An Experimental Investigation of Runoff Production in Permeable Soils

THOMAS DUNNE

McGill University, Montreal, Canada

RICHARD D. BLACK

Cornell University, Ithaca, New York

Abstract. In an area of low intensity rainfall and permeable soils, three hillside plots were instrumented for a study of runoff-producing mechanisms. Runoff from the plots was measured at the ground surface, the base of the root zone, and in the zone of perennial groundwater seepage. Data on soil moisture, water-table elevation, and piezometric head were also collected during natural and artificial storms. The data showed that, as the infiltration capacity of the soil exceeded the rainfall intensities that occurred and that were applied, overland flow generated by the mechanism described by Horton did not occur. Although soils and topography were those generally thought to be conducive to subsurface stormflow, the runoff produced by this mechanism was too small, too late, and too insensitive to fluctuations of rainfall intensity to add significantly to stormflow in the channel at the base of the hillside. When the water table rose to the surface of the ground, however, overland flow was generated on small areas of the hillside. Only when this overland flow occurred were significant amounts of stormflow contributed to the channel by the hillside. The return periods of storms that would produce such overland flow were found to be very large.

INTRODUCTION

Overland flow on large areas of hillside, described by *Horton* [1945] and others, has not been observed in the 43-square-mile watershed of the Sleepers River in northeastern Vermont. Infiltration capacities of the forested and pastured soils of the area exceed the vast majority of measured rainfall intensities. Total yields of storm runoff are small. The maximum recorded rate of runoff on the Sleepers River Experimental Watershed was 0.10 inches per hour resulting from a rainfall of 3.37 inches in 38 hours on a 16-square-mile catchment. Runoff hydrographs, however, have the same general features as those from other areas where overland flow is observed. They have the same general shape, and respond quickly to rainfall. They show many of the same kinds of relationships between rainfall, runoff, and watershed condition as are recognized in areas known to experience overland flow.

In the absence of evidence of overland flow to supply storm hydrographs, many hydrologists have postulated the mechanism of subsurface stormflow. *Whipkey* [1965, p. 74] defined subsurface stormflow as underground, storm-period flow that reaches the stream channel without entering the general groundwater zone. *Kirkby and Chorley* [1967, p. 7] used the term 'throughflow' to denote 'flow which takes place physically within the soil profile.' *Hewlett and Hibbert* [1965] described their concept of 'translatory flow.' They wrote, 'Above the zone of saturation, we may regard such movement as due to thickening of the water films surrounding soil particles and a resulting pulse in water flux as the saturated zone is approached.'

AIMS OF THE PRESENT STUDY

The magnitude and timing of subsurface contributions to channel runoff and the conditions under which significant amounts of subsurface stormflow are produced are generally unknown. In the absence of universally accepted theoretical tools and detailed information on the physical characteristics of soils and channels, the phenomena listed above can be determined only from intensive field study. To this end, a small catchment in the glaciated upland of the Sleepers River Experimental Watershed near Danville, Vermont, was selected for a detailed study of runoff production in an area of low intensity rainfall and highly permeable soils. The following report will deal only with data on contributions to streamflow from the permeable soils of the steep hillslopes during natural and artificial rainstorms.

THE EXPERIMENTAL AREA

The watershed in which the study was conducted is a 60-acre basin, carved into a glaciolacustrine terrace that lies against a steep, till-covered hillside of well-jointed, calcareous schist. Within this watershed, a hillside was chosen for intensive study (Figure 1). The 0.6-acre hillside has a southerly slope that varies from 30% to 100% and has a relief of 60 feet. The surface outlet for the watershed drains the toe of the slope. The hillside receives no drainage from above as it is separated by a narrow, flat-topped divide from an equally steep slope on its northern side. It has a relatively simple profile and consists of three sections which differ in plan form. To the west is a section whose contours are convex (plot 1); in the center is a concave portion (plot 2); and to the east the contours are straight (plot 3). *Hack and Goodlett* [1960], *Troeh* [1964], and others have suggested that there is a relationship between soil drainage and slope shape. Topography, should, therefore, be reflected in the pattern of antecedent soil moisture which is generally considered to be a major control of runoff production.

Geologically the slope is part of a dissected lake bed (Figure 2) and consists of a 22-foot-thick layer of sand (containing less than 50% silt) overlying 38 feet of varved silt and fine sand (more than 65% silt), which in turn is founded on silty clay till. Dissection and subsequent mass movement of sandy material downslope has resulted in deposition of a 1- to 3-foot-thick layer of highly permeable material over the lower silt loam.

The soils of the slope are well-drained Brown Forest sandy loams on the straight, eastern section, and well-drained Brown Podzolic sandy loams on the concave, central, and convex western portions. The major difference between these soils is that the saturated conductivity, bulk

