly moving warm front ahead of a low pressure cell. Temperatures remained above freezing throughout the event, reaching maximums of between 45° and 50° at all stations (Tables 7 & 8). The relative humidity was 100 percent from about 9:00 PM on the 6th until about 6:00 AM on the 8th.

Snow was continuous above about 1600 feet, but was present elsewhere only in favorable locations. Because only watershed W-1 and W-2 were still predominately snow covered, this event is not an ideal example of concurrent rain and melting snow. The lower watersheds would be expected to behave as they would in a summer storm occurring at a time when the soil is near saturation; the upper watersheds should react approximately as they did in the first event reported.

Rain began to fall at 7:00 AM on April 7 and continued at a nearly constant intensity until late afternoon, when it became a low intensity drizzle of less than 0.05 inch per hour.

Runoff began at all gaging stations from 30 to 45 minutes after precipitation started. In the upper watersheds, where the snow was primed by the melting of the preceding period and there was no soil moisture deficiency, runoff began with less delay than in the lower watersheds. The small wooded watershed of W-1, which was slow to react in the October storm because of the initial wetting of leaves and also lagged in the rainfall event of March 31 because of the condition of the snow, was now reacting in a manner similar to the other watersheds (Table 9).

Because of the uneven distribution of rain in both time and amounts and the lack of complete snow cover, there was no definite pattern to the sequence of events. This small storm combined with snowmelt did, however, produce the highest instantaneous rate of runoff for the 3 1/2 years of record at W-5.

TABLE 9

A COMPARISON OF THE TIME SEQUENCE FOR FIVE

HYDROGRAPHS OF SNOWMELT PLUS RAINFALL RUNOFF

Watershed	Rain Began	Runoff Began	Intense Rain Ended	Hydrograph Inflection	Hydrograph Peak	Amount of Intense Rain Inches
W-1	0700	0830	1700	1730	1800	0.79
W-2	0700	0730	1640	1700	1830	0.70
W-3	0700	0730	1630	1700	1830	0.67
W-4	0730	0815	1630	1800	1930	0.68
W-5	0800	0845	1630	1800	1930	0.70

Refer to Tables 7 & 8 for heating factors for this event.

SUMMARY AND CONCLUSIONS

The timing and shape of runoff hydrographs are much more dependent upon channel characteristics such as the stage-discharge relationship and drainage density for events occurring during the snowmelt season as compared with those for other seasons.

When snow is present but not melting, the time lag from the end of intense rain to the inflection of the hydrograph is apparently dependent upon some exponential function of the permeability and depth of snow in the vicinity of the gaging station. Watersheds with the most snow respond slowest, regardless of watershed size or other characteristics, and also yield proportionately less runoff (computed in watershed inches). Similarity to summer event hydrographs increases with the length of time that the rain continues, as the contrubuting area within a snow-covered watershed grows much more slowly. If the rain continues long enough, this similarity is very noticeable, as in Fig. 3.

The hydrograph of an isolated snowmelt event differs from that of an isolated summer rain for two major reasons. The contributing area of a snow-covered watershed is initially small, and increases gradually to the limits of the watershed as the melt season progresses. Channel velocities are much greater during the snowmelt season due to consistently higher stages.

For a snowmelt event air temperatures are to some extent synonymous with rainfall, and the rising pen trace of a thermograph is comparable to a rainfall mass curve.

The highest instantaneous rates of spring runoff occur at the end of the snowmelt season, when conditions favor a rapid discharge to the channels. The maximum spring rate for the four years of record on the Sleepers River was caused by snowmelt combined with rainfall in three years, and snowmelt alone in one year. The rain of only 0.60 to 0.80 inch on April 7, 1962, (event number 3) combined with snowmelt to set a new record for the instantaneous rate of discharge from watershed W-5.

DISCUSSION by Arthur R. Eschner, Research Forester

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Snow melt, or snow and rain, during relatively short periods in winter and early spring is the source of one-half to two-thirds or more of the annual runoff in the streams of northeastern United States. However, the opportunity to analyze intensive snowpack measurements and meteorological and runoff data together is relatively rare, and a paper containing this detailed information is most welcome. The series of gaging stations on a single small stream is also rather unique in this area and, in the future, analyses may be expected to provide considerable information on the contribution of discrete areas within a major watershed to the quantity and timing of streamflow of the main stream.

Mr. Johnson has presented data to show the role of the snowpack as a storage medium for spring precipitation; and, in the later events, as a source of runoff whose conversion to streamflow is determined by the availability of energy.

This simple summary is inadequate to explain the events described, with the possible exception of references to the upper two or three watersheds.

On March 31 and April 1 the snowpack was described as "over ripe" below 1,400 feet elevation. This is borne out by the average watershed snow specific gravity figure of 0.333 for March 29 shown in Table 3. It seems likely that the snowpack at elevations below 1,400 feet was contributing to runoff soon after the beginning of rainfall, especially if the temperature of the rain was above freezing, as indicated. Furthermore, after a week of above freezing weather in late spring it seems reasonable to expect that soil moisture storage would be completely filled and there would not be any need for satisfying soil moisture before runoff could begin. Indeed the 32 percent moisture content of the soil should be approximately field capacity for a medium textured soil.

In the October event, to which the March-April rain-on-snow event is compared, although the surface soil was probably as fully recharged as in the latter storm there may have been some storage opportunity still available in the lower soil horizons and bedrock in the lower watersheds with, supposedly, deeper soils. This would be reflected in the differences in the channel precipitation's contribution and the river bank contribution to runoff, as well as poorer definition in runoff of the most intense rain.

Above 1,400 feet in March-April the snow may have been more effective in storing the precipitation which occurred as rain although it seems possible--with the range in elevation on the watersheds, and the near freezing temperature of the air--that at the higher elevations much of the precipitation may have come as freezing or frozen rain, sleet, or snow which would have little effect on the hydrograph.

The final 3 events appear to be confounded by the absence of snow at lower elevations and the different mean elevations of the watersheds, but they are illustrative of where topographic and vegetational influences on the rate of snowmelt may be most pronounced. Under the weather conditions of April 5 and 6 the snow on southerly aspects may have been disappearing gradually, remaining only where shielded by topography or vegetation. Radiation may have been the most important source of energy in the 2nd and 3rd events, on April 5 and 6, but one should not overlook other potentially important sources of energy, such as sensible heat of the atmosphere or latent heat of condensation.

It would be interesting to compute the possible magnitude of this last heat supply from Sverdrup's equations for vapor and heat transfer, using the instrumentation which has been installed on the watersheds.

Whether radiation is in fact the most important source of energy or not, I would not credit it with a direct role in heating the ground surface 1° under a 21 inch snowpack. It seems far more likely that energy contributed by percolating meltwater from an isothermal snow pack might explain the increase in ground surface temperature from 30-31°.

From the data presented, there does not appear to be any firm basis for the conclusions deduced concerning the shape and timing of runoff hydrographs during the snow melt season as compared to other seasons, although, the data are interesting and indicative of the complex situations present on many watersheds during the spring snow melt runoff season.