THESIS

STORM RUNOFF CHARACTERISTICS OF THREE SMALL WATERSHEDS IN WESTERN OREGON

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY Loyd O. Barnett, Jr.

ENTITLED STORM RUNOFF CHARACTERISTICS OF THREE SMALL WATERSHEDS IN WESTERN OREGON

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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Permission to publish this report or any part of it must be obtained from the Dean of the Graduate School.

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INTRODUCTION

The science of hydrology, though young, is rapidly increasing in importance as demands on the water resources of this and other countries accelerate. Much has been learned about water and the hydrologic cycle, yet many basic questions remain unanswered. The complexities and interrelationships within the hydrologic cycle defy simple measurement and analysis and such categories as precipitation, infiltration, runoff, and ground water are so broad as to merit voluminous literature on each. This study is concerned primarily with runoff -- yet it takes into consideration precipitation, infiltration, and ground water, each in some detail.

It is widely recognized that there are a number of factors affecting the runoff from any watershed. These factors differ from watershed to watershed and even adjacent watersheds invariably have some difference between them. Besides the normally expected variations in precipitation and other climatic factors, such things as slope and topography, geology, soils, vegetation, drainage, size, and shape of watersheds vary widely and in doing so vary their effects on hydrologic characteristics.

In recent years much work has been done by research scientists in attempting to evaluate and give quantitative expression to the effect which the above-cited and other factors have on the end product -- water received at the mouth of a watershed. Many useful methods and techniques of analysis have been developed which have allowed a better understanding of the processes involved as well as giving a basis for more accurate prediction of runoff, its volume and timing, etc. However, application of research techniques and findings has been hampered by the fact that the hydrologist must usually start with runoff, the integrated product of many factors, and work backward in an attempt to determine how these factors have contributed to the process of converting precipitation into streamflow.

In watershed management research it is practically impossible to control all of the factors involved in order to study the effect of one particular factor. Rather the researcher must observe and measure all apparently significant factors and attempt to account for their effects and interactions. This is no simple task for many are difficult to measure and express quantitatively. The probability of accurate research and correct interpretation is consequently enhanced when watersheds with several similar characteristics are available for study.

Of necessity, the hydrologist has often turned to statistics as a tool to evaluate these factors. Such analysis usually requires data from a large number of watersheds or else a large number of events from one or several watersheds. (1)

Problem

This study is an attempt to describe and compare the runoff characteristics for three experimental watersheds in the H. J. Andrews Experimental Forest, Blue River, Oregon, during winter, or wet season, storm periods, as virtually all floods and high flows occur during the prolonged wet season. It also attempts to explain how several watershed characteristics may affect differences in the resultant hydrographs of storm runoff.

On the western slopes of the Cascade Mountains large unburned areas which have heretofore remained inaccessible are now being opened up by logging. The predominant practice of patch clear cutting and the accompanying vegetative changes undoubtedly produce some hydrologic changes in the immediate area. Research foresters are presently trying to evaluate these hydrologic changes brought about by logging and road building. The usual method is to use a control watershed -- a nearby undisturbed watershed resembling as closely as possible the experimental watershed -- and, after a period of calibration, attempt to measure and attribute the differences brought about by harvesting practices. A better knowledge and understanding of the hydrologic interrelationships of watersheds in their natural state would be useful in more accurately evaluating effects of management practices.

This study takes data from a nine-year period before any major treatment was initiated. Further studies will be conducted by the Pacific Northwest Forest and Range Experiment Station following a period of treatment. Several techniques of hydrograph analysis developed in other areas and under somewhat different conditions have been tried. Prominent among these is the unit hydrograph, which wasoriginally intended as the principal means of comparison of storm runoff characteristics. However, during this study it was found that the unit hydrograph technique did not lend itself readily to analysis of the long period, low-intensity storms which are of primary concern in these watersheds. Therefore, several other methods were tried for characterization of storm runoff characteristics.

Because of the small number of watersheds and the few storms analyzed for each watershed, no statistical analysis is used. Rather, most results are presented graphically or in tabular form.

REVIEW OF LITERATURE

Subsurface Flow and Ground Water

While much has been written on runoff and its correlation with precipitation, antecedent condition, watershed characteristics, etc., only a small portion of this literature has been devoted to the actual mechanics of the transformation of rainfall into quickly available streamflow. Since Horton put forth his theory of infiltration capacity (22), most studies have been concerned with surface runoff. Some have taken ground water into consideration, though usually for the purpose of more accurately determining surface flow. Though subsurface flow, a component of runoff which is neither surface runoff nor normal ground water, has often been recognized, it has been studied relatively little and attempts to isolate and measure it have been very few. As an example, Horner (21) in a discussion of the role of land in transforming rainfall into streamflow includes subsurface detention and subsurface storage among the many factors which affect this process but they are treated qualitatively and quantitative determination is restricted to infiltration and surface runoff.

C. R. Hursh (24) was one of the first to recognize and describe the phenomenon which he defined as "subsurface-stormflow,"

> "...that portion of the stormflow which infiltrates into the surface-soil but moves away from the area through the upper soil horizons at a rate much in excess of normal ground-water seepage."

He stated that although surface infiltration rates might exceed rainfall intensity, lower permeability of subsurface profiles would cause a lateral movement in the upper soil much more rapid than ground water flow but not as fast as flow over the ground surface.

Later, Hursh and Brater (26) working on a 40-acre watershed at the U. S. Forest Service Coweeta Hydrologic Laboratory in North Carolina, tested for subsurface stormflow by plotting 1/4 to 1 hour depletion ratios -- ratio of flow at time, t, to flow 1/4 or 1 hour earlier -- following the cessation of channel precipitation flow and found them to be much higher than those known to be true of surface runoff. They concluded that at the sharp break in the depletion ratio curve a distinction could be made between that part of subsurface flow which behaves more nearly like channel precipitation and that part which resembles ground water flow. Several ground water wells located near the stream peaked at about the point of break in the depletion ratio line, then followed a recession similar to that of the stream hydrograph. In discussion they suggested that in storms with negligible surface runoff stormwater came from:

1) Channel precipitation.
2) Contributions from areas of normally shallow water tables located in close proximity to the stream and occurring in soil profiles quickly saturated.
3) Storm water moving through layers of porous soil material and under a considerable gradient, reaching the stream during the period of storm hydrograph.

4) Storm seepage from large bodies of colluvial or other porous soil material which has filled in along streambanks.

5) Seepage as a result of piling up a high water table in talus slopes in close feeding relation to a surface stream. These are fed by rapid seepage or percolation from steep slopes and would contribute to the upper portion of the recession curve.

Barnes (2), (25) stated that streamflow could be separated into components of surface flow, storm seepage (subsurface flow), and base flow by means of a semi-log plot of the recession curve. He found that each of these components had a distinctive and constant depletion factor and their recession curves were of the form:

$$Q = Q_o K^t$$

where Q and Q_o are discharge at two instants separated by the time period t, and K is a constant or depletion factor.

In one of the few recorded measurements of subsurface flow, Hursh and Hoover (28) measured flow at 2" and 12" depths on runoff plots in the southern Appalachians. Under forest cover they found much more flow in the 2-12" layer than in the 0-2" layer, but on abandoned cultivated land flow was greatest in the surface layer or "plow depth." They concluded that the most important soil hydrologic characteristics were those concerning porosity and included detention and retention storage capacity and the transmission rate of water.

Working with volcanic ash soils in northern New Zealand, van't Woudt (45) measured lateral movement on a 32 degree slope with "windowed" vertically oriented lysimeters. He found greatest lateral movement high on the slope and concluded that subsurface flow was a result of three factors which tended to obstruct rapid vertical infiltration at some depth in the soil profile. These factors are:

1) A relatively thin layer at the surface which has become wetted during the course of a rainstorm, on top of still unwetted soil.
2) A buildup of moisture in the A horizon due to a low infiltration capacity of the B horizon as compared with the A which results in lateral flow through that layer to the foot of the slope.
3) A similar buildup and lateral flow where application of water to the surface is not rapid enough to increase the pressure potential sufficiently for water to move from a fine top soil into underlying coarser soil.

Riesbol (34) reported the results of studies at Coshocton, Ohio in which the downward rate of percolation was measured in eight foot deep lysimeters. He found that the lag between center of mass of precipitation and center of mass of the percolation hydrograph was 16-29 hours. He went on to describe a method which could be used to compute lag or time between infiltration and reappearance as runoff using recession, storage-discharge, and ground water level-discharge curves.

Hursh and Fletcher (27) working on a 7-acre watershed at Coweeta analyzed deep soil as a reservoir similar to a ground water aquifer and had considerable success in correlating ground water well elevations with hydrograph peak rates and times. By comparing stream and ground water well hydrographs they computed detention storage opportunity within each successive foot of saturated soil profile as the ground water declined. Using laboratory determined macro-porosity data they calculated that an aquifer of 2 acres in size was necessary to maintain flow.

In 1944 Hursh (25) reviewed the available literature on the subject and pointed out the need for better methods of separating the components of flow on the hydrograph. He suggested two possible explanations for subsurface flow:

1) "...rapid spilling of the over-charged ground-water aquifer through extremely porous upper soil-horizons."
2) "...relatively shallow penetration of storm-water into porous upper soil-horizons and its rapid lateral flow with the slope to natural outlets."

Several writers have suggested that much of what is often termed subsurface flow is actually ground water flow greatly increased during storm periods. Horton (23) says that ground water stage reaches a maximum when inflow equals discharge and the discharge approaches a theoretical maximum equal to rain intensity. Topographic features such as the intersection of the water table by gullies may lower the stage to which it might otherwise rise, and runoff ascribed to the "soil becoming saturated" may actually be due to ground water inflow having become equal to outflow. In support of the role of ground water during storms, Wenzel (46) states that ground water flow may react very quickly to precipitation and may reach a peak of 10-20 times normal base flow. A small rise in ground water level along a reach of stream will cause a large increase in cross section of aquifer discharging into the stream. In addition, subsurface flow from up slope may cause a sharp increase in the slope of the water table at the stream edge.

Roessel (35) also believed that ground water was often more important in producing storm runoff than subsurface flow and suggested that ground water might be affected almost immediately by rainfall (late in a storm) through a change in hydrostatic pressure.

> "When the field moisture deficiency is satisfied, a drop of rain does not need to traverse the zone above the capillary fringe to exert its influence. Its added pressure at the top will permit a drop at the bottom to reach the fringe and make the water table rise."

He reanalyzed the classic Swiss experiments at Rappengraben and Sperbelgraben and suggested that the reason Rappengraben was more sensitive to rainfall and yielded greater runoff from an equal amount of rain was because it had more and larger springs -- thus water flowed a shorter distance to an outlet -- rather than because of a difference in vegetative cover. To support his hypothesis he ran laboratory tests on sand aquifers of different lengths. The shorter aquifers were found to be more sensitive to water application and had a much lower detention capacity.