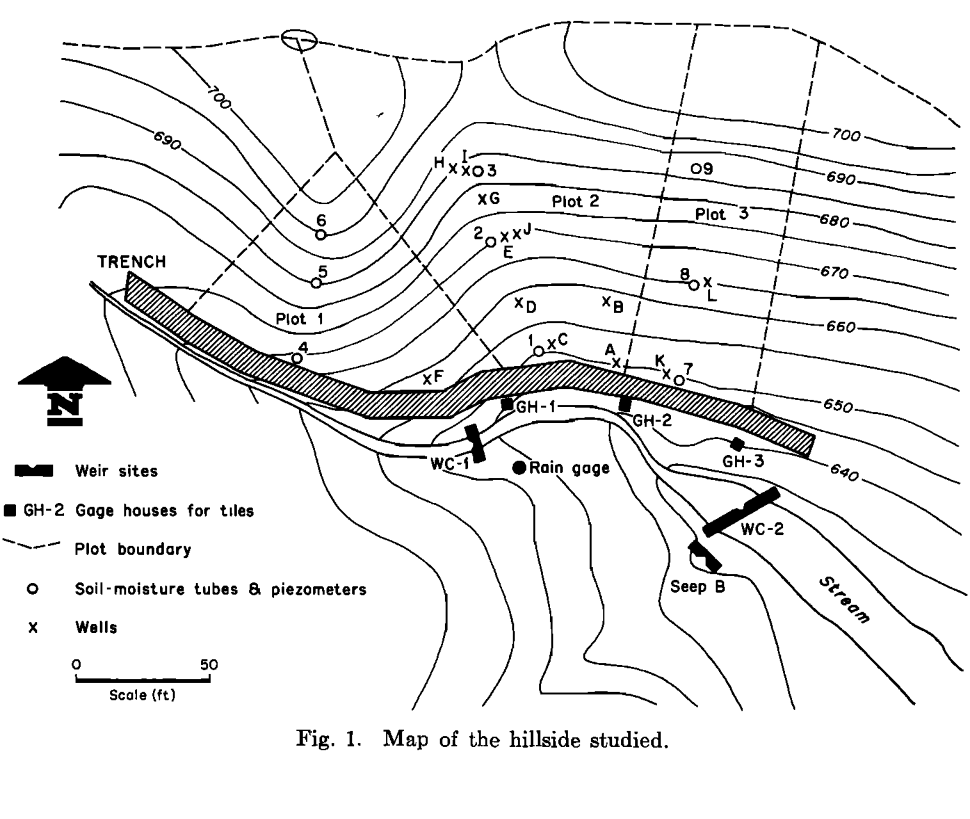

Fig. 1. Map of the hillside studied.

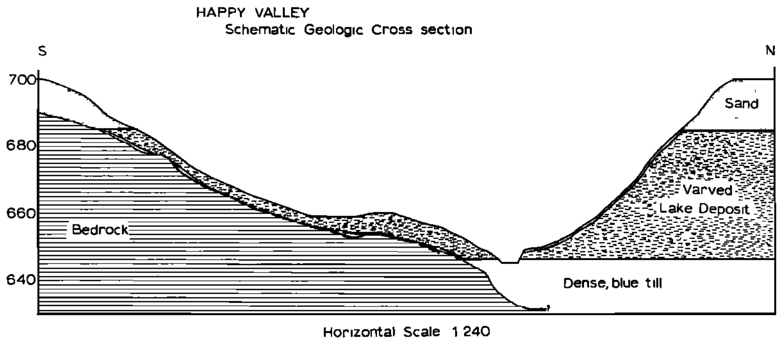

Fig. 2. Schematic geological cross section of the experimental area.

density, structure, and amount of root penetration change abruptly at a depth of 12 to 30 inches in the Brown Podzolic soils. On the straight slope there is a gradual change of soil structure, an increase in density, and a decrease in saturated conductivity as depth increases. Although the slope is now in pasture, pine woodland covered the area until a fire destroyed the woodland approximately 30 years ago. The soil is interlaced with old root holes, worm holes, and structural channels that seem to provide conditions that are conducive to subsurface stormflow.

INSTRUMENTATION

Runoff from the hillside was intercepted by drains installed in a 275-foot-long trench (Figure 1). The depth of the trench varied from 5 to 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 trench draining the 0.13-acre convex hillside, and two 50-foot-long sections draining the 0.30-acre concave slope and the 0.17-acre 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 3). The flow from each interceptor was measured in gage houses at the eastern 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 is shown in Table 1. A roof was built over the trench and surface drain to prevent direct entrance of precipitation.

Channel runoff was gaged continuously at four locations in the 60-acre watershed for comparison with the runoff produced on the hillside plots. One gaging station (WC-1) lay immediately above the outlet from plot 1; another gaging station (WC-2) lay immediately below plot 3 (Figure 1). On the right bank of the stream the slope draining to the reach of channel between the weirs had an area of only 400 square feet.

Natural rainfall was measured with a 6-inch, 24-hour weighing rain gage. During artificial storms a random network of thirty 4-inch-diameter cans was used to measure rainfall. Total amounts of rain were computed as Thiessen-

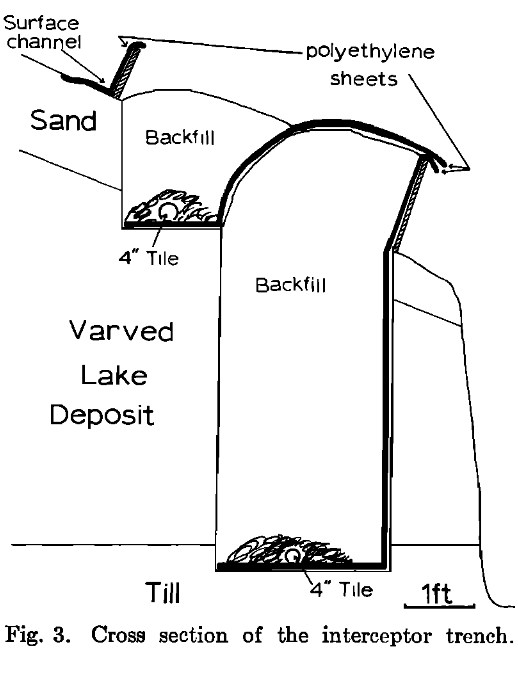

Fig. 3. Cross section of the interceptor trench.

weighted averages of the water caught in these cans.

A nuclear depth probe was used to measure soil moisture. Three access tubes, 7 feet deep, were placed in each plot (Figure 1): one at the base of the slope, one halfway up the slope, and one three-quarters of the way up the slope. Readings were taken weekly throughout the year, daily during snowmelt, before and after natural rainstorms, and several times during and after artificial rainstorms.

Measurements of water-table elevations were made in ¾-inch pipes at the 12 locations shown in Figure 1. Readings were taken weekly throughout the year, several times daily during snowmelt, and every few minutes during natural and artificial rainstorms. Soil water pressure was measured in ¾-inch diameter piezometers at the locations shown in Figure 1. A set of four piezometers at depths of 10, 8, 6, and 4 feet was located at each station. Two-foot-deep piezometers were also installed at locations 1 and 2. Piezometric readings were made at the same time as the water-table measurements.

EVENTS STUDIED

Data were collected in the following types of events:

1. Summer storms.
2. Large, natural autumn storms on unusually wet antecedent conditions.
3. Simulated rainstorms of high return period.
4. Natural rainstorms that occurred so soon after the simulated storms that they could be considered as a part of the same event.

