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Rainfall-Runoff Characteristics for a Mountainous Watershed in the Northeast United States

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A 112 square kilometer research watershed was instrumented to study basic hydrologic processes in the mountainous areas of the Northeastern United States. Within this area the rainfall-runoff relationships are characterized by fast response but relatively low volumes of runoff. There is very little evidence of surface runoff and the partial-area hydrology concept appears to describe the runoff process. A partial area storm runoff process has been described and experimentally verified for an extremely small area in this watershed. This process attributes storm runoff to channel and near channel areas where surface runoff is generated because the groundwater or perched water table has intersected the surface and there is no resulting infiltration. Storm data for nine watersheds have been analyzed and the results demonstrate that the partial area concept can be generalized to large areas. Other data relating to the general hydrology and water balance of this watershed are also described.

Introduction

Rainfall-runoff characteristics in the United States vary greatly depending upon the climate, soils and land use. The U.S. Department of Agriculture has a comprehensive experimental program to characterize the basic hydrological relations throughout the country. This approach is necessary for the Department to carry out its small watershed protection programs and to evaluate the impact of various management alternatives on land and water resources.

The Sleepers River Watershed near Danville, Vermont is one of about a dozen intensively instrumented research areas in the United States. This particular area was chosen as representative of much of the glaciated upland and mountainous regions in New England and eastern New York. The watersheds that drain these regions supply a large percentage of the water required for agriculture, industries, and cities in the northeastern United States and also create the potential for serious flooding. The purpose of this research watershed was to investigate important hydrologic factors as the temporal and areal variations of precipitation and snow melt, the role of ground water flow, the hydraulics of steep mountain streams, basic rainfall runoff relationships and the effects of land use on runoff.

This paper presents a description of the basic climatic and rainfall-runoff relationships as they apply to mountain hydrology. A partial area runoff concept is analyzed with respect to its applicability to large areas.

Basin Characteristics

Topography

Glacial features dominate the topography in the Northeastern United States. The terrain is generally described as hilly to mountainous with many peaks higher than 1,200 m. The Sleepers River Watershed is in the Northeast corner of Vermont and drains into the Connecticut River. The total area of the watershed is 112 square kilometers. Fig. 1 shows the general drainage network and the topography of the area. The average slope of the watershed is about 8 percent. This, however, is not indicative of the general ruggedness of the upper one-third of the head-water area, over which slopes range from 25 to 30 percent. The distribution of slopes is given in Table 1.

Geology

The geology of the area is generally described as very slightly anticlinal with no faults. The eastern portion (94% of watershed) is the Waits River Formation made up of calcareous granulite, calcareous schists, and cal-silicate rocks interbedded with quartz-mica schists and micaceous quartzite. The western portion (6% of watershed) is the Gile Mountain formation of dark and light gray schists. Both formations are dense and relatively impervious with no solution chambers.

Soils

The "flashy" nature or response of the various drainages in the Vermont highlands reflects the sloping nature of the land and relatively well drained soils. The complete vegetative growth, both grass and forest in this region, is more attributable to the frequency of rainfall during the growing season than to the moisture storage properties and fertility of the soils.

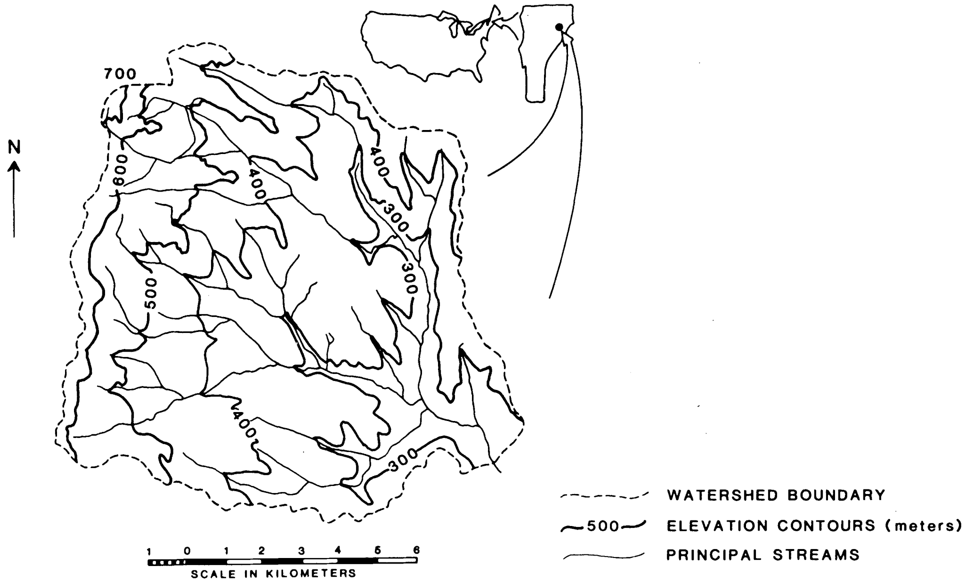

Fig. 1. Map of Sleepers River Research Watershed showing topography and principal drainage network.