Though sustained streamflow from large ground water aquifers has been demonstrated in many areas, it is difficult to visualize extensive water tables existing on very steep slopes as are found in many mountain watersheds. Yet base flow continues through prolonged dry periods on many such watersheds, with a low rate of recession. Such is the case at Coweeta (and at the H. J. Andrews). In order to test the theory that this flow could be sustained through long, slow drainage of soil moisture, Hewlett (17) constructed an artificial soil profile 32' long on a 40 degree slope. The soil was saturated with water and allowed to drain to a water table at the foot of the slope constructed to simulate a stream bed. Water continued to drain from this profile for 71 days. Though most of the discharge came during the first part of the period (20% in the first three days), the discharge during the last 50 days was equivalent to a rate of 0.3 csm or about the order of magnitude of observed minimum flows at Coweeta.

Unit Hydrograph

Since Sherman (38) first put forth the concept of the unit hydrograph in 1932 it has become an almost universally accepted theory and has received wide application. Bernard's addition of the distribution graph (5) greatly increased its usefulness and made possible comparison of unit hydrographs from different size watersheds through expression of runoff volumes as percent of total runoff. Several general dimensionless hydrographs have been developed on a regional basis and successfully used to generate synthetic unit hydrographs (9)(31)(4).

Many modifications of the unit hydrograph have been made in order to widen its range of applicability. Though originally designed for large watersheds on which daily precipitation records could be used, several early authors tested it on small watersheds (e.g., less than 10 square miles) and concluded that where rainfall intensity records were available the unit hydrograph was a valuable tool for the analysis of surface runoff (7)(16). Determination of the unit hydrograph as originally outlined is dependent upon having a relatively short storm which is uniform in both time and areal distribution -- the storm duration must not exceed the period of rise or time of concentration. Often no such storm is available and it is necessary to develop the unitgraph from a long period complex storm. Several techniques have been developed for this purpose including trial and error (8), least squares (40), and "progressive addition" (3). Linsley, Kohler, and Paulhus (30) outline one of the more common methods of determination. This was the principal method attempted in this study.

Because of its widespread popularity and usefulness, the limitations of the unit hydrograph have sometimes been overlooked. Barnes (3), in discussing several of the assumptions on which it is based, states that a large percentage of volume treated as surface runoff is actually interflow or subsurface flow, and that the time base is not constant for unit storms of different runoff volumes. Hawkins (15) points out that it falls short on the assumption that the entire watershed is contributing runoff.

Effect of Watershed Characteristics

In addition to its use in prediction of flood runoff and design storms the unit hydrograph has served as a useful tool to characterize storm runoff from given watersheds and relate it to measurable watershed characteristics. The most widely used expressions of runoff are peak flow -- in csm or distribution percentage for the peak period -- and some expression of the time lapse between rainfall and runoff, i.e., lag, time of concentration, period of rise, etc. Variously defined units of lag have usually been related to watershed size, shape, and channel slope. In a study of watersheds in the Appalachian Mountains, Snyder (39) found that basin lag, which he defined as time from centroid of rainfall to the hydrograph peak, could be expressed by the formula

$$t_p = C_t(LL_c)^{0.3}$$

where t_p is lag in hours, L is length of the main stream from outlet to divide in miles, L_c is distance from the outlet to a point on the stream nearest the centroid of the basin, and C_t is a basin constant. He then used lag and area to determine peak flow. Lag was found to be affected by storm characteristics, i.e., variations in time and areal distribution.

Taylor and Schwarz (41) related unit hydrograph lag and peak flow to duration of rainfall excess and to the watershed characteristics of length of main stream, length to centroid of area, and channel slope.

Hickok, Keppel, and Rafferty (18) analyzed a number of hydrographs from 14 small watersheds in the southwest and found lag time to correlate best with area, average landslope, and drainage density. Lag time and time of rise varied considerably and it was concluded that lag time gave a much more reliable index of watershed influence, being less affected by rainfall intensity and duration.

In its hydrology handbook the Soil Conservation Service (44) estimates lag empirically as 0.6 times the time of concentration. Time of concentration is determined either by analysis of the hydrograph recession or calculated from length and slope of the main stream.

Most of these determinations have been empirical in nature and resultant formulas included constants which are applicable mainly to areas of similar geology and climate, thus limiting their use in other areas.

The synthesis of dimensionless hydrographs through the use of watershed parameters has come into quite common usage. However, Gray (14) criticizes the validity of the common means of relating unit hydrographs to topography and other watershed characteristics because of the interrelationship of the parameters usually used under the assumption that they are independent. For example, L and L_c which are often used in combination are related to each other and to area. When regional influence was given consideration he found that the slope of the main stream could also be correlated with these three factors. In a study of 340 drainage basins in the northeast, Langbein (29) confirmed some of these relationships and also found that drainage density usually increased with average land slope, and that steep channel slopes were usually associated with steep land slopes.

In a study at Coweeta, Hoover and Hursh (19) found that higher elevation watersheds, which had steeper slopes and shallower soils, produced much higher peaks than did lower elevation watersheds which had generally gentler slopes and deeper soils (68-167 csm as compared to 22-32 csm).

Other Methods of Analysis

In recent years several writers have attempted to represent the hydrograph of runoff with a mathematical formula. The advantages of such a formula in characterizing runoff are obvious. Edson (10) used a two-parameter equation in which peak discharge and time of peak are determined from watershed characteristics. In a refinement of this method Reich (33) took 47 hydrographs from 14 watersheds and fitted a three-parameter mathematical model to them. Multiple regressions were then developed for predicting each of the three hydrograph parameters from storm and watershed characteristics and antecedent moisture.

The recession curve of a hydrograph after precipitation has ceased is made up of depletion from storage and as such should reflect watershed characteristics. It was through analysis of this recession curve that Barnes (2) suggested separation of the three components of flow. In a comparison of snowmelt streamflow from the Fool Creek and East St. Louis Creek watersheds of the Fraser Experimental Forest in north-central Colorado, Goodell (13) suggested comparison of the recession curves as a means of calibration prior to treatment of one watershed. In a later study on the same watersheds, recession analysis was used to separate individual daily contributions to stream flow and to determine whether base flow had been affected by management practices (12).

Many graphical methods have been used to compare runoff characteristics between watersheds or between time periods -- usually before and after treatment -- on a single watershed. These are fairly simple to carry out and give a visual indication of similarities and differences. The Tennessee Valley Authority has utilized a number of these methods in evaluation of land treatment effects on watershed hydrologic characteristics (42)(43). Among these are: peak discharge vs. runoff, surface runoff vs. precipitation and antecedent moisture, and percent runoff vs. time. Horton (22) and Horner (20) have used the technique of plotting mass precipitation and mass runoff on the same time scale in determining watershed infiltration capacity from the hydrograph.

METHODS AND MATERIALS

Study Area

The study was conducted on experimental watersheds #1, #2, and #3 of the H. J. Andrews Experimental Forest which is located approximately 45 miles east of Eugene, Oregon as shown in Figure 1. The experimental forest is located on a tributary of the McKenzie River which in turn flows into the Willamette River near Eugene. The H. J. Andrews Experimental Forest was established in 1948 for the study of forest and watershed problems associated with the conversion of mature and overmature Douglas-fir and upper-slope (mountain hemlock-noble fir) forests to productive young-growth stands. A number of studies covering a wide variety of problems in forest and watershed management are presently being carried out by the Pacific Northwest Forest and Range Experiment Station in cooperation with the Willamette National Forest.

The three experimental watersheds were chosen for studies of the effect of logging on streamflow and sedimentation. Trapezoidal flumes were installed in 1952 and all three watersheds remained in an undisturbed state until 1959 when roads for logging and access purposes were constructed on Watershed #3. Further treatment planned is as follows: Watershed #2 will be held in an undisturbed condition as the control. Watershed #3 will be logged by the standard staggered-setting system as practiced on National

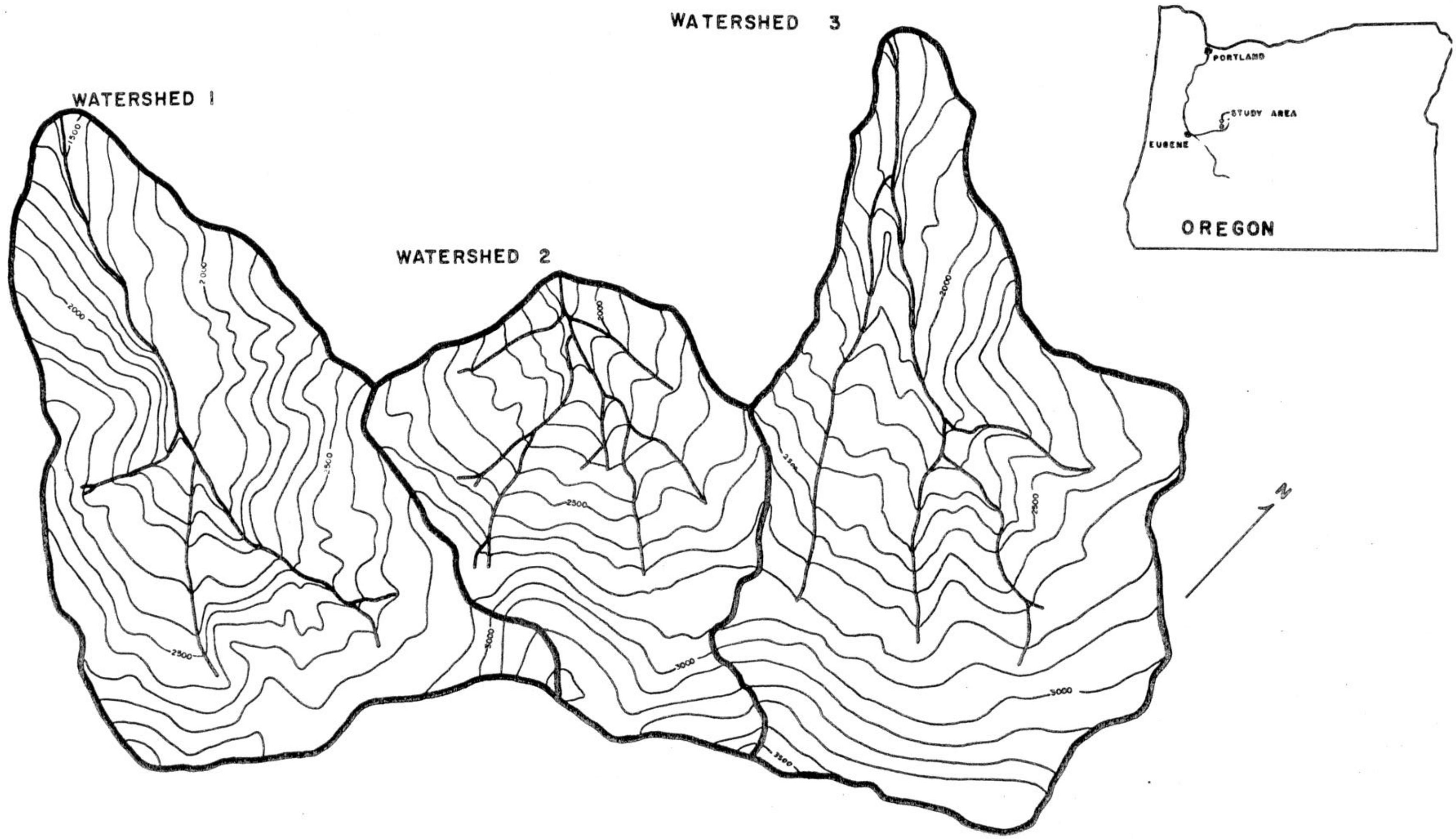

FIGURE 1. EXPERIMENTAL WATERSHEDS, H.J. ANDREWS EXPERIMENTAL FOREST

CONTOUR INTERVAL = 100 FEET. SCALE 0 1/4 1/2 MILE

Forests west of the Cascade Summit. Under this system approximately 25% of the area is clearcut in patches during the first cutting cycle. Watershed #1 will be 100% clearcut and will be logged by the Wyssen skyline method. This system involves a minimum of road construction and soil disturbance.