RESULTS

Summer Storms

Thirty-five storms ranging in amount up to 1.09 inches were recorded during the course of the study. The maximum 5-minute and 30-minute intensities of these storms were 3.12 inches and 1.18 inches per hour respectively. The return periods of the storms were less than two years. A larger, more intense storm occurred after one of the artificial rainstorms, but this will be discussed separately.

No significant storm runoff was produced on the hillside in these storms. Neither overland flow nor flow from the base of the root zone were measured. Flow from the lower tiles occurred throughout the summer but did not usually respond to individual rainstorms. Groundwater discharge began to respond slightly after a period of rainy days, but the maximum outflow rate during the summer of 1967 was only 0.0009 cfm per foot of channel, (equivalent to 1.31 cfm for a drainage density of eight miles per square mile, which is an average for the subwatersheds of the Sleepers River Experimental Watershed). As it is a central thesis of this paper that runoff production is spatially nonuniform, to express runoff in inches and inches per hour would therefore be misleading, especially for very small watersheds. In this paper, runoff volumes are expressed in cubic feet and runoff rates are expressed in cubic feet per minute (cfm).

TABLE 1. Numbering System Used in Referring to the Various Flow Collectors in the Interceptor Trench

Level of Collector	Plot: Convex (1)	Concave (2)	Straight (3)
Surface	1-1	2-1	3-1
Base of root zone	1-2	2-2	3-2
Zone of perennial seepage	1-3	2-3	3-3

The reasons for the lack of runoff were the high infiltration capacity and storage capacity of the soils on the hillside. The infiltration capacity of these soils was measured to be greater than 3.15 inches per hour. From June 1, 1967, to October 1, 1967, the storage capacity of these soils exceeded any rainfall event that has been measured at a nearby gage in the last 76 years. Measurement of soil moisture before and after storms showed that rainwater was stored in the upper three feet of soil during the storm and drained slowly to the water table during the next few days. Throughout the summer months, the water table stood 4 to 5 feet below the center of plot 2.

It appears, therefore, that summer storms having a recurrence interval of less than two years do not exceed the soil moisture deficit and replenish the water table during the course of a storm. Nor does rainfall occur with sufficient intensity and duration to form a perched water table within the root zone. Yet streamflow in the watershed responds quickly to every one of these storms.

Large, Natural Autumn Storms

In the early part of October 1967 the soil gradually became wetter, and the water table stood closer to the surface than in the preceding summer months. It was therefore more probable that rainfall would displace soil water in the vadose zone [*Horton and Hawkins*, 1965], causing a response of the water table and consequent subsurface stormflow. Conditions were made even more favorable for this process by adding water to the slope during the testing of an irrigation system and during artificial storms.

In spite of the wet antecedent condition of the hillside, the response of runoff to heavy rains was slight. On October 10, 1967, a 1.35-inch rainstorm with a maximum 30-minute intensity of 0.62 inches per hour (recurrence interval of less than two years) occurred when the water table at well D was only 2.1 feet below the ground surface. Table 2 shows the amounts and lag times of stormflow generated by this rainfall on each of the plots. The total amounts of rain falling on each plot are included for comparison. The data demonstrate that even when the antecedent soil moisture is abnormally high, heavy rains produce a negligible amount of subsurface storm runoff, and that this runoff lags the beginning of rainfall by one or more hours. During the same 10-hour period covered by the data in Table 2, 377 cubic feet of channel runoff were generated between weirs WC-1 and WC-2. Similar results were obtained in other autumn storms.

Another characteristic of the stormflow from this slope was its lack of sensitivity to changes in rainfall intensity, despite the sensitivity of streamflow at the base of the slope. Figure 4 presents a summary of data on rainfall intensity, water-table elevations, and runoff for the 0.70-inch storm of October 18, 1967. This storm occurred on soils that were extremely wet because of irrigations and heavy rains during the preceding two weeks. The water-table depths in wells C, D, and E before the storm were 1.3 feet, 1.35 feet, and 2.7 feet respectively. In spite of the proximity of the water table to the ground surface, only in well D did the water table begin to respond during the first hour of

TABLE 2. Amounts of Rainfall and Stormflow, and the Time Lags between the Beginning of Rainfall and the Initial Response of Flow from each of the Tiles on the Trenched Slope during the 1.35-inch Rainstorm of October 10–11, 1967

	Stormflow,* cubic feet	Stormflow,* inches	Time Lag, minutes
Convex hillside			
Plot 1			
Rainfall	628.	1.35	
Channel 1-1	1.7	0.004	36
Tile 1-2	2.8	0.006	204
Tile 1-3	33.4	0.072	80
Concave hillside			
Plot 2			
Rainfall	1470.	1.35	
Channel 2-1	8.0	0.007	54
Tile 2-2	15.2	0.014	195
Tile 2-3	12.0	0.012	142
Straight hillside			
Plot 3			
Rainfall	679.	1.35	
Channel 3-1	0	0	
Channel 3-2	0	0	
Channel 3-3	1.7	0.003	260

* Stormflow is defined as total flow minus base flow for the 10-hour period from 1900, October 10 to 0500, October 11.

rainfall. Discharge from tile 2–3 followed the same pattern as that of the water-table elevations. It began to increase after channel runoff had declined and did not show the marked sensitivity to changes of rainfall intensity demonstrated by the flow from weir WC-2. Neither overland flow nor flow from the base of the root zone occurred in this storm. The storm produced only 15 cubic feet of stormflow out of the 1516 cubic feet of rain that fell on the three plots.

Large Artificial Rainstorms

Data from natural rainstorms showed that even the concave plot (2) with its steep slope, shallow impeding layer, and unusually wet soil conditions could not produce significant amounts of subsurface stormflow to supply the responsive channel hydrograph in the vast majority of storms that occur on this area. Artificial storms were therefore produced on plots 2 and 3 to study the processes that would occur in rare large storms. The return period of these storms varied from two to greater than 100 years. It is difficult to judge the return period of the antecedent soil moisture conditions, since only one year of soil moisture and groundwater data are available. Weather during that year was normal, however, and conditions before each storm can be roughly compared with those during the rest of the year. The reactions of the plots were different because of the differences in soils and topographic form. Space does not permit presentation of all the data on which the following description is based. For further details the reader is referred to a report by *Dunne* [1969].