Table 1 – Distribution of slopes by percent of area in Sleepers River Watershed

Percent Slope	0-3%	3-8%	8-15%	15-25%	25-35%	Over 35%
Percent of Area	3	30	31	23	12	1

Soils on the watershed range from coarse-textured sandy loams and loamy sands at higher elevations to fine-textured silt loams on benches, lower slopes, and along narrow bands adjacent to stream channels. Generally, these soils are glacial tills and lacustrine silts derived from schists interbedded with limestone. It is not uncommon to find soil depths ranging from zero to several inches over exposed rock outcrops to four to six feet between outcroppings.

Cover and Land Use

The vegetation cover for the watershed has been relatively stable and indications are that most of the cover patterns existed at least several decades before the Sleepers River Research Watershed was established. Fig. 2 shows the major land uses of the area. About one-third of the watershed area is open in grassland, cultivation, roads, and farm buildings. The remaining two-thirds of the area is in some form of forest cover – generally second and third growth deciduous and coniferous species. Most of the open agricultural land is in "permanent" grass cover for pasture, hay, or unused pasture. Only a small percent of the agricultural land is cultivated for row or intertilled crops. In addition to the soil properties, the

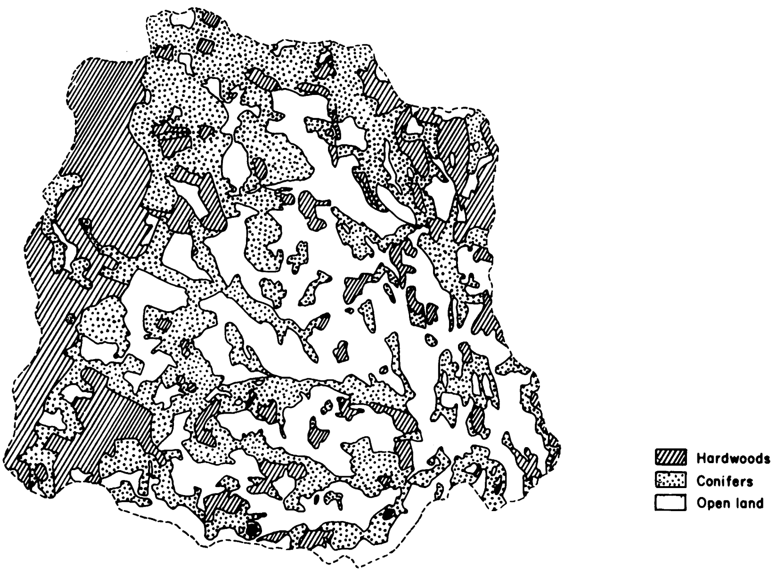

Fig. 2. Land use map of Sleepers River Research Watershed.

extensive forest and grassland cover enhances the surface infiltration characteristics of the watershed soils. Consequently, surface runoff is uncommon and soil erosion is not considered a problem.

General Climatic Features

General climatic features of the New England area include rapidly changing weather, large temperature ranges, even distribution of precipitation and considerable diversity of weather with time and place.

The mean annual temperature for the watershed is about 4.5°C. The summers in the watershed area are relatively cool with the mean temperature in July about 20°C. Winters are cold with January temperatures averaging about -8°C. It is not uncommon for the station in the watershed to experience 50 days during a winter season when the minimum temperature is below -17°C. The growing season in the watershed region varies between 100 and 130 days (Lautzenheiser 1959).

Monthly average precipitation in Vermont is fairly evenly distributed throughout the year; however, variations in monthly totals can be extreme. Usually, there is adequate summer precipitation for crops throughout the State. Widespread floods and droughts are infrequent. Thunderstorms produce the heaviest rainfall intensities and are potential local flood sources. The mean annual precipitation in the northerastern corner of the State is about 965 mm, approximately one-fourth to one-third of which is snow. The watershed region generally experiences continuous snow cover throughout the winter, with total snowfall averaging about 2,500 mm.