Topography:--The topography of the three watersheds is geologically young and is generally rough with average slopes greater than fifty percent. Side slopes dropping into major stream channels are steep to precipitous. Slopes of 80-100% are not uncommon and rock outcrops are frequent. Areas of benches and gentle slopes, probably a result of past colluvial activity,* are present and alternate with steep, thin-soiled slopes, particularly on Watersheds #2 and #3. Figure 1 illustrates the topography of the three watersheds and Figure 2, the slope-area curve, gives some indication of the relative slope of the watersheds. As Figure 2 and Table 1 show, Watershed #1 has considerably more area at a slope of greater than 80% than either of the other watersheds.

The watersheds are oriented with drainage from southeast to northwest and range in elevation from about 1500 feet at the gaging stations of #1 and #3 to over 3500 feet.

The drainage pattern is dendritic. Drainage density has been computed by two methods -- one utilizing stream lengths as

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*A large slide occurred on Watershed #3 in December 1961, depositing more than 5,000 cubic yards of mud, rock, and log debris in log jams in the main channel and scouring nearly 3,000 feet of creekbed to bedrock. Cause of the slide was believed to be a steep and unstable soil mantle, a logging road constructed across the watershed, and a sequence of snow and rainstorms which thoroughly wet the soil (11).

Table 1

WATERSHED SLOPES[a]

	Watershed #1		Watershed #2		Watershed #3	
	Acres	% Area	Acres	% Area	Acres	% Area
0 to 20% slope	12.1	5.1	16.7	11.2	41.5	16.6
20 to 40% slope	23.0	9.7	31.0	20.8	44.3	17.7
40 to 60% slope	38.4	16.2	24.8	16.6	41.7	16.7
60 to 80% slope	90.7	38.3	48.4	32.5	57.3	22.9
>80% slope	54.0	22.8	26.2	17.6	45.0	18.0
Exposed rock	18.8	7.9	2.0	1.3	20.3	8.1
Total	237.0	100.0	149.1	100.0	250.1	100.0
Weighted average slope[b]	66.0%		55.4%		54.8%	
Average slope by contour method[c]	63.5%		57.0%		56.0%	

[a]Areas from map by Wollum (49).

[b]Average determined by multiplying midpoints of slope classes by percent area within each class and computing a weighted average. For hydrologic purposes exposed rock was included within the >80% slope class. Midpoint of this slope class was taken as 90%.

[c]Determined by formula, $S = DL/A$, as explained in text.

determined from a topographic map with a scale of 16"/mile, including intermittent streams; the other using lengths as measured in a survey during the dry season. The drainage densities are included in Table 2 and it is interesting to note the difference between methods, particularly on Watershed #1.

Figure 2. Slope-Area Curves

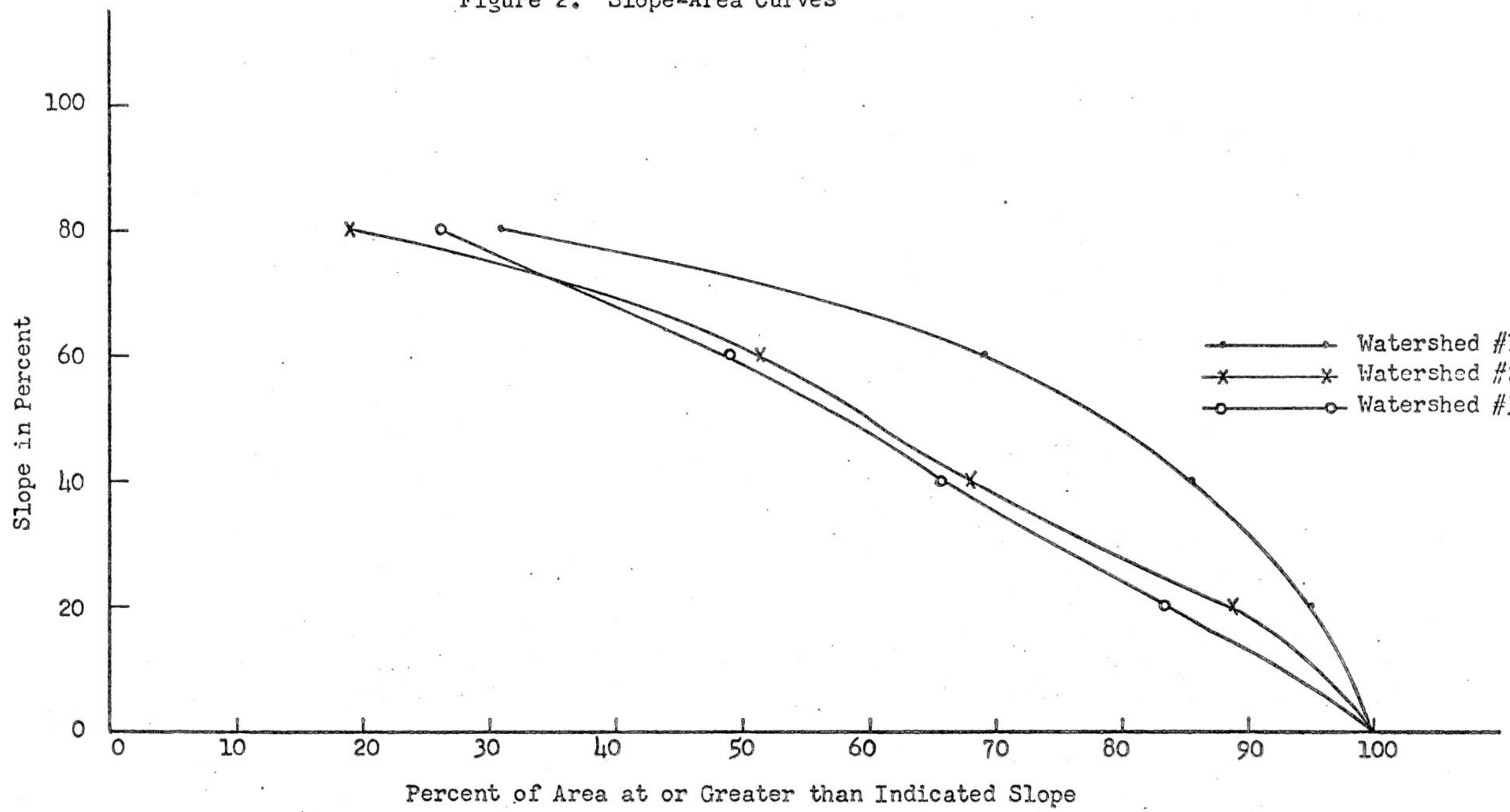

TABLE 2

WATERSHED SHAPE AND TOPOGRAPHIC CHARACTERISTICS

	Area	Compactness Coefficient	Circularity Ratio[a]	Drainage Density miles/square mile		L^b	L_c^c	Stream Slope[d]
	Acres			From Dry Season Survey	From Topographic Map	miles	miles	Percent
Watershed #1	237	1.25	0.634	3.92	5.78	0.975	0.568	28.2
Watershed #2	149	1.18	0.704	7.34	5.88	0.688	0.362	39.9
Watershed #3	250	1.30	0.580	5.08	4.68	1.062	0.616	31.6

[a]Circularity ratio = watershed area/area of circle with equal perimeter.

[b]Length of longest collecting stream extended to topographic divide.

[c]Length along main stream to point nearest centroid of area.

[d]Average slope of longest collecting stream extended to topographic divide.

Watersheds #1 and #3 are more or less fan-shaped and have compactness coefficients (watershed perimeter/circumference of a circle with equal area) of 1.25 and 1.30, respectively. Watershed #2, being between them and having the gaging station located further upstream from the mouth, is relatively ovoid in shape and has a compactness coefficient of 1.18.

Geology and soils:--The area and the three watersheds are underlain by igneous and volcanic rock with a complex history. No detailed work has been done in the area but it has been described generally. Geologically, the area lies within the western Cascades which are marked by volcanic activity of eruptive fissures forming narrow, irregular dikes (47).

Soil surveys on the experimental watersheds have confirmed the presence of basaltic and andesitic lava flows at the higher elevations overlying tuffs, breccias, and agglomerates at lower elevations.

Like the volcanic parent material, the pattern of soil distribution is quite complex. However, the soils can be generally grouped into three types:

1) A residual clay loam formed from andesite and basalt which is common on the steeper slopes and ridgetops;
2) A residual silty clay loam formed from agglomerates, tuff, and breccia which is characteristic of mid-slope and low-ridge positions;
3) A clay loam formed from colluvial materials which occupies gentle slopes and benches. (6)

Soil structure has generally been described as being medium to fine subangular blocky in the upper horizons grading to massive or structureless in the C horizon of several series.

Except for some of the colluvial soils forming bench areas, the soils are generally shallow, often less than two feet in depth. Figure 3 shows areas of deep and shallow soils on the watersheds. As can be seen from this figure and Table 3, 65% of the area of Watershed #1 is in shallow soils and exposed rock while Watersheds #2 and #3 are between 40-45% shallow soil and exposed rock.

Table 3

SOIL DEPTHS

	Watershed #1		Watershed #2		Watershed #3	
	Acres	% Area	Acres	% Area	Acres	% Area
Deep soils[a]	80.1	33.8	80.8	54.2	149.7	59.9
Shallow soils	138.0	58.3	66.3	44.5	80.1	32.0
Exposed rock	18.8	7.9	2.0	1.3	20.3	8.1
Total	237.0	100.0	149.1	100.0	250.1	100.0

Data from soils-vegetation survey report by Wollum (49).

[a]Deep soil mapped as that deeper than two feet.

Two soil surveys have been conducted on the area, one in 1960 by Wollum (49) and one in 1962 by a Forest Service soil-survey team. A brief resume of the soil types as described in the most recent survey is given in the appendix.