On October 25, 1967, a 1.72-inch storm lasting two hours delivered 1902 cubic feet of water to the concave plot (2) at the rate of 15.8 cfm. The return period of this rainfall in the study area is approximately 25 years [*U. S. Weather Bureau,* 1955]. Because of heavy rains and irrigations in the previous month the soil was as wet as it had been during the snowmelt period, which is the wettest time of the year in this area. Before the storm, depths to the water table at wells C, D, and E were 2.1 feet, 1.6 feet, and 2.2 feet respectively.

Measurements of water-table elevations, piezometric head, and soil moisture [*Dunne,* 1969] showed that within half an hour of the onset of rain a perched water table began to develop in plot 2. The water table rose to the surface over the central depression below well E. Runoff data presented in Figure 5 show the marked difference in response of stormflow from the various horizons of the soil. After rain had been falling for 75 minutes, flow from the lower tile (2–3) began to increase slowly from its initial rate of 0.023 cfm to 0.319 cfm two hours after the end of rainfall. Flow from the base of the root zone (tile 2–2) began at the same time as the initial response of tile 2–3. Discharge increased abruptly to a maximum of 0.776 cfm at the end of rainfall and declined more slowly. The flow from the root zone was associated with the rapid rise of the water table into the permeable, sandy horizon at the base of the slope.

A small trickle of water, deposited directly in the channel by the sprinklers flowed from the surface channel (2–1) during the first 65 minutes of the storm. There was, however, no gene-

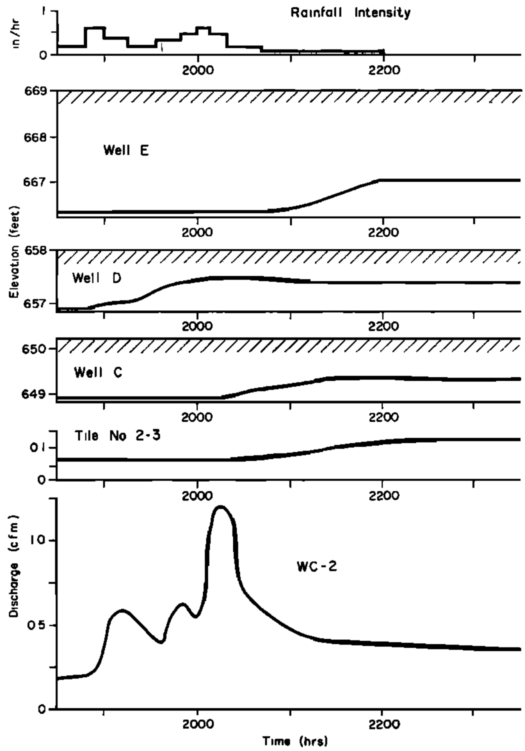

Fig. 4. Rainfall, changes in water-table elevation, and runoff from tile 2-3 and weir WC-2 during and after the 0.70-inch rainstorm of October 18, 1967.

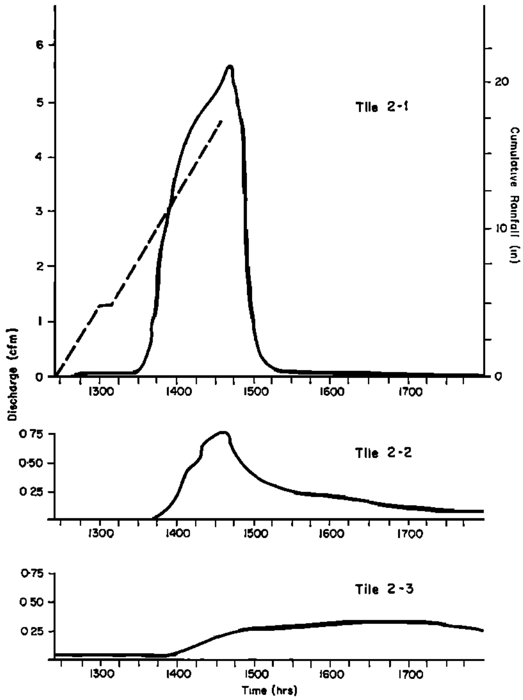

Fig. 5. Discharge from the three tiles draining plot 2 (concave) during and after the artificial storm of October 25, 1967.

ration of Hortonian 'precipitation excess' on the slope as the rainfall intensity did not exceed the infiltration capacity of the soil to produce overland flow. Flow from channel 2–1 suddenly began to increase 65 minutes into the storm. In the 70 minutes from 1330 to 1440 the flow rate increased from 0.027 cfm to 5.615 cfm, and 270 cubic feet of water flowed from the surface channel. Ten minutes after the end of rainfall, the flow began to decline even more rapidly than it had risen. Water emerged from the soil surface over most of the central depression of the plot. The seepage was particularly obvious below slight breaks of slope where the sandy loam thinned.

The water that was measured as overland flow was a combination of 'return flow' from the upper horizon of the soil and of rain that had fallen directly onto the saturated area that developed over a small portion of the hillside in the central concavity of the plot where the water table had reached the ground surface. An attempt was made to estimate the contributions to surface runoff from the two sources mentioned. The area over which water was seen flowing at the ground surface at the end of the storm was mapped. The rate of rainfall onto this area was calculated to yield the contribution of direct precipitation. By the end of the storm 1.364 cubic feet of runoff per minute (24.3% of the peak surface runoff rate) were being produced in this way, while 4.264 cfm were produced by water that had emerged from the soil surface in the central hollow of the concave slope. It is probable that the area covered by overland flow was underestimated, since it was difficult to see some of the thin films of overland flow around the margins of the saturated area. Apart from the possibility of this error, however, the data give values for the separate contributions that are reasonable in the light of similar calculations made for one of the natural storms that produced overland flow (see later).