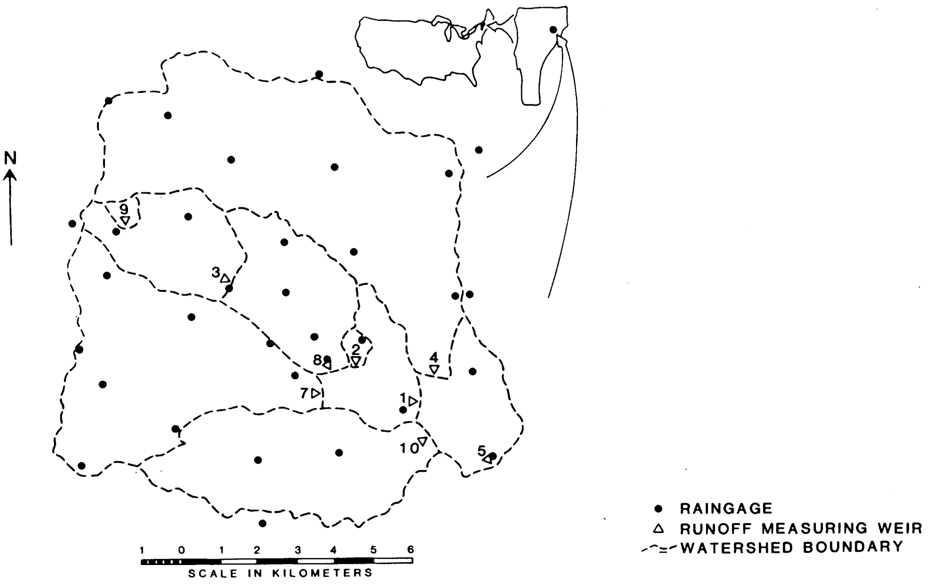

Fig. 3. Map of Sleepers River Research Watershed showing basic instrumentation and the nine watersheds analyzed.

Instrumentation and Data Reduction

The watershed has been intensively instrumented to measure all components of a hydrologic mass balance. In studying a watershed mass balance, the object is to measure as many components of the hydrologic budget as possible. The following equation illustrates the hydrologic mass balance

$$P = Q + ET + \Delta SM + \Delta GW \qquad (1)$$

where P = precipitation, Q = runoff, ET = evapotranspiration, ΔSM = change in soil moisture, and ΔGW = change in ground water. The foundation of instrumentation consisted of a 31-station rain-gaging network and a stream-gaging network of 17 reinforced concrete weirs. Other concomitant data were collected at selected locations; these included air and soil temperature, wind, pan evaporation, relative humidity, net and short wave radiation, snow depth and water content, and soil moisture. Fig. 3 shows the location of the raingages and nine watersheds studied in this paper.

In general, the data were collected with recording instruments or spot observations, reduced to a computer compatible form, and stored in a data bank. Rainfall and runoff breakpoint and monthly summary data were used for the study.

The runoff data were presented as total stream-flow and further data reduction in the form of base flow separation was necessary. The separation technique used in this study was simple but objective. A computer program was developed to

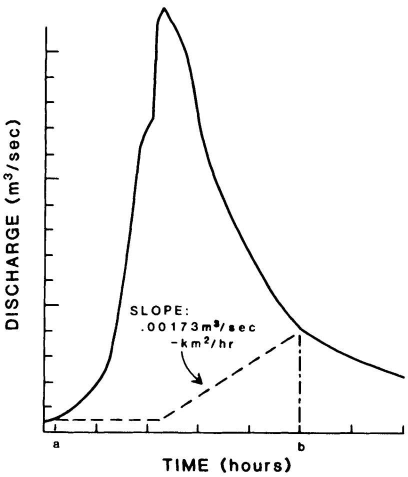

Fig. 4. Schematic showing baseflow separation procedure.

extend the base flow until the time of the hydrograph peak; the base flow was then extended at a slope of .00173m^3/sec-km^2/hr until it intersected the recession of the hydrograph. The procedure is illustrated in Fig. 4. The value of .00173m^3/sec-km^2/r was chosen by analyzing a number of hydrographs from watersheds of different sizes in the study area. This number is the average from several hydrographs based on a subjective decision where the most rapid change in slope of the recession curve occurred.

General Hydrology and Runoff Characteristics

Precipitation Characteristics

Fig. 5a displays the mean annual isohyetals based on 14 stations with a common 7-year recording period. Linear interpolation was used to define the position of the isohyetals. The most important information on this map is the more than 400 mm difference between gages 1 and 11 which are separated by 12 km and an elevation of 490 meters. By comparing the isohyetals in Fig 5a with the elevation contours in Fig. 1, the relationship between elevation and annual precipitation becomes evident. On the average, annual precipitation increases approximately 80 mm for each 100-m increase in elevation.

When analyzed on a seasonal basis, the winter precipitation totals indicate greater control by elevation than the summer season totals. The period May through September was considered the summer season because of the large number of thunderstorms (two or more were selected as an arbitrary separation), and the remaining months were considered the winter season. Figs. 5b and 5c display the seasonal isohyetal maps. Examination of these maps reveals a smaller

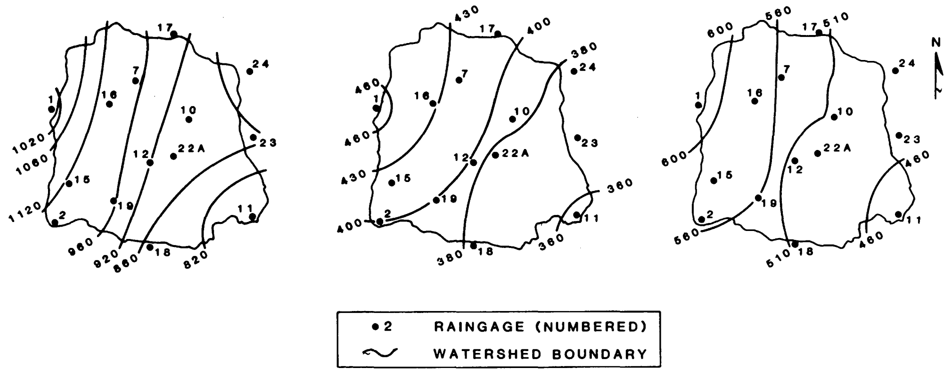

Fig. 5. Isohyetal maps showing (a) annual; (b) summer (May-September); and (c) winter (October-April) rainfall patterns; averages for 1959-1966. From Engman and Hershfield 1969.

areal variation in the summer than in the winter. This can probably be explained by the random distribution of many summer thunderstorms as opposed to the elevation-controlled winter precipitation.