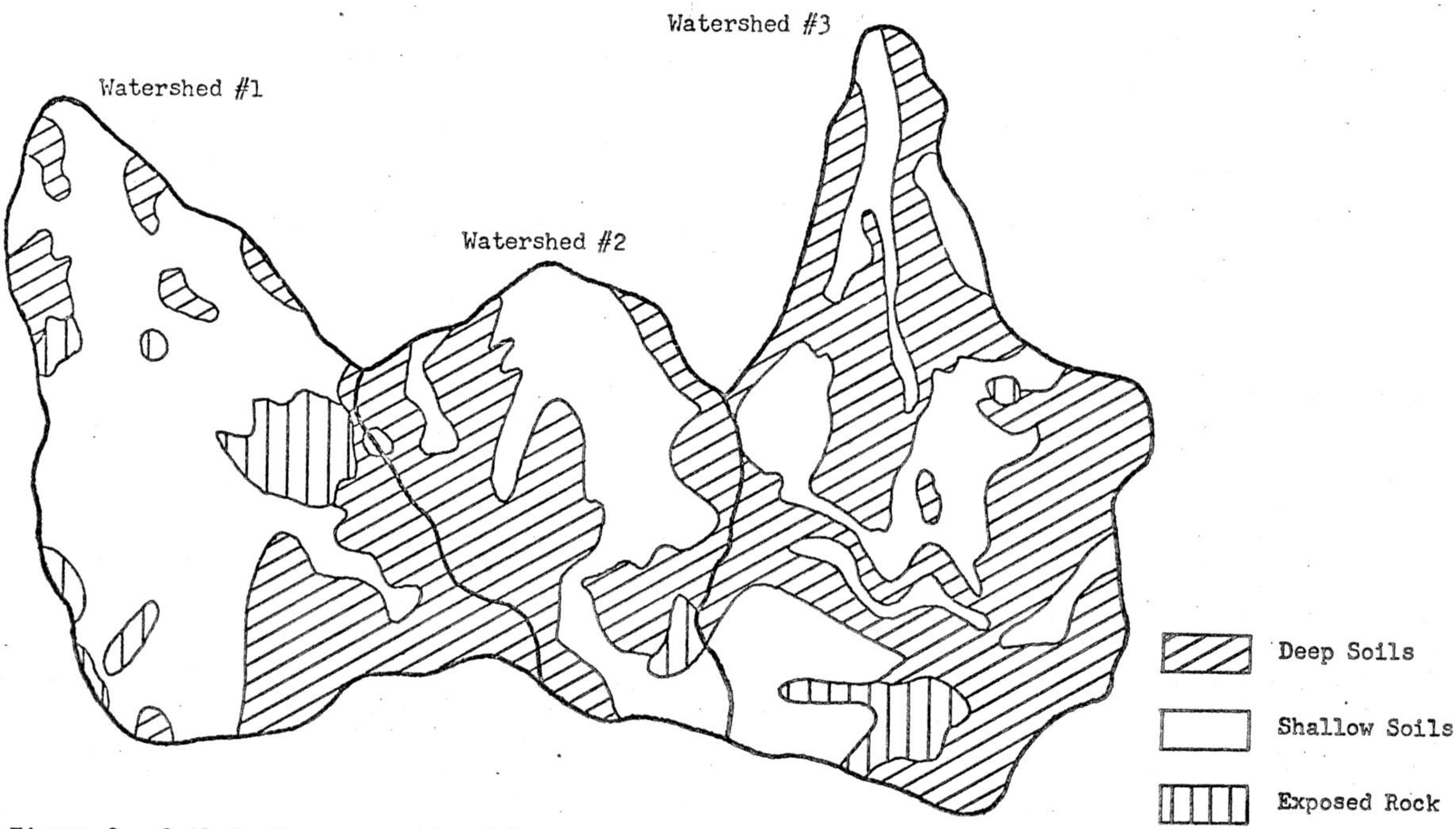

Figure 3. Soil depths on experimental watersheds, H.J. Andrews Experimental Forest. Taken from map by Wollum.

The soil survey which mapped depth differentiated between deep and shallow soils at a depth of two feet. Thus both residual and colluvial soils are included within the deep soils classification. Some of the colluvial soils are quite deep -- more than ten feet -- as the soil series descriptions in the appendix indicate. These deep colluvial soils probably have considerable hydrologic significance, as will be discussed later.

Most of the soils are well drained to moderately well drained with moderate to moderately rapid permeability. The one exception is the Slipout series, mapped as occupying a small area of Watershed #3, which is described as being imperfectly drained and having moderately slow permeability. Bulk densities have been determined on several soils and generally averaged between 0.8 and 1.1.

Some idea of the potential for detention storage can be obtained from determinations of non-capillary pore space in the top four feet of the soil at three sites in Watershed #3. Using soil moisture-tension measurements and bulk densities, the total non-capillary pore space was determined to be 7.8, 5.5, and 5.4 inches in the top four feet of soil at these three sites*. Approximately half of this non-capillary pore space, or potential detention storage, was in the top foot of soil. Though these figures cannot be used to represent the watershed as a whole, they do illustrate the large storage capacity of the soil and help explain why surface runoff is virtually non-existent, even during prolonged intense storms.

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*Non-capillary pore space was assumed to be the difference between volume of water held in the soil at saturation (total pore space) and at a tension of 60 centimeters of water. Total porosity was determined from bulk density by the formula

$$\text{Total porosity (in percent)} = 100\left(1 - \frac{\text{Bulk Density}}{2.65}\right).$$

Data for bulk density and porosity is shown in the appendix.

Vegetation:--Although vegetation changes progressively with altitude within each watershed, it is not noticeably different among the three watersheds. It consists primarily of old-growth Douglas-fir[1/] with an understory of hemlock, yew, chinquapin, dogwood, and vine maple. Hemlock and western redcedar, the site climax species, become more abundant at higher elevations at the expense of the Douglas-fir. Western redcedar, incense cedar, big-leaf maple, and alder are found along creeks and near marshy spots where soil moisture conditions are favorable. Common shrubs are rhododendron, salal, Oregon grape, and huckleberry. Due to the dense crown canopy (about 90%) herbaceous vegetation is sparse. Among the more common species are twinflower, oxalis, swordfern, goldthread, and beargrass (49).

Climate and hydrology:--The climate of the area is generally mild. It is quite rainy in the late fall, winter, and spring but warm and dry during the summer months. The mean temperature in July is about 65° F. and in January about 39° F. Temperatures usually exceed 100 degrees for a brief period in the summer but rarely reach 0 degrees in the winter. Mean water year precipitation over a 7-year period averaged 92 inches with a range of 73.6 to 109.8 inches; primarily in the form of rain. Rainfall intensities are low -- usually less than 0.25 inches/hour, with few storms reaching 0.50 inches/hour, even for short periods.

During the 7-year calibration period annual runoff from the three watersheds averaged about 60 inches or about 65% of

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[1/] For a list of scientific names of common species see appendix.

precipitation, varying from 45.4 to 81.1 inches. Water balance studies have indicated that the remaining 35% may be broken down into interception -- 12%, and evapotranspiration losses -- 23%. Lowest periods of streamflow occur in late summer prior to fall rains and have varied from August to early November. To date the recorded extremes of high and low flow indicate a ratio of nearly 1000 to 1 (37). Figure 4 shows the monthly distribution of precipitation and runoff of Lookout Creek, the stream into which all three experimental watersheds drain.

According to observers there is no visible surface runoff during even the heaviest rains but temporary streams flow in every possible channel and water "literally squirts out of the road cuts from top to bottom." During prolonged, intense storms runoff rates on Watershed #1 have reached 80% of rainfall intensity (36).

Instrumentation

Precipitation:--Rainfall intensity records are available from a Leupold and Stevens Q-12 recording rain gage located at a climatic station below the mouth of Watershed #2. Four additional standard rain gages and two rain and snow storage gages are located within the three watersheds and around their periphery. Precipitation recorded at different elevations was compared and, over the short period of concurrent record -- 1-2 years, found to be approximately 5% greater at the highest elevation than the climatic station for annual precipitation. Little difference was found for short period winter storm precipitation.

Runoff:--Runoff from the experimental watersheds has been gaged since 1952 with trapezoidal flumes. Rothacher (37) describes

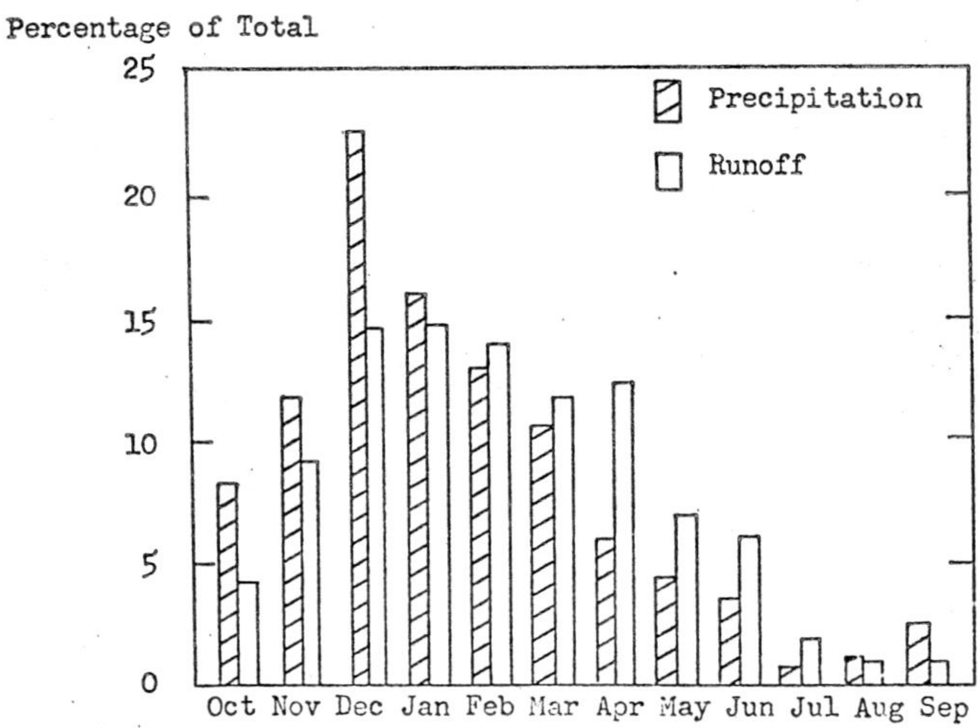


Figure 4. Average annual distribution of precipitation and runoff from the Lookout Creek drainage, H.J. Andrews Experimental Forest. (from Bernsten and Rothacher (6))

the installations as follows:

> Each of the small watersheds is gaged with a trapezoidal flume 9 feet long and 14 feet wide with approximately a 9-inch-wide flat floor. Side slopes of the flume were constructed at approximately 25 degrees to a height of three feet. The floor of the flume has a 3 to 5 degree slope downstream. This design, based on laboratory tests, gives a laminar flow through the control section at all stages. A trapezoidal flume was used rather than a sharp-crested weir because it is self-cleaning and has a relatively large capacity. The flumes as described can handle approximately 100 cfs.