In the 2-hour period of the artificial storm, plot 3 received 1.94 inches (1096 cubic feet) of water. The return period of a rainfall of this magnitude in the Sleepers River Watershed is approximately 50 years [*U. S. Weather Bureau*, 1955]. In the absence of an impeding layer, a perched water table did not form. The water table varied in depth from 4 to 7 feet in the lower half of the plot and percolation and displacement of water in the unsaturated zone were so slow that the water table did not begin to rise until the end of rainfall. It never reached the ground surface and so no significant stormflow was produced. The only source of runoff was that from the lower tile, which rose to a peak of 0.143 cfm nine hours after the end of the storm.

Overland flow from 8% of the irrigated area completely dominated the pattern of runoff production on the hillside during the 1.72-inch artificial storm, as Figures 6 and 7 show. Although some of the flow had subsurface origins, and may be classified as 'interflow' according to the definition of *Linsley et al.* [1949], the fact that it ran over the surface was of major impor-
and calculation of velocities of subsurface flow
tance. Measurement of overland flow velocities showed that on emerging from the soil surface, the speed of the water increased by a factor of 100 to 500. This allowed a much larger quantity of water to be supplied to the stream channel than could have been removed by subsur-

face stormflow. The establishment of surface runoff on this and other slopes (during other rainfalls), in effect, caused an increase in the drainage density of the watershed which drastically reduced the distance which water had to travel through the soil before it reached the surface. Since velocities of subsurface flow are so slow, even on slopes as steep and permeable as the one described in this report, the distance that water must travel through the soil is an important control of storm runoff production. If the rain had been insufficient to raise the water table to the surface, little storm runoff would have been produced on this slope. Even when the permeable A-horizon was saturated throughout its depth, it could only convey runoff to the channel at the rate of 0.016 cfm per foot of channel. This figure is small by comparison with actual rates of channel runoff production in this 60-acre watershed. Any increase in the efficiency of the evacuation of water would therefore have a large effect on runoff production.

On October 16, 1967, a 1.14-inch artificial storm lasting two hours with a return period of three years yielded similar results. Figure 8 shows that overland flow dominated the storm hydrograph. Soil moisture profiles and water-table elevations showed that the processes were the same as those observed on October 25. The differences in timing and in peak flow rates could be explained in terms of differences of antecedent conditions and rainfall intensity. A 2.41-inch storm lasting two hours was produced on July 17, 1968. Although the return period of this storm is greater than 100 years and antecedent moisture conditions were wetter than normal for early summer, very little storm runoff was produced. A perched water table developed in plot 2, but only intersected the ground surface over a small area near the base of the concavity. By the end of the storm the rate of surface runoff from channel 2–1 was rising rapidly, but the peak rate was only 0.802 cfm. The slope seemed to have just attained the threshold condition at which further rainfall would produce large amounts of runoff. A natural storm occurring immediately after the irrigation confirmed this. On October 5, 1967, an artificial storm occurred in which the important threshold of saturation was not reached. The 1.03-inch storm lasted for one hour on soil conditions that were wetter than normal for early autumn. The amounts of stormflow produced by this and the other artificial storms described are listed in Table 3.

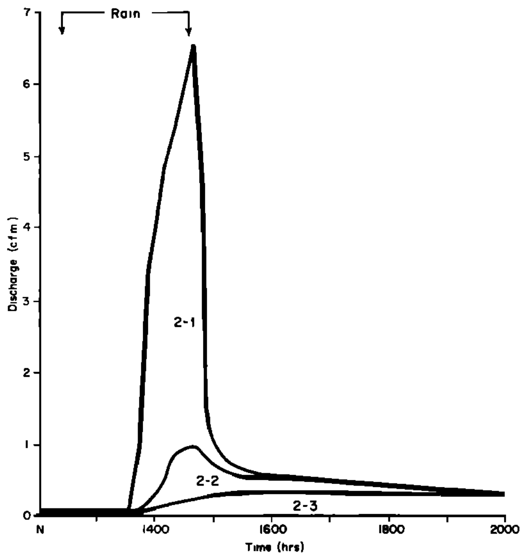

Fig. 6. Combined hydrograph of flows from plot 2 (concave) during the artificial storm of October 25, 1967.

Natural Storms Following Artificial Storms

Two of the artificial storms described previously were followed within a short time by large natural storms. These storms were of shorter duration and higher intensity than the artificial storms, and they occurred on antecedent conditions that were much wetter than those normally encountered by the intense rains of summer. Figure 9 shows the response of runoff at various levels in plot 2 during a 0.88-inch rain that occurred 10 hours after the artificial storm of October 25, 1967. Runoff rates and water-table elevations were receding after the artificial storm, but well readings showed that the water table rose to the surface over the central concavity before the main burst of rain. Overland flow again dominated the hydrograph (Table 4).

One-half hour after the end of the 2.41-inch artificial storm of July 17, 1968, 1.83 inches of rain fell in two bursts; one burst of 3.15 inches per hour lasted for 21 minutes, and the second burst of 2.75 inches per hour lasted for 13 minutes (Figure 10). The return period of this

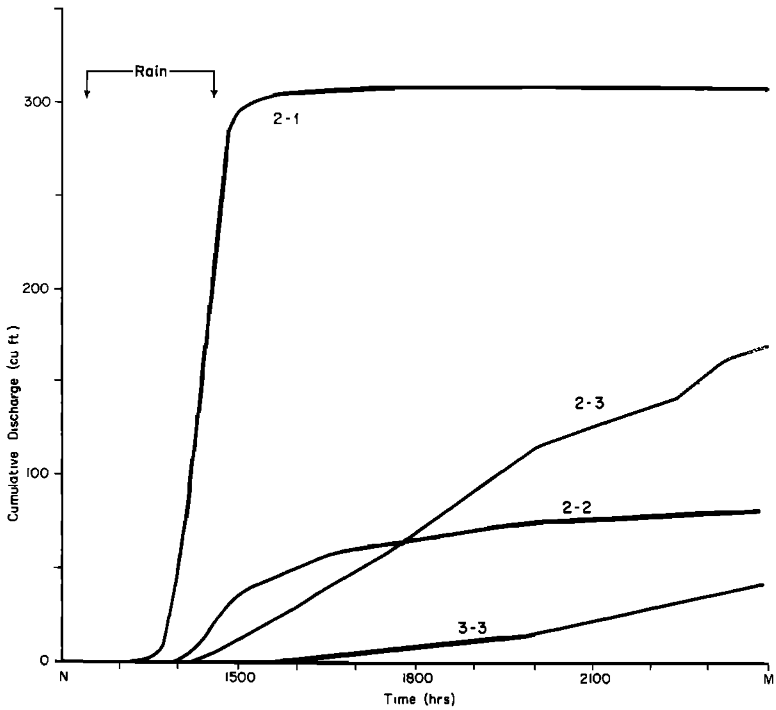

Fig. 7. Cumulative flow for the tiles producing runoff during and after the storm of October 25, 1967.