The summer season has a greater frequency of hourly and daily precipitation amounts greater than 2.5 mm, whereas the winter season has a greater frequency of hourly and daily precipitation amounts less than .25mm. In addition, these frequency data show an increase with elevation. Much of the annual difference in precipitation between high and low elevation gages is caused by the cumulative effect of many small winter events at the higher elevations.

Storm rainfalls are generally uniformly distributed over the watershed during the winter season. Isocorrelation maps drawn from a large sample of storms, where at least one gage received 10 mm or more, indicate good correlation between a central gage and all other gages. In a study of the spatial distribution of daily precipitation, Hendrick and Comer (1970) showed that the interstation correlations were independent of elevation but the amounts of precipitation were elevation dependent. This population of data could be presumed to be made up of individual storms. However, for summer storms, the correlation drops off rapidly with distance. This is indicative of the random nature of thunderstorms, which make up a considerable portion of the summer precipitation.

Both the areal and temporal variations in rainfall over the Sleepers River Watershed are relatively uniform when compared with other regions in the United States (Hershfield 1967). Thus, for most use in hydrologic mass balances the precipitation component can be determined relatively accurately. The accuracy of the precipitation data is extremely good when compared with the accuracy of determining other hydrologic variables, especially evapotranspiration and ground water storage.

Runoff Characteristics

The Sleepers River (W-1) and Houghton Brook (W-4) form the two principal channels, (both having approximately 44 square kilometer drainage areas) that drain the watershed. Both streams are located in narrow valleys with little or no valley storage or "flood plain" areas. Because of the topography and geology of the area, the channels do not store water for appreciable periods.

The two major channels are fed by mountain-type streams in the headwater sources. Channel gradients are quite variable, but usually average from 2 to 6 percent slopes. Because of the rocky disorganized masses of boulders and bedrock outcropping in the channel's reaches, channel roughness is quite high. Many of the small feeder streams retain some flow throughout the year. This "perennial" or at least, long-term intermittent nature of flow, is more attributable to frequent storm input than to favorable water storage characteristics of the soils.

The generally steep channel gradients and the narrow channels combine to give these streams their "flashy" character. While there are numerous peaks throughout the year, seldom do individual peaks attain flood magnitude. During the period of record (1959-1979) only one serious flood (June 30, 1973) was recorded. Peak flows characteristically have short durations, except when low intensity, long duration frontal rainfall occurs or during major snowmelt periods.

Nonstorm period flow sources are not readily identifiable, especially as true ground water. It is more likely that baseflow tends to be of a transient, subsurface seepage, wet-weather seepage, or perched ground-water table source. These temporary sources are recharged and maintained by the frequent storms.

Table 2 summarizes the monthly and annual runoff for the nine watersheds. In general, the total runoff is approximately 50% of the rainfall and appears to be more dependent upon rainfall input then on size or other watershed characteristics. The watersheds with headwaters in the higher elevations have more runoff but they also have more precipitation. One other noticeable feature of this area is the high runoff period during the snowmelt of March, April, and May. Roughly one-half the annual runoff occurs during the approximately two-month period from mid-March to mid-May.

As mentioned above, streams draining very small regions are or are nearly perennial in their flow. The amount and frequency of their flow is directly related to the amount and frequency of precipitation. However, the watershed characteristics also appear to play an important role in water yield. Comer and Zimmermann (1969) attribute differences in low flow yield to the types of soils present in a given area. During a 6-year period, the minimum flows per unit of area in a 8.4 km^2 basin (W-3) were 0.0068 mm/h compared with 0.00076 mm/h in an adjacent 21.9 km^2 basin (W-7). As the climate, geology, and land use in the two basins are similar, the differences in low flow were attributed to differences in topography and in soils. Fifty-four percent of the larger, low-yielding basin has slopes of 8 percent or less; slopes of 8 percent or less occur in only 28 percent of the smaller

Table 2 – Seven-year (1963-69) average rainfall and runoff (mm) from selected watersheds, Sleepers River, Danville, Vermont