The flumes are equipped with standard Leupold and Stevens A-35 stage recorders. Stage-discharge ratings have been made in the field by means of the velocity head rod.

Data Reduction

Storm runoff and precipitation:--Stage hydrographs for the period of record since 1952 were examined for storms which could be isolated and analyzed. Six storms were selected and used for the study. The maximum recorded flows were not included as these were usually from longer-period, more complex storms which are more difficult to analyze.

Since the exact recession curves of the three watersheds were not known, base flow had to be arbitrarily separated from storm runoff. In view of the disagreements regarding hydrograph separation in the literature and the results of later recession analysis, it is felt that any separation of base flow without considerably more information than was available would be arbitrary. A constant time of stormflow runout from time of peak was applied to each watershed for all six storms. This time period for each watershed was arrived at by examining the hydrographs and subjectively estimating the point at which storm runoff appeared to cease. At this point there is normally a visible break in the recession curve. For each watershed the average time of these recessions was computed and then applied to all six storms for separation of base flow.

The method of separation used is explained by Linsley, Kohler, and Paulhus (30) and consists of extending the recession existing prior to the storm to a point under the hydrograph peak. A straight line is drawn from this point to the point on the recession hydrograph at which storm runoff is determined to have ceased.

Although the accuracy of base flow separation by this method for a particular storm may be questioned, it was felt that since the method used was constant throughout the study it would not greatly affect the accuracy of the storm hydrographs for comparison purposes or interpretations. Runoff volumes were then calculated from stage-discharge relations.

For one storm, that of November 16-20, 1960, a distinct second storm following the peak by 6-8 hours was separated as outlined by Linsley, Kohler, and Paulhus (30).

For each storm the hyetograph of hourly rainfall intensities was plotted on the same time scale as the storm hydrograph in order to examine the hydrograph reactions to rainfall intensity fluctuations. The rainfall intensity was assumed to be constant over the three watersheds. This assumption is based on the fact that the storms experienced here are of the widespread frontal type with low intensities. Examination of records from the rain gage network showed no orographic effect and little variance in total precipitation from this type storm. Since there is no effect on total storm precipitation, there is no reason to believe that there is an effect on intensity of precipitation.

Lag:--The definition of lag adopted for this study was the time from centroid of the period of effective rainfall to the time when 50% of storm runoff has occurred. The centroid of effective precipitation was determined graphically from a mass plot of precipitation and storm runoff.

Recession coefficient:--The term, recession constant, is normally used for this value. However, as the values determined were anything but constant, recession coefficient was settled upon as a more appropriate term.

In order to eliminate the effects of channel precipitation and channel storage, the period of recession was taken as beginning three hours after the peak or three hours following cessation of rainfall, whichever was later. Recessions of total flow were plotted on semi-log paper and recession coefficients computed for periods during which the semi-log recession plot approximated a straight line. For purposes of computation a time-period of 6 hours was chosen. Thus recession coefficients were determined by the formula

$$R_c = \frac{Q_{t+6}}{Q_t}$$

where R_c is the 6-hour recession coefficient, Q_t is discharge at any time t, and Q_{t+6} is discharge 6 hours later.

Watershed characteristics:--The basin characteristics which were thought to have a significant effect on storm runoff --

both volume and time distribution of runoff -- were measured. Watershed perimeters and stream lengths were measured with an opisometer from a map constructed by research foresters of the H. J. Andrews Experimental Forest from a compass and chain survey. The centroid of area was determined by the standard means of vertically suspending a cardboard outline of the watershed separately from several points and finding the point of intersection of plumb lines from these points of suspension.

Average basin slope was measured as outlined by Wisler and Brater (48), i.e., by the formula

$$S = 100 \frac{DL}{A}$$

where S is the average slope of the basin in percent, D is the contour interval in miles, L is total length of contours in miles, and A is the basin area in square miles. Data for the slope-area curve was obtained from area within slope classes as mapped by Wollum in his soil-vegetation survey.

<u>Other</u>:--Data on soils was obtained from a soils-vegetation survey conducted in the summer of 1960 as reported by Wollum (49). Parallel transects were taken across the watersheds (at right angles to the main drainage) at ten and twenty chain intervals. Soil depth, slope, aspect, and vegetation were recorded on plots at two chain distances, and mapping by soil series, soil depth, and slope was done in the field using aerial photographs.

Base flow at the beginning of storm periods was measured and used as an index of antecedent moisture conditions. This index may not fully account for recent rains which have reduced available moisture storage without materially increasing base flow. However, most of the storms selected followed a period of at least a week with no appreciable rainfall.

ANALYSIS

The six storms selected for analysis as described in chapter III varied from 2.39 to 7.67 inches of rainfall and storm runoff as separated from base flow ranged from 0.57 to 4.59 inches. Table 4 lists the storms used and principal data from these storms.

Unit Hydrograph

When the study was initiated the unit hydrograph was planned as the principal means of characterization and comparison of runoff characteristics of the three watersheds. With the low intensity rainfall, highly porous soils, and high infiltration capacities there is very little actual surface runoff, but rather subsurface flow. However, the subsurface flow behaves differently than normal ground water base flow and is easily distinguishable as storm runoff. Therefore, it was believed that the unit hydrograph would be applicable for purposes of analysis with the principal difference being the much longer time periods than would be necessary with surface runoff from the same size watersheds.

As even the shortest storm had a duration of effective precipitation longer than the estimated time of concentration, the storm period was broken into "unit" storm periods. After examination of the hydrographs, three hours was chosen as a convenient time unit to use. Accordingly, analysis of the complex hydrographs began with estimates of the amounts of effective, or excess,

TABLE 4

STORM DATA USED IN STUDY

Storm	Date	WS #	Rainfall	Effective Duration	Storm Runoff		Losses	Antecedent Flow	Peak Flow	Time to Peak	Lag Time
			inches	hours	inches	percent	inches	csm	csm	hours	hours
1	2/16-20/53	1	5.09	31	2.29	42.8	2.91	3.29	54.11	19.5	11.5
		2			1.30	25.5	3.79	5.58	23.92	18.25	15.25
		3			1.73	34.0	3.36	3.35	34.51	15.5	13.0
2	12/19-23/53	1	4.01	18	2.96	73.8	1.05	4.56	62.56	12.5	14.75
		2			2.83	70.6	1.18	9.02	49.65	17.0	21.0
		3			2.93	73.1	1.08	5.86	44.80	17.5	22.0
3	11/16-20/56	1	2.39	11	0.73	30.5	1.66	0.74	25.52	12.0	15.0
		2			0.71	29.7	1.68	1.04	17.82	10.0	20.0
		3			0.57	23.8	1.82	1.13	23.68	10.0	12.5
4	12/6-10/57	1	5.88	20	2.88	49.0	3.00	0.88	79.97	19.0	12.0
		2			2.63	44.7	3.25	1.34	50.44	19.5	18.5
		3			2.34	39.8	3.54	1.34	56.65	18.5	14.5
5	11/22-27/60	1	5.55	24	3.55	64.0	2.00	3.32	79.87	18.75	12.5
		2			3.57	64.3	1.98	4.47	63.60	24.0	17.5
		3			3.15	56.8	2.40	4.35	60.60	21.75	14.75
6	2/19-23/61	1	7.67	33	4.59	59.8	3.08	11.61	92.96	22.5	12.25
		2			4.43	57.8	3.24	14.73	74.95	23.0	16.25
		3			4.57	59.6	3.10	10.34	74.11	22.5	15.75
Average		1	5.10	22.8	2.83	53.3	2.28	4.07	65.83	17.4	13.0
		2			2.58	48.8	2.50	6.03	46.73	18.6	18.1
		3			2.55	47.8	2.55	4.40	49.06	17.6	15.4
Ratio of Maximum to Minimum		1	3.21	3.00	6.29	2.42	2.93	15.68	3.64	1.88	1.30
		2			6.24	2.77	3.21	14.16	4.21	2.40	1.38
		3			8.02	3.07	3.28	9.15	3.13	2.30	1.76

precipitation, $Q_1, Q_2, \ldots, Q_n$, resulting from successive three-hour storm periods. This was done by examining the rainfall hyetographs and the stage hydrographs, taking into consideration the antecedent moisture conditions. As outlined by Linsley, Kohler, and Paulhus (28), the equation for any three-hour ordinate, q_n, of the total hydrograph in terms of excess precipitation, Q, and unit hydrograph distribution ordinates, U, is

$$q_n = Q_n U_1 + Q_{n-1} U_2 + Q_{n-2} U_3 + \ldots + Q_1 U_n .$$

Thus the distribution graph ordinate, U_n, can be determined by the formula:

$$U_n = \frac{q_n - (Q_n U_1 + Q_{n-1} U_2 + Q_{n-2} U_3 + \ldots + Q_2 U_{n-1})}{Q_1} .$$

Using this method, each computation depends on all previously computed values of U, which in turn depend upon the values of excess precipitation, Q, initially assigned. Any errors become cumulative and may eventually lead to large negative ordinates. When this occurs, the excess precipitation is redistributed among the three-hour storm periods, giving new values for Q. The process is repeated until the computed final hydrograph ordinates give a fair approximation of the actual recorded hydrograph.

This method was attempted on all three watersheds on storm 2 and on Watershed #2 for storm 3. In every case negative values of U developed before the peak section was reached. Some 8-15 distributions of excess rainfall were used in each trial but little improvement in results was obtained over the original distributions which were assigned through a knowledge of the storms and antecedent conditions. Since this method is quite laborious and time-consuming, it was decided not to pursue it further.