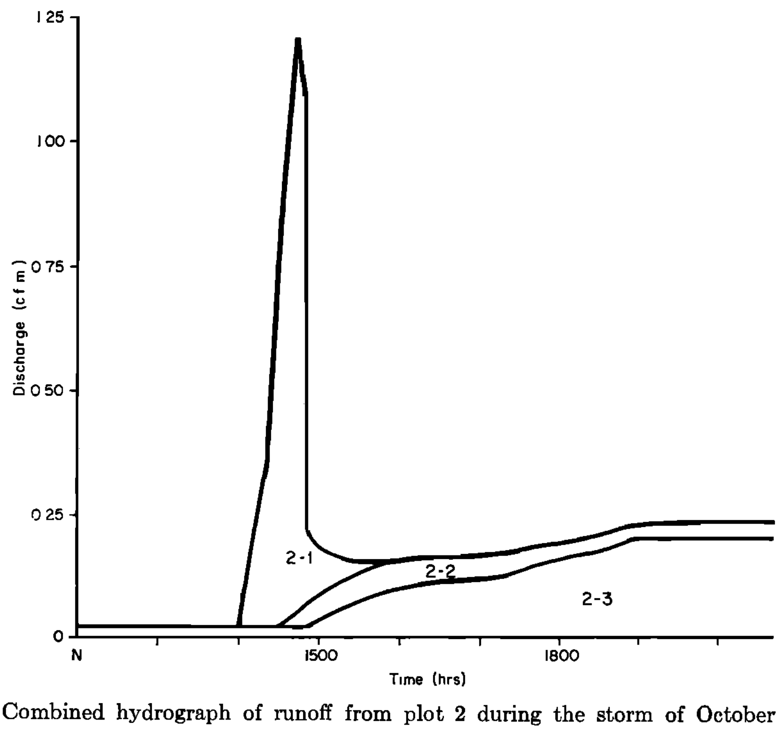

Fig. 8. Combined hydrograph of runoff from plot 2 during the storm of October 16, 1967.

TABLE 3. Amounts of Stormflow in Cubic Feet Produced on Plots 2 and 3 in Artificial Rainstorms*

Source	October 5, 1967	October 16, 1967	October 25, 1967	July 17, 1968
Plot 2				
Rainfall† Runoff	1139	1261	1902	1462
Channel 2-1	0	32	309	24
Tile 2-2	0	14	78	?
Tile 2-3	11	46	123	2
Total	11	92	510	26
Plot 3				
Rainfall† Runoff	494	536	1096	1109
Channel 3-1	0	0	0	0
Tile 3-2	0	0	0	0
Tile 3-3	1	6	21	0
Total	1	6	21	0

* Stormflow is defined as total flow minus base flow for the period from the beginning of rainfall until six hours after the end of rainfall in the case of the October storms. The stormflow period for the July storm is from the beginning of rainfall until one-half hour after the end of rainfall, when a large natural rainstorm began.

† See text for amounts of rainfall expressed in inches.

storm is approximately 50 years. If the natural and artificial storms are considered as one event, the return period for the combined storm is several hundred years [*U. S. Weather Bureau*, 1955]. Antecedent conditions were abnormally wet for an intense summer storm. The natural rainstorm reinforced the effect of the preceding irrigation on the outflow from tile 2–3. Total stormflow from the lower part of the soil profile, however, was still negligible. Tile 2–2 was leaking during this storm so that no runoff could be collected. Previous irrigations when the root zone was fully saturated, however, had shown that a peak discharge rate of no more than 0.6 cfm to 0.8 cfm could be expected from tile 2–2.

Surface runoff from plot 2 reached the highest level recorded during the study, increasing from 0.060 cfm at the beginning of the storm to 14.305 cfm at the end of the first intense pulse of rain 30 minutes later (Figure 10). After a rapid recession, runoff increased from 0.802 cfm to 12.934 cfm in the second burst of rain. Overland flow was again produced by a combination of return flow and direct precipitation onto the saturated area of the hillside. Mapping of the saturated area allowed a rough calculation of the contributions from both sources. At the end of the first period of intense rain the approximate rate of runoff produced by direct precipitation was 8.289 cfm, while return flow contributed runoff at the rate of 6.016 cfm. By the end of the second burst of rain the contributions were 7.220 cfm from direct precipitation and 5.714 cfm from return flow. The contribution from direct precipitation was controlled by the intensity of the rain and the area of the soil that had become saturated. As this saturated area expanded throughout the storm, the area of the slope over which water could emerge from the ground surface and run quickly downslope increased, resulting in an increase of the contribution to the hydrograph from this source.

In both natural storms, runoff from plot 3 was negligible. Water-table elevations were 5 to 10 feet below the ground surface, and although the water table and piezometric levels rose sharply towards the end of each storm, little subsurface stormflow was measured. The data demonstrated the extreme damping effect of unsaturated percolation and of storage and transmission in the groundwater body. Overland flow did not occur because the water table did not rise to the ground surface. Consequently only a few cubic feet of stormflow were produced.