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
P =	R – 1	67.05	71.88	84.58	90.68	100.08	98.04	90.93	129.03	83.31	84.84	130.81	108.71	1,140.71
	R – 22	40.13	41.15	57.66	69.34	79.76	78.99	100.08	95.00	58.93	59.94	93.73	75.69	850.65
Q =	W– 1	20.54	15.75	46.74	136.70	74.46	27.66	13.84	13.87	11.14	21.37	37.38	35.31	454.76
P =	R – 22	40.13	41.15	57.66	69.34	79.76	78.99	100.08	95.00	58.93	59.94	93.73	75.69	850.65
Q =	W– 2	19.49	17.35	63.48	106.93	60.72	30.95	17.18	13.27	10.23	13.73	23.69	29.55	402.94
P =	R – 1	67.05	71.88	84.58	90.68	100.08	98.04	90.93	129.03	83.31	84.84	130.81	108.71	1,140.71
	R – 6	53.59	47.75	64.26	77.47	92.96	84.58	88.39	108.71	63.50	73.91	103.38	79.50	937.77
Q =	W – 3	26.77	21.02	46.11	162.91	104.33	40.74	24.80	23.59	19.16	28.20	43.04	4 41.90	582.57
P =	R – 10	45.21	48.77	59.18	74.17	88.39	84.58	89.92	105.92	61.98	66.04	100.84	84.58	910.08
Q =	W– 4	20.40	16.18	46.36	136.89	87.80	33.29	16.77	15.64	12.95	22.11	37.03	33.91	479.32
P =	R – 1	67.05	71.88	84.58	90.68	100.08	98.04	90.93	129.03	83.31	84.84	130.81	108.71	1,140.71
	R – 11	40.89	39.62	55.88	67.06	73.66	73.15	101.60	84.58	56.13	58.93	92.96	78.23	823.21
	R – 22	40.13	41.15	57.66	69.34	79.76	78.99	100.08	95.00	58.93	59.94	93.73	75.69	850.65
Q =	W– 5	30.81	21.93	62.01	142.22	77.69	28.40	15.36	12.99	12.07	21.87	37.81	38.09	502.77
P =	R – 19	58.17	55.37	71.37	78.74	90.93	85.85	93.98	102.11	63.50	74.93	113.54	94.74	1,137.92
Q =	W– 7	17.87	14.46	54.84	174.55	86.67	28.40	11.78	12.60	10.02	23.69	43.97	35.60	514.45
P =	R – 3	54.61	60.71	78.23	87.88	101.09	96.77	92.46	124.46	75.18	79.76	116.59	94.49	1,062.74
Q =	W– 8	21.21	17.27	44.66	127.59	77.44	32.41	17.20	16.83	14.24	22.19	35.33	33.53	459.89
P =	R – 1	67.05	71.88	84.58	90.68	100.08	98.04	90.93	129.03	83.31	84.84	130.81	108.71	1,140.71
Q =	W–9	18.55	13.82	37.99	174.80	116.82	31.99	12.34	12.72	10.54	21.50	38.81	32.13	517.40
P =	R – 19	58.17	55.37	71.37	78.74	90.93	85.85	93.98	102.11	63.50	74.93	113.54	94.74	1,137.92
Q =	W– 10	18.14	14.82	57.80	141.20	71.59	28.17	16.09	14.28	10.22	18.46	35.00	36.56	462.33

basin. Poorly and very poorly drained fragipan soils (Typic and Humic Fragiaquepts) occupy 44 percent of the larger basin, as opposed to only 22 percent of the smaller, steeper basin. These soils have an 0 horizon, an A horizon with high organic content, and a fragipan at depths generally between 12 and 18 inches. It was concluded that these soils retard or impede deep percolation to storage, and to retain moisture in the surficial horizons even at high tensions. In the smaller basin, high base flow is probably sustained by the slow release of moisture from the deeper, surficially well-drained soils that prevail in it.

Partial Area Hydrology

Background

Storm runoff in the Sleepers River Watershed exhibits all the characteristics of classical surface runoff; i.e., fast responding, flashy, with textbook types of hydrographs. Field observations during storms indicated little or no surface runoff in much of the watershed. Further analysis of data showed that although the storm hydrographs responded quickly to rainfall intensity, the total volume of runoff was quite small, generally being on the order of 10 percent or less. Tables 3 and 4 list the rainfall and resulting runoff for selected large storms in watersheds W-1 and W-2 for the period under study. In addition, comparing plots of hydrographs for the same event exhibit very similar time responses to rainfall inputs. Many watersheds, regardless of their size, have rising portions of the hydrographs that are nearly co-linear. Because of this timing coincidence, one can conclude that the runoff does not travel far before it is in the channel network.

Dunne and Black (1970a) conducted a very intensive experiment of the runoff process in this area. They had observed that during storms only a small portion of the drainage basin near the stream was actively involved in contributing surface runoff. Three hillside plots were instrumented to study the runoff producing mechanisms. Soil moisture, water table elevations, piezometric heads, as well as rainfall and runoff, were measured. They also had the capability to apply an artificial storm through a sprinkler irrigation system.

Dunne and Black's (1970a, b) study explained the runoff process but they did not propose a model that could be generally used on larger areas.