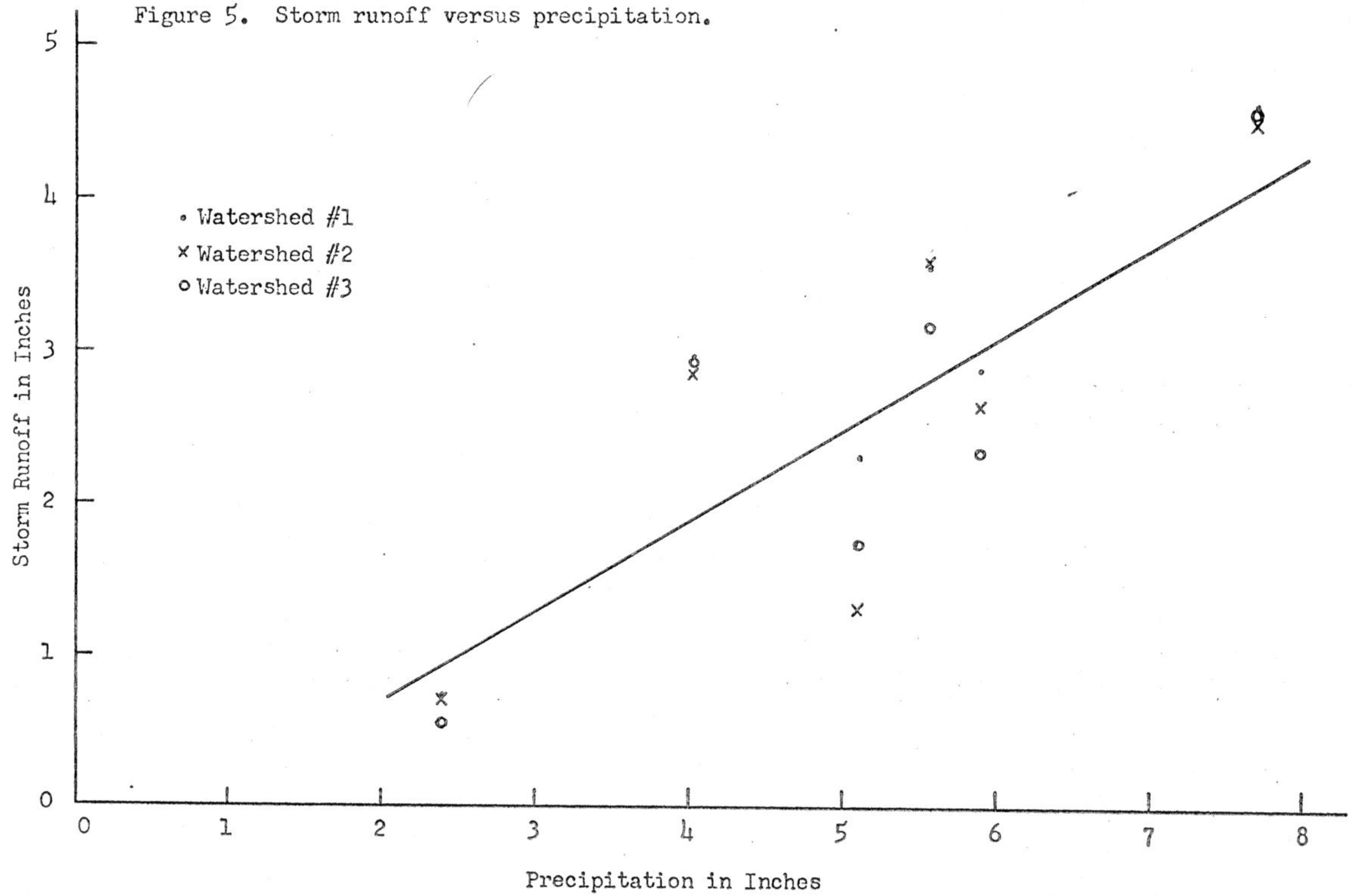
The "progressive addition" method outlined by Barnes (3) was also tried. This is similar to the above but begins on the recession side of the hydrograph and works backward until a complete set of positive runoff ordinates is obtained. This sequence of excess precipitation volumes is then used for a forward run and the runoff ordinates computed. The ordinates computed by reverse and forward runs are plotted on the same time scale. The distribution of excess rainfall is adjusted between sets of runs until the hydrograph ordinates computed by forward and reverse runs agree favorably. This method was also tried on storms 2 and 3. Barnes found that this method was successful in developing unit graphs which coincided very closely in a maximum of 4 to 5 trials. However, as many as 8 to 10 trial distributions were used on these storms without visible improvement. On storm 2, Watershed #1, reasonable looking hydrograph ordinates were developed on the reverse run; however, in every case the forward run developed large negative ordinates immediately following the peak.

After considerable expenditure of time with no fruitful results, it was decided to abandon the unit hydrograph approach in favor of other means of comparison.

Runoff Volume and Peaks

As might be expected there was considerable variation in storm runoff, both in amount and in runoff expressed as percent of precipitation. Figure 5 shows storm runoff versus precipitation.

Figure 5. Storm runoff versus precipitation.



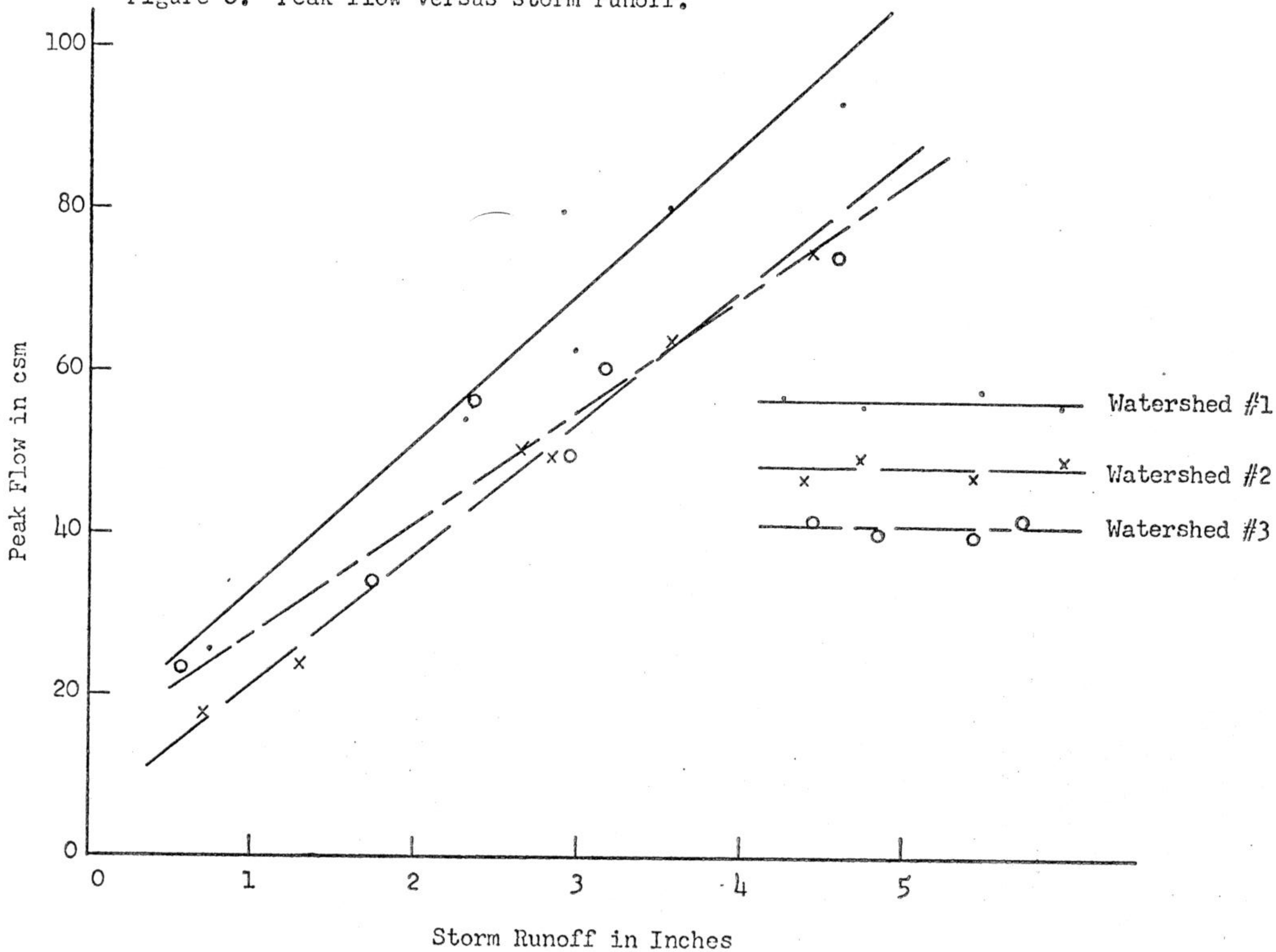
Though Watershed #1 usually produced the greatest volume of runoff from a given storm, there was little difference between watersheds on several storms. The relative effect of antecedent moisture as indicated by base flow at beginning of storm can be seen in Table 4. Storm 3 which has the lowest percentage runoff has the lowest antecedent flow. Variation in percentage runoff is not completely explained by the index of antecedent moisture, however, as is demonstrated on storm 1.

Peak flow in csm for the six storms correlates quite well with storm runoff as is shown in Figure 6. The correlation is particularly good on Watershed #2. From the regression lines which have been fitted visually, it appears that Watershed #1 has the steepest regression line, i.e. peak flow increases most per increase in storm runoff, while Watershed #3 shows the least response of peak to increase in runoff.

Time Distribution of Runoff

In order to characterize and compare storm runoff for the three watersheds composite distribution graphs were constructed from average three-hour distribution percentages of the six storms. In order to reduce the variation caused by differences in duration of effective precipitation, the time of peak flow was taken as a starting point and time measured in both directions from peak. The amount of cumulative storm runoff was measured at three-hour intervals from 6 hours before peak to 12 hours following peak flow and the three-hour increments converted to percent of total runoff. Because of the progressively slower rate of change in the recession

Figure 6. Peak flow versus storm runoff.



side of the hydrograph, measurements were taken at six-hour intervals between 12 and 24 hours following the peak and at twelve-hour intervals between 24 and 48 hours. Measured increments over this period were converted to average equivalent three-hour distributions. The instantaneous peak rate was converted to the equivalent three-hour distribution percent and an average peak rate determined. Table 5 shows average three-hour distribution percentages and Figure 7 shows the composite distribution hydrographs for the three watersheds. The average period of rise -- time interval from beginning of effective precipitation to peak -- was determined for each watershed and used to locate the peak. Because of variations in rainfall duration and period of rise, three-hour distribution percentages were not calculated for the portion of the composite hydrographs prior to -6 (6 hours before peak); this part of the composite hydrographs was estimated from hydrograph examinations and fitted so that the area under the curve was equal to the average percent of runoff during this period. That portion of the storm runoff hydrographs more than 48 hours following peak flow was not included as this last 38-42 hours contained only 5-9% of the total storm runoff and would have required greatly reducing the time scale. The composite hydrographs as shown in Figure 7 are plotted on a time scale with the start of effective precipitation as zero.

As Figure 7 shows, the composite distribution hydrograph of Watershed #3 has a very sharp peak flow section. Examination of the data showed that this high average was caused by storm 3 in which an instantaneous peak of 19.3% was reached as compared to the next highest peak of 11.3%. Watersheds #1 and #2 also had higher peak distribution percentages on this storm but not to the extent of Watershed #3. The reason for this difference is the low storm runoff of 0.57 inches on Watershed #3 as compared to 0.73 and 0.71 inches on Watersheds #1 and

#2. As all five other storms contained more than twice this amount of runoff, another set of composite hydrographs was constructed using storms 1, 2, 4, 5, and 6. It was felt this would give a set of hydrographs more representative of runoff from the large storms which are typical of the wet season. Table 5 includes the three-hour distribution percentages of the five-storm average. An indication of its improvement over the six-storm average can be determined by the reduction in variation* as shown by the maximum/minimum ratios, "V", of the two analyses. The reduction in variation is most pronounced on Watersheds #2 and #3. Figure 8 shows the composite hydrographs derived from the five-storm average. As this figure shows, Watershed #1 has the highest peak, peaks first, and has the steepest recession limb. Watershed #2 peaks latest, has the lowest peak percentage, and sustains the highest percentage flow throughout most of the recession. Watershed #3 is intermediate between the two but more closely resembles Watershed #2. Figure 9 shows the cumulative runoff in percent and further points out the faster runoff of Watershed #1.