DISCUSSION

The data collected in this Vermont watershed do not support some of the claims that have

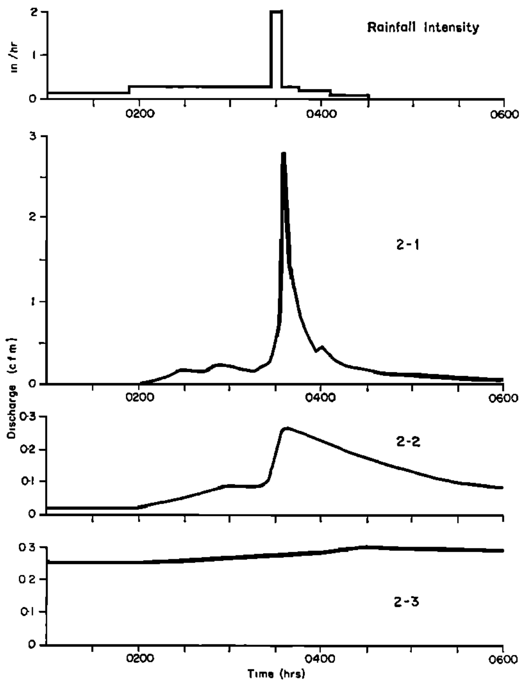

Fig. 9. Rainfall and runoff data from plot 2 for the 0.88-inch natural storm of October 26, 1967.

been made in the recent literature on subsurface runoff production in humid areas. Subsurface stormflow, as defined by the writers quoted in the introduction to this paper, was not an important contributor to the storm hydrograph in this watershed, despite soil conditions that are generally considered ideal for such a mechanism. A similar study carried out on a shallow, poorly drained soil in the same catchment [*Dunne*, 1969] and in another basin in the same area confirmed this conclusion.

On the hillside described in this report, subsurface stormflow produced virtually no runoff during natural storms, in spite of the fact that in the autumn of 1967 the water table was only one or two feet below the ground surface along the central concavity. Even when the water table was so close to the surface, there was a considerable volume of pore space available for storage of rainfall, and very little soil water was displaced into the stream. Storms that generally occur in this region are not of sufficient magnitude to fill this storage capacity and contribute to the water table at rates sufficient to produce large amounts of storm runoff. Even extreme events such as the 3.81-inch rainfall of July 17, 1968, failed to produce stormflow from the straight hillside. On the concave plot, however, the combination of a shallower water table and an impeding layer did allow the generation of subsurface stormflow during irrigations. The runoff produced, however, was remarkable more for its small magnitude and late response than for its importance to total storm runoff. The only runoff-producing mechanism which approached channel runoff in amount and sensitivity was overland flow on a small concave portion of the hillside that comprised 5% to 10% of the total area of plots 2 and 3. This runoff was produced by a combination of return flow and direct precipitation onto the saturated area. Only when water was released from the extreme damping effect of unsaturated and saturated subsurface percolation by breaking through the ground surface could it contribute to channel runoff at a significant rate.

The data on the relative unimportance of subsurface stormflow from the hillside are surprising in view of some recent papers on this subject. *Whipkey* [1965] measured subsurface flow from a 36-inch-deep sandy loam forest soil in Ohio. Although Whipkey did not claim as much, the results he obtained have been accepted as proving that subsurface stormflow is a major contributor to stream hydrographs.

TABLE 4. Amounts of Stormflow in Cubic Feet Produced on Plots 2 and 3 by Natural Rainstorms Following Artificial Rainstorms*

	October 26, 1967	July 17, 1968
Plot 2		
Rainfall†	973	2023
Channel 2-1	64	346
Tile 2-2	46	?
Tile 2-3	45	40
Total	155	386
Plot 3		
Rainfall†	511	1114
Channel 3-1	0	19
Tile 3-2	6	43
Tile 3-3	37	25
Total	43	87

* Stormflow is defined as total flow minus base flow for the period from the beginning of rainfall until six hours after the end of rainfall.

† See text for amounts of rainfall expressed in inches.

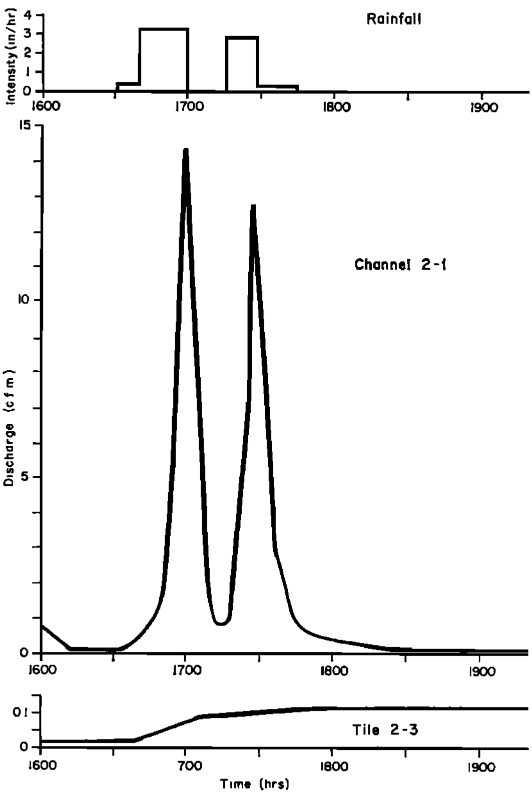

Fig. 10. Rainfall and runoff data for plot 2 (concave) in the natural storm of July 17, 1968.

Kirkby and Chorley [1967, p. 8], for example, claim that Whipkey's data show that '. . . throughflow is capable of producing runoff peaks in river hydrographs.' A closer look at Whipkey's data and comparison with results from the present study throw considerable doubt on the role of subsurface stormflow from hillsides as a major contributor to hydrograph peaks. The available evidence, in fact, suggests that water remaining below the soil surface on its way down hillsides to a stream contributes only a small part of the water supplying the peak of a river hydrograph.