Betson's (1964) early work defined the partial area runoff process as being the results of variable but consistent infiltration rates in a watershed. Engman and Rogowski (1974) proposed a partial area model that delineated the contributing area by soil properties that resulted in differences in infiltration rates to generate surface runoff. However, Dunne and Black (1970a) concluded, in general, that Hortonian (Horton 1933) surface runoff (when rainfall intensities exceed the infiltration capacity) did not occur. This was primarily because the area is in a region of generally low intensity rainfalls and highly permeable soils. Dunne and Black (1970b) further concluded that subsurface storm flow as proposed by Whipkey (1965), Kirkby and Chorley (1967) and Hewlett and Hibbert (1965) was "too small, too late, and too insensitive to fluctuations in rainfall intensity to add significantly to storm flow in the channel". Rather, Dunne and Black (1970b) proposed a process based on partial contributing areas adjacent to the stream that can expand or contract seasonally or during a storm. These partial areas are generally where the water table intersects the ground surface or drainage is in some other way impeded. These areas remain in a near saturated condition and have little available storage for rainfall; consequently, when it rains most of the water will run off. In addition, water escaping from the saturated soil to the surface will become a part of the storm runoff. This proposed mechanism appears to be valid because the relatively small volumes of runoff can be accounted for by relatively small portions of the watershed (5-10 percent) contributing nearly 100 percent of the storm flow.

Lee and Delleur (1976) proposed a partial contributing area model that was based on the stream network. Their model is based on three assumptions which appear to be valid for the Sleepers River Watershed. These are

1 – The locations with equal distances along the stream network to the outlet have the same runoff travel time; i.e., the velocity of flow along the stream network is uniform.
2 – The total stream length upstream of a particular point on a stream network is proportional to the tributary drainage area at that particular point; i.e., the drainage density is a constant within a watershed.
3 – At any given time the ratio of response area to drainage area at a stream reach interval is equal to the ratio of response area of the whole basin to total watershed area. This implies that the response areas are uniformly distributed along the stream reaches.

Selected storm events have been analyzed by a simplified version of the Lee and Delleur (1976) model. The routing portion of their model was not used. Rather, the data were analyzed to determine what the contributing area was for each storm based on Lee and Delleur's approach. If the contributing areas were fairly consistent from storm to storm or if their derived sizes could be justified by antecedent conditions, then we would conclude that the model was appropriate for this watershed.

Analysis of Data

On a storm by storm basis, the gross contributing area was calculated assuming this source of runoff was 90 percent efficient. That is, 10 percent of the rainfall was assumed to be lost through the B-horizon and not available for storm runoff. In Lee and Delleur's (1976) analysis of Indiana watersheds, they found the value

Table 3 – Rainfall-runoff data and calculated partial areas for selected storms, W-1 (43.1 km^2)

Date	Precip (mm) R–1	Precip (mm) R–22	Runoff (mm) W–1	Partial area (km^2)
August 12, 1964	37.6	45.7	2.33	2.96
June 7, 1965	43.2	35.6	3.41	3.80
July 18, 1965	35.6	52.8	1.42	1.92
September 1, 1965	40.6	38.1	4.31	5.07
September 21, 1966	32.2	27.9	.63	.94
October 10, 1967	22.9	35.8	4.14	8.66
October 18, 1967	42.4	28.2	5.42	6.11
September 11, 1968	41.6	39.6	1.78	2.05
May 19, 1969	50.3	47.2	17.0	16.17
June 13, 1969	14.2	35.8	2.37	8.06
June 15, 1969	38.4	29.2	5.23	6.53
August 23, 1970	31.8	31.8	.23	.36
August 28, 1970	30.7	22.1	.41	.62
August 3, 1971	70.0	52.3	5.35	3.69
August 20, 1971	21.1	21.1	.16	.36
August 22, 1971	34.8	28.2	1.36	1.87
August 27, 1971	102.6	66.5	13.8	6.45
June 28, 1972	54.9	12.4*	1.87	1.64
July 3, 1972	25.4	24.1*	2.49	4.71
July 10, 1972	39.9	25.4*	2.60	3.12
June 16, 1973	56.1	49.8*	10.7	6.27
June 29, 1973	152.1	125.5*	38.3	12.04
September 6, 1973	61.0	27.9*	1.99	1.56

*R–12

used for the B-horizon losses to be negligibly small and used a value of zero. Tables 3 and 4 list the storm data (rainfall and runoff) for watersheds W-1 and W-2 and the calculated contributing areas. These areas are the gross estimate of the area within the watershed that would be necessary to produce the storm hydrograph if 10 percent of the rainfall were "lost" over these areas. This implies that over all other portions of the watershed all of the rainfall was infiltrated. The average partial areas and the maximum and minimum partial areas for all nine watersheds calculated from the storm data are shown in Table 5.