Examination of Table 5 shows that Watershed #2 has the least variation in distribution percentages among storms, i.e., lowest maximum/minimum ratio, V, and that Watersheds #1 and #3 are almost equal in this respect.

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*Not to be confused with the statistical term, variance. Because of the small number of samples in each group (5 or 6) it was not felt justifiable to use statistical methods of analysis. However, this does not limit presentation of data to the mean values only, and the ratio of maximum value to minimum value was chosen as a means of giving a relative indication of the range in values. This method is presented as a tool in distribution graph analysis by Wisler and Brater (45).

Figure 7. Composite time distribution hydrograph of runoff - six storm average.

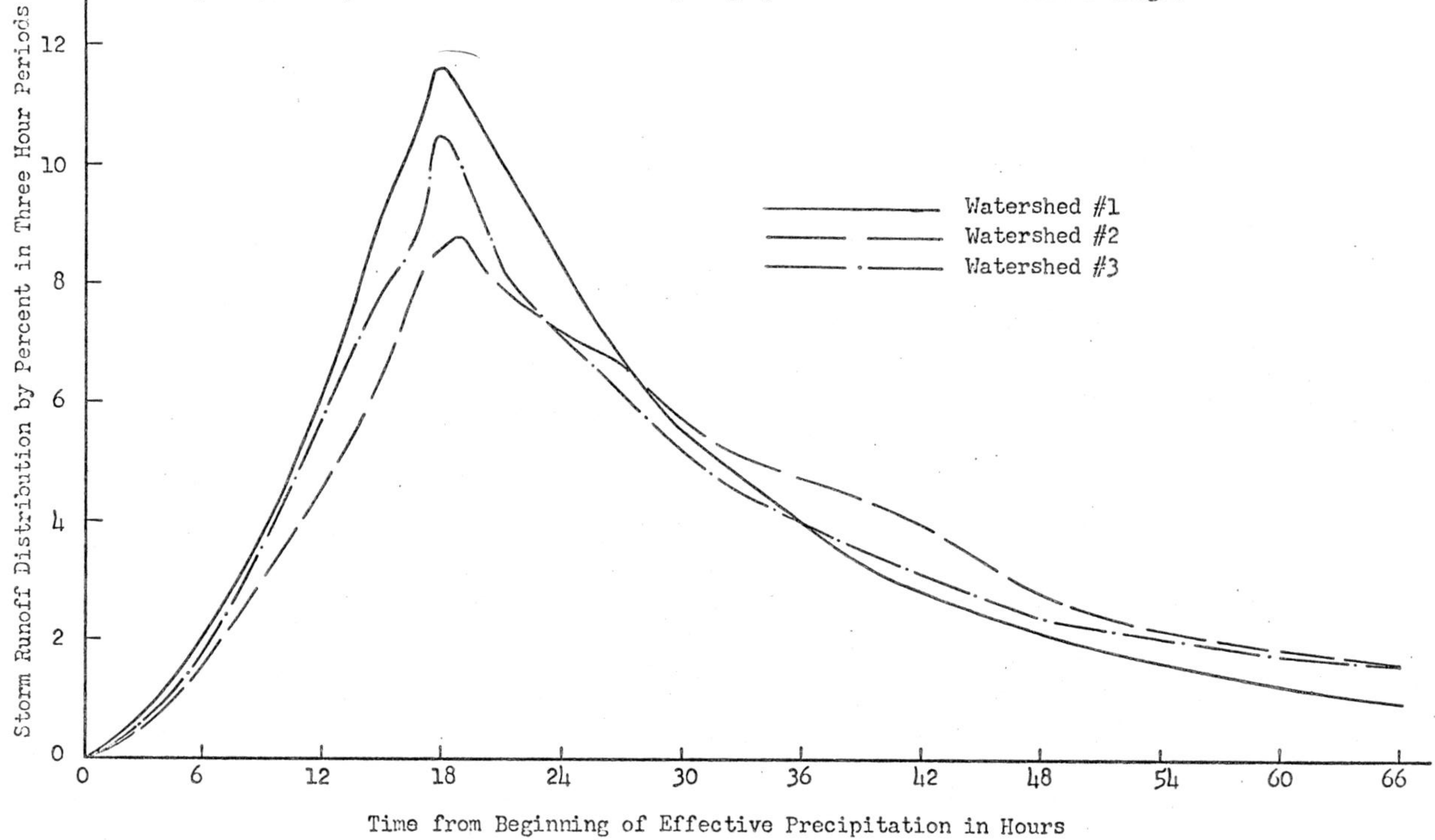


Figure 8. Composite time distribution hydrograph of runoff - five storm average.

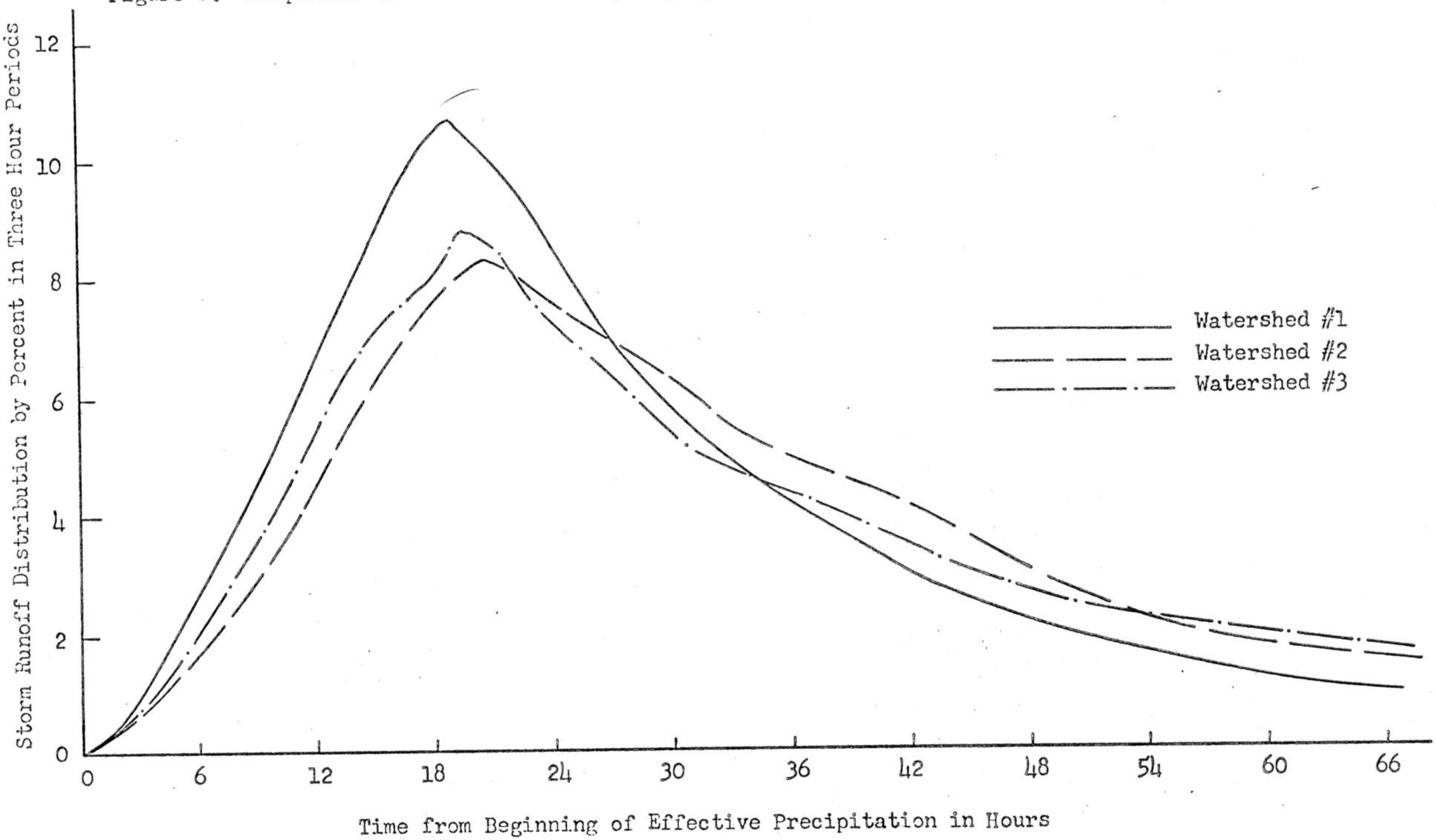
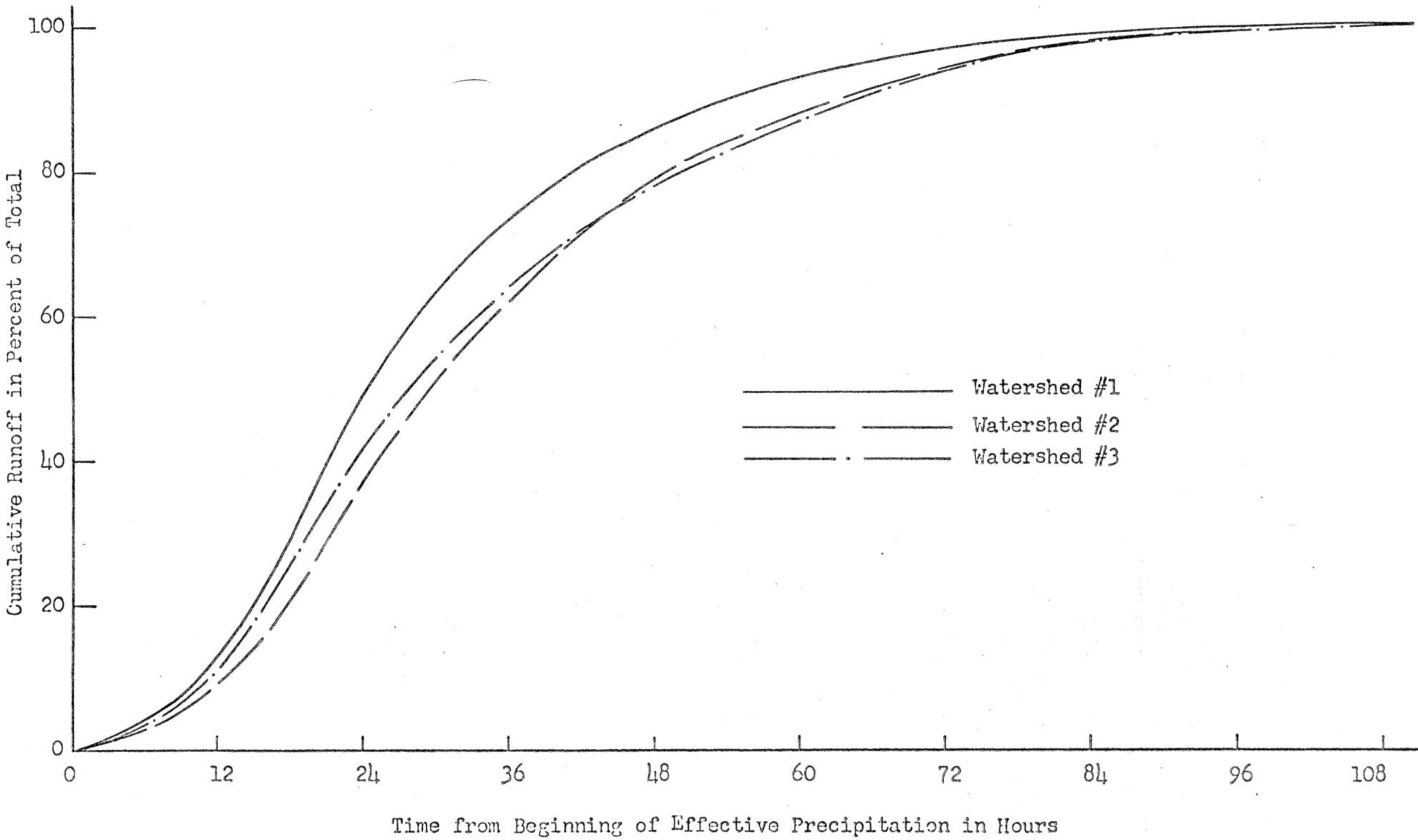