No data are available on the behavior of the stream at the base of the slope Whipkey studied. Nor are any data available on runoff produced on the slope during natural storms. No indication is given in his paper of the extent to which his 'wet' and 'dry' antecedent conditions or the magnitude of his artificial rainfalls represent conditions under which river hydrographs are formed in that region. The area, however, is not too different from the present experimental area to invalidate comparisons. The hillside described in the present paper proved to be more favorable for subsurface stormflow than the one Whipkey studied. The slope used in the present study was much steeper and the impeding layer of the concave plot was generally at a shallower depth. Although under pasture at the time of the study, the slope had been covered by pine woodland 30 years before, and the A-horizon of the soil had an open structure interlaced with root holes and worm holes. The saturated hydraulic conductivity of the A-horizon (estimated from field data by the same method Whipkey used) was greater (13.5 inches per hour) than the one he calculated for the Ohio slope (11.3 inches per hour).

The total amount, peak rate of flow, and responsiveness of subsurface stormflow from the concave slope described in the present study were equal to or greater than those described by Whipkey. On the Ohio slope, a 4-inch storm with an intensity of two inches per hour occurring on a soil profile that had drained from saturation only a few days previously, did not begin to yield runoff until one-half hour after the end of rainfall. The peak flow rate from this storm was 0.016 cfm per foot of hillside. Total runoff in the 24 hours following this storm amounted to only 10% of applied rainfall. On the concave plot used in the present study, a 2-hour long storm of only 1.72 inches also resulted in a peak flow rate of 0.016 cfm per foot of hillside. Ten percent of rainfall left the hillside in the 6-hour period following the end of the storm. The delay before the onset of this flow was smaller than in the example given by Whipkey.

The comparison of results listed above shows that subsurface stormflow on plot 2 in the present study was larger and more responsive than the study described by Whipkey. Comparison of this runoff with channel runoff from the 60-acre watershed, however, showed that subsurface flow from the hillside was a relatively small and rare contributor to the stream hydrograph. The reaction of flow from the trenched hillside during the fall of 1967 when the water table was only 1.3 feet below the soil surface, suggests that even at the base of a hillside where the water table is close to the surface, reaction of the saturated zone was slow by comparison with that of streamflow. Channel runoff data incorporated into another report [*Dunne*, 1969] confirm this.

Significant amounts of stormflow were produced on the hillside by return flow and by direct precipitation onto the saturated area that developed over a small portion of the hillside where the water table reached the ground surface. Although the return flow had the same origin as the flow that remained below the soil surface, its emergence from the ground caused it to have features that were lacking in its subsurface counterpart. The first of these was its greater velocity, which was 100 to 500 times greater than the calculated velocities of subsurface flow. This allowed more water to travel from a larger contributing area in the time available than did the velocity of subsurface flow. The second important feature of the return flow was its greater sensitivity to fluctuations of rainfall intensity, which could be accounted for by the short distance of flow beneath the soil. Only when the water table intersected the soil surface and established conditions suitable for overland flow could large areas of the slope supply water to the channel without the impedance of many feet of subsurface flow. The generation of stormflow by direct precipitation onto the saturated area was also sensitive to fluctuations of rainfall intensity and to the duration of the storm. At the end of rainfall, water drained from the surface and upper few inches of the soil within minutes, and the rate of runoff was drastically reduced. A similar process was observed during artificial storms on an area of shallow, poorly drained soils in the same watershed. In these soils subsurface stormflow contributed between 1% and 5% of the peak runoff rate, while direct precipitation and return flow each contributed almost 50% of the peak rate.

CONCLUSIONS

The findings of this study are in general agreement with the 'partial-area' concept of storm runoff production [*Betson*, 1964; *Ragan*, 1967]. Significant amounts of storm runoff were only produced on small areas of hillside where the water table reached the surface. Subsurface stormflow occurred in large storms but was not an important contributor to total storm runoff despite conditions favorable for its existence. The importance of an area of hillside as a producer of storm runoff depended on its ability to generate overland flow. This latter was the only form of runoff that occurred in sufficient amounts to make a substantial contribution to channel runoff during storms. Furthermore, it was the only form of runoff which exhibited sensitivity to changes of rainfall intensity in a manner similar to channel runoff. A comparison of data from the two irrigated plots also confirms the 'partial-area' concept of storm runoff production.

Acknowledgment. This study was made while the authors were employed at the USDA Sleepers River Experimental Watershed, Danville, Vermont.

REFERENCES

Betson, R. P., What is watershed runoff?, *J. Geophys. Res., 69*(8), 1541–1551, 1964.

Dunne, Thomas, Runoff production in a humid area, Ph.D. dissertation, Johns Hopkins University, Baltimore, Maryland, 1969.

Hack, J. T., and J. C. Goodlett, Geomorphology and forest ecology of a mountain region in the Central Appalachians, 66 pp., *U. S. Geol. Survey Prof. Pap. 347*, 1960.

Hewlett, J. D., and A. R. Hibbert, Factors affecting the response of small watersheds to precipitation in humid areas, *Proc. Int. Symp. Forest Hydrol.*, Pennsylvania State University, University Park, 1965.

Horton, J. H., and R. H. Hawkins, Flow path of rain from the soil surface to the water table, *Soil Sci., 100*(6), 377–383, 1965.

Horton, R. E., Erosional development of streams and their drainage basins, *Geol. Soc. Amer. Bull., 56*, 275–370, 1945.

Kirkby, M. J., and R. J. Chorley, Overland flow, throughflow and erosion, *Int. Assoc. Sci. Hydrol. Bull., 12*(2), 5–21, 1967.

Linsley, R. K., M. A. Kohler, and J. H. L. Paulhus, *Applied Hydrology*, 689 pp., McGraw-Hill, New York, 1949.

Ragan, R. M., An experimental investigation of partial area contributions, Berne Symposium, International Association of Science and Hydrology, 1967.

Troeh, F. R., Landform parameters correlated to soil drainage, *Soil Sci. Soc. Amer. Proc., 28*, 808–812, 1964.

U. S. Weather Bureau, Rainfall intensity-duration-frequency curves for selected stations in the United States, Alaska, Hawaiian Islands and Puerto Rico, 53 pp., *Tech. Pap. 25*, 1955.

Whipkey, R. Z., Subsurface stormflow from forested slopes, *Int. Ass. Sci. Hydrol. Bull., 10*(2), 74–85, 1965.

(Manuscript received August 6, 1969; revised December 29, 1969.)