Although the size of the contributing area is somewhat dependent upon storm size, it is also dependent upon the antecedent conditions. The calculated partial area was used as the dependent variable in a regression analysis that performed all possible linear regressions with the following independent variables: five-day antecedent rainfall, storm rainfall amount, storm maximum rainfall intensity, and

Table 4 – Rainfall-runoff data and calculated partial areas for selected storms, W-2 (0.59 km^2)

Date	Precip (mm) R-22	Runoff (mm) W-2	Partial area (km^2)
August 23, 1964	45.7	2.92	0.04
June 7, 1965	35.6	1.61	.03
July 18, 1965	52.8	3.06	.04
September 1, 1965	38.1	2.38	.04
September 21, 1966	27.9	1.11	.03
October 10, 1967	35.8	3.39	.06
October 18, 1967	28.2	2.93	.07
September 11, 1968	39.6	3.12	.05
May 15, 1969	47.2	8.96	.12
June 13, 1969	35.8	5.40	.10
June 15, 1969	29.2	2.79	.06
August 23, 1970	31.8	.75	.02
August 28, 1970	22.1	.92	.03
August 3, 1971	52.3	5.92	.08
August 20, 1971	21.1	.19	.01
August 22, 1971	28.2	1.60	.04
August 27, 1971	66.5	6.56	.06

Table 5 – Calculated partial areas for the Nine Sleepers River Watersheds.

	Area	Partial area (km^2)		
Watershed	Km^2	Average	Maximum	Minimum
W-1	43.1	4.56	16.17	0.36
W-2	.59	.05	.12	.01
W-3	8.4	1.00	4.29	.13
W-4	43.61	4.60	15.13	.23
W-5	111.59	11.48	36.56	1.17
W-7	21.89	3.96	10.71	.21
W-8	15.70	1.56	4.32	.16
W-9	.47	.048	.195	.005
W-10	16.38	1.97	7.07	.21

baseflow rate at the start of the storm. Table 6 lists the results of the individual regressions for the four independent variables and the multiple linear regression for all four independent variables. In all cases except one, the independent variable baseflow produced the single highest R^2 value. Figs. 6 and 7 show the linear relation between the calculated partial area and baseflow for watersheds W-1 and

Table 6 – Values for calculated partial area vs. independent variables

Watershed	Maximum Intensity	5-day antecedent rainfall	Total rain	Baseflow before storm	All four variables
1	.073	.041	.157	.653	.693
2	.201	.007	.164	.376	.632
3	.039	.039	.292	.626	.784
4	.049	.125	.562	.486	.743
5	.107	.150	.389	.601	.741
7	.082	.030	.067	.174	.251
8	.070	.069	.343	.723	.813
9	.003	.067	.570	.638	.895
10	.166	.221	.651	.670	.905

W-2. In all cases either antecedent precipitation or the maximum intensity produces the lowest individual R^2 values. The regressions using 2 and 3 variables fell between the single variable regressions and the 4 variable regression.

Most of the watersheds had fairly similar results from these regressions. Watershed W-2 had fairly small R^2 values but with all four variables the R^2 of .632 was obtained. Only in watershed W-7 were all regressions so low that they appear to describe no relationship between the assumed partial area and the selected independent variables. In addition, it can be seen in Table 5 that W-7 has a relatively larger portion of the watershed as its partial area. Approximately 18 percent of W-7 is made up of contributing areas whereas all other watersheds are consistently grouped around a 10 percent value.

Discussion of Partial Area Hydrology

The regression analysis showed that, except for W-2 and W-7, the calculated partial areas could be explained to a great degree by the amount of baseflow at the beginning of the storm. Thus, the process that Dunne and Black (1970b) studied on the small scale can be generalized to the larger watersheds. Also, it appears that the Lee and Delleur (1976) model adequately describes the storm runoff process in this area and is a practical approach for representing the partial area hydrology in large areas.

If the partial source areas consisted mostly of saturated or near saturated regions adjacent to the stream, then it would make sense that the baseflow is a good indicator of the dynamic nature of these areas. These areas could be expected to produce baseflow through slow seepage to the channel. Thus, the larger the areal extent of these areas the greater the baseflow. Presumably these areas maintain their high moisture contents through gradual accretion of saturated and unsaturated water flow from up-slope areas. In a study of soil moisture movement in a soil model with an artificial water table as its base, Hewlett (1961) observed a

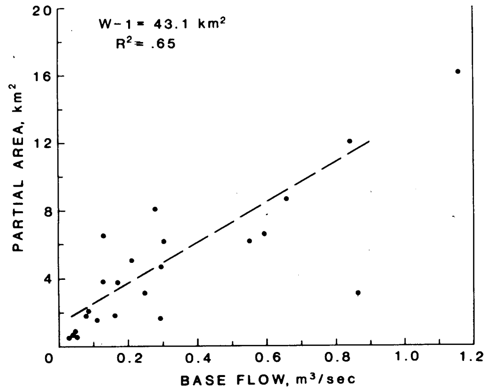

Fig. 6. Relationship between baseflow before the storm and calculated partial area, W-1.

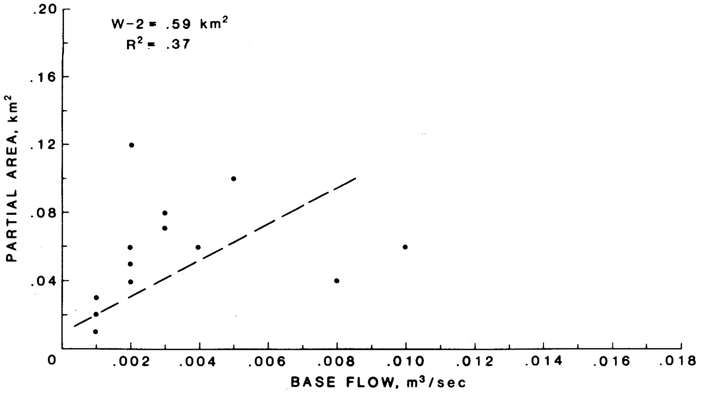

Fig. 7. Relationship between baseflow before the storm and calculated partial area, W-2.

general migration of unsaturated water downslope to maintain relatively high moisture levels at the bottom. Although primarily a study of soil moisture as a source of base flow, Hewlett did observe that this moisture migration would result in less storage for rainfall at the bottom of the slopes than at the top. This being the case, a disproportionate amount of surface runoff would occur from the lower slopes. Hewlett also discussed the dynamic aspect of this observation; as the rain volume increases, the area contributing to stormflow will increase. A similar process has been described for a swale area in Pennsylvania (Rogowski et al. 1974) in which detailed water balance data were used to demonstrate how such areas can maintain high antecedent moisture between storms. Based on the relatively high R^2 values for baseflow, one can conclude that the process described by Dunne and Black (1970b) is also valid for these larger watersheds.

Total storm rainfall produced R^2 values near those of the baseflow to somewhere midway between baseflow and the other two variables. It is expected that total rainfall should be somewhat related to runoff.

The independent variables antecedent rainfall did not give high R^2 values. This can be interpreted as antecedent precipitation being relatively unimportant in delineating the partial source areas. Because of moisture migration to these areas they are always relatively wet and the moisture in the remainder of the watershed would have little impact, if indeed, its contribution were minor. These results tend to support the mechanism proposed by Dunne and Black (1970b).

The consistently low R^2 values for maximum rainfall intensity can be interpreted as additional support for Dunne and Black's (1970b) concept. If rainfall excess were generated over portions of the watershed during periods of high rainfall intensity, one would expect higher R^2 values. Because these are generally quite low it supports Dunne and Black's (1970b) contention that Hortonian runoff is not a major factor in the area's hydrology.

Watersheds W-2 and W-7 were the two basins that did not follow the general pattern of the other seven. Also, watershed W-4 had a slightly higher R^2 value for total rainfall than for the baseflow regressions. The reasons why these basins differed from the others can only be speculated at this time. Watershed W-2 may be too small to exactly meet assumptions 2 and 3 necessary to use Lee and Delleur's (1976) model. Specific drainage patterns in small watersheds would tend to affect the results more than in large areas where the averaging of many drainage patterns helps to satisfy the assumptions.

Watershed W-7 is not typical of the others in this area. Previously cited work by Comer and Zimmermann (1969) described quite different low flow characteristics which they attributed to different distribution of soils. If this is the case one can probably expect quite different storm responses also. This appears to be the case and none of the independent variables tested appear to be related to the calculated partial area. Either these variables were not important for this watershed or the partial area concept was not applicable as used. This analysis could not isolate a plausible explanation of the runoff process.

In watershed W-4, total storm rainfall had the highest R^2 value but not greatly higher than the R^2 value for baseflow. Again, this analysis was not able to determine why this drainage basin should be different from the others. It does differ physically from W-1 (nearly the same size) by having a slightly longer main channel and a swamp area that is not present in the other basins. However, it is unclear if or why these would be important.

Whereas this study did show that the runoff process proposed by Dunne and Black (1970b) could be extrapolated to large areas by a model such as Lee and Delleur's (1976), there are specific watersheds that cannot be modeled with these concepts. Additional work needs to be done on identifying contributing areas within watersheds and representing them in a general way. The approach proposed by Lee and Delleur (1976) appears to be a usable model if one can learn how to modify the data when the assumptions are not precisely met.

Summary

This paper has described some of the physical characteristics, instrumentation, and basic hydrology for a mountainous watershed in the Northeastern United States. Although there are slight differences from watershed to watershed, roughly one-half of the incident rainfall leaves the area as stream flow and because of snow melt, roughly one-half the annual runoff occurs in approximately two months. Except during unusually dry periods, watersheds of roughly one-half km^2 area and greater have perennial flow and a well developed channel system. Storm runoff hydrographs are fast responding but have relatively small volumes of runoff; in most cases less than ten percent of the incident precipitation. The partial area concept described by Dunne and Black (1970b) appears to describe the storm runoff process in these watersheds. In this concept the partial or source areas consist of saturated or near saturated regions adjacent to the stream which are the sources of storm runoff. These areas could also be expected to produce baseflow through slow seepage to the channel. Thus, the larger the areal extent of these areas the greater the baseflow.

A partial area model developed by Lee and Delleur (1976) was used to calculate the contributing areas for storms in nine watersheds varying from about 0.5 km^2 to 112 km^2. Regression analysis with the calculated contributing areas and several variables showed the strongest relation with baseflow before the storm. These results tend to support the mechanism proposed by Dunne and Black (1970b) and indicate that Lee and Delleur's (1976) model gives a good partial area representation for large areas.

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