TABLE 5

AVERAGE TIME DISTRIBUTION BY PERCENT IN THREE HOUR PERIODS

Time in Hours Peak as 0	Six Storm Average						Five Storm Average					
	Average Percent Runoff by Three Hour Periods			Range of Dist. Percent (Maximum/Minimum), V			Average Percent Runoff by Three Hour Periods			Range of Dist. Percent (Maximum/Minimum), V		
	WS #1	WS #2	WS #3	WS #1	WS #2	WS #3	WS #1	WS #2	WS #3	WS #1	WS #2	WS #3
Total Prior to -6 Hr.	11.7%	11.3%	11.9%	10.00	13.57	10.94	13.6%	13.2%	13.9%	4.32	1.92	2.01
-6												
	7.4	6.0	6.8	2.54	2.86	1.77	8.1	6.7	7.1	1.63	1.36	1.59
-3												
	10.3	8.3	8.6	1.52	1.48	1.88	10.0	7.9	7.9	1.52	1.33	1.65
Peak	11.6	8.8	10.5	1.67	1.43	2.68	10.7	8.3	8.8	1.36	1.10	1.54
	10.9	8.2	9.7	1.51	1.15	2.19	10.3	8.1	8.5	1.30	1.15	1.49
3												
	9.4	7.3	7.6	1.34	1.10	1.48	9.1	7.4	7.4	1.21	1.10	1.48
6												
	7.6	6.8	6.9	1.19	1.21	1.66	7.5	6.8	6.5	1.17	1.21	1.42
9												
	6.2	6.0	5.7	1.37	1.37	1.49	6.1	6.1	5.4	1.37	1.37	1.36
12												
	4.95	5.0	4.6	1.41	1.44	1.27	4.85	5.0	4.65	1.41	1.44	1.27
18												
	3.4	4.4	3.65	1.56	1.52	1.44	3.4	4.4	3.7	1.56	1.46	1.44
24												
	2.25	2.75	2.52	1.47	1.33	1.53	2.22	2.75	2.6	1.47	1.33	1.53
36												
	1.32	1.9	1.88	3.00	2.09	1.78	1.22	1.7	1.9	3.00	1.70	1.78
48												
Total	94.6%	91.3%	91.3%				95.0%	92.8%	91.4%			
Average V				1.69	1.54	1.74				1.55	1.32	1.50

Figure 9. Cumulative time distribution of runoff.



As might be expected from storms with a wide range of time durations, the time from beginning of effective precipitation to peak flow varied considerably. If storm 3 which had a time to peak of 12, 10, and 10 hours, respectively, is omitted, variation is reduced and Watershed #2 again shows the lowest V value.

The time from 10% of peak flow to peak has been suggested (3) as a more accurate index of the period of rise of the hydrograph. This time was measured and averaged 2 to 4 hours less than total time to peak. With the exception of Watershed #2 (excluding storm 3) it gave a wider range of variability than total time to peak.

The lag time, as computed from centroid of effective precipitation to the time when 50% of runoff has occurred, gave one of the most accurate indices of storm runoff. It is interesting to note that the longest lag periods occurred on the storms having shortest duration. Watershed #1 had the smallest range of variability and Watershed #3 the greatest. Elimination of storm 3 had no effect on the range of variability for Watersheds #2 and #3 and negligible effect on Watershed #1. Thus lag time seems to be primarily affected by watershed characteristics. Evaluation of the watershed characteristics which affect lag presents a difficult problem, however. The parameters most commonly quoted in the literature as being related to lag are L, L_c, and stream slope, S, with lag time being proportional to some power of LL_c and inversely proportional to the square root of S. These parameters have been related to watershed lag where surface flow was the principal source of storm runoff. On the experimental watersheds of the H. J. Andrews Experimental Forest where subsurface flow is the dominant process, no clear relationship could be shown. Watershed #2 which had the lowest values of L and L_c and the highest value of S (as measured to the divide), had the longest lag time, 18.1 hours as compared to 13.0 and 15.4 hours on Watersheds #1 and #3. Values of $LL_c/S^{1/2}$ were computed and found to be 1.04, 0.39, and 1.16 for Watersheds #1, #2, and #3, respectively.

Recession Analysis

Because of the arbitrariness of the method of base flow separation, total flow rather than storm flow was used for recession analysis. When total flow was plotted on semi-log paper it was found that the recessions did not lend themselves to an obvious simple breakdown into two or three straight lines. Rather, they were still roughly curvilinear overall, but could usually be broken down into four to six straight line segments. Figures 10, 11, and 12 show the recessions plotted so that the six recessions for each watershed coincide at discharges of 3.70, 2.33, and 3.91 cfs, respectively, which are the equivalents of a flow of 10 csm. As these figures show, there is a considerable variation in the recession slopes. On all three watersheds storm 2 has the lowest overall recession slope (or highest recession coefficients) and storm 3 the greatest recession slope. Again, Watershed #2 shows the least variation between storms and Watershed #1 the greatest amount as is pointed out by Figures 10-12 and Table 6.

Recession coefficients over comparable ranges of csm (on the same storms) have been plotted for Watersheds #1 and #3 versus Watershed #2 and approximate regression lines fitted.

Figure 10. Hydrograph recessions of Watershed #1.

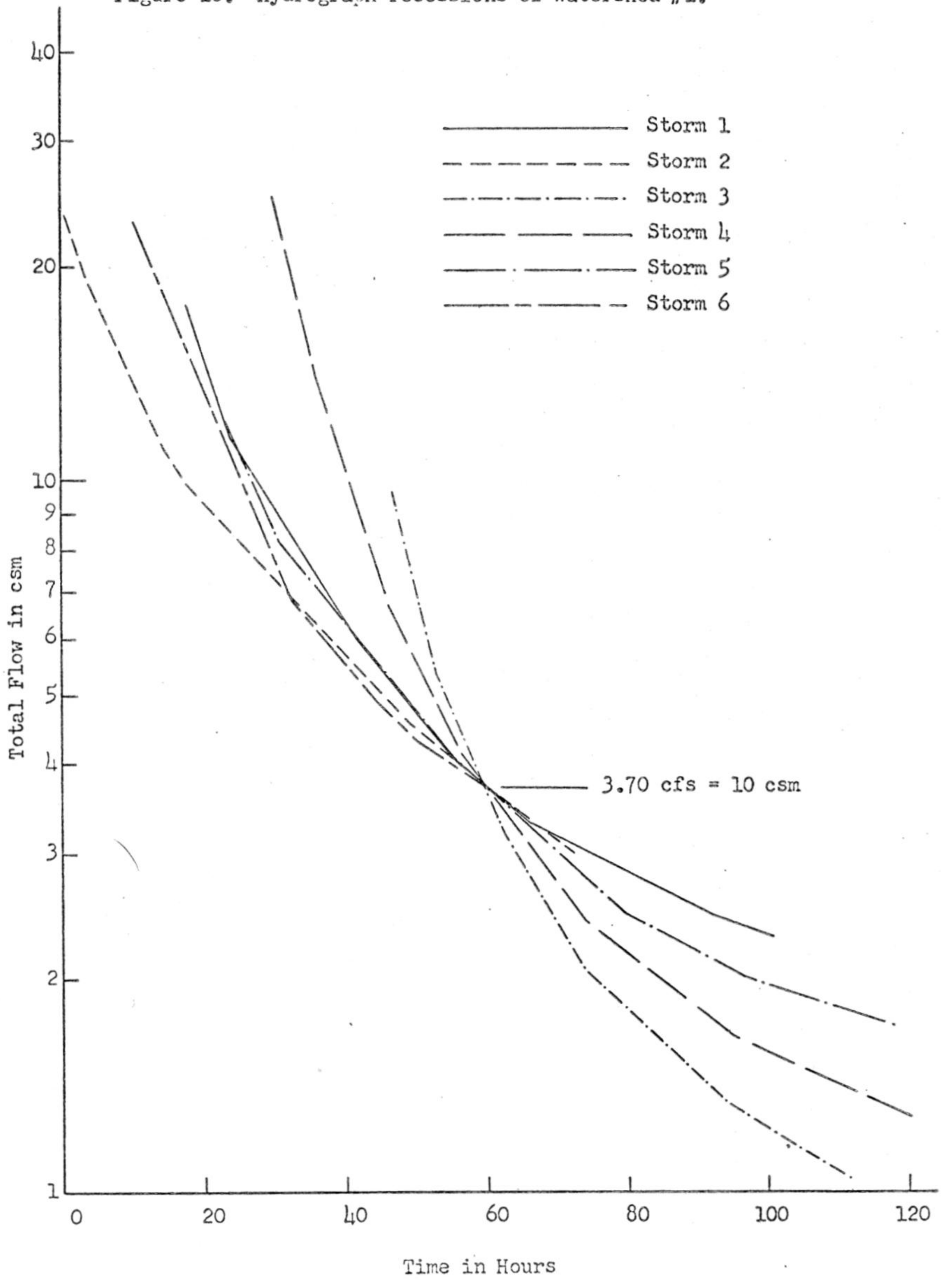


Figure 11. Hydrograph recessions of Watershed #2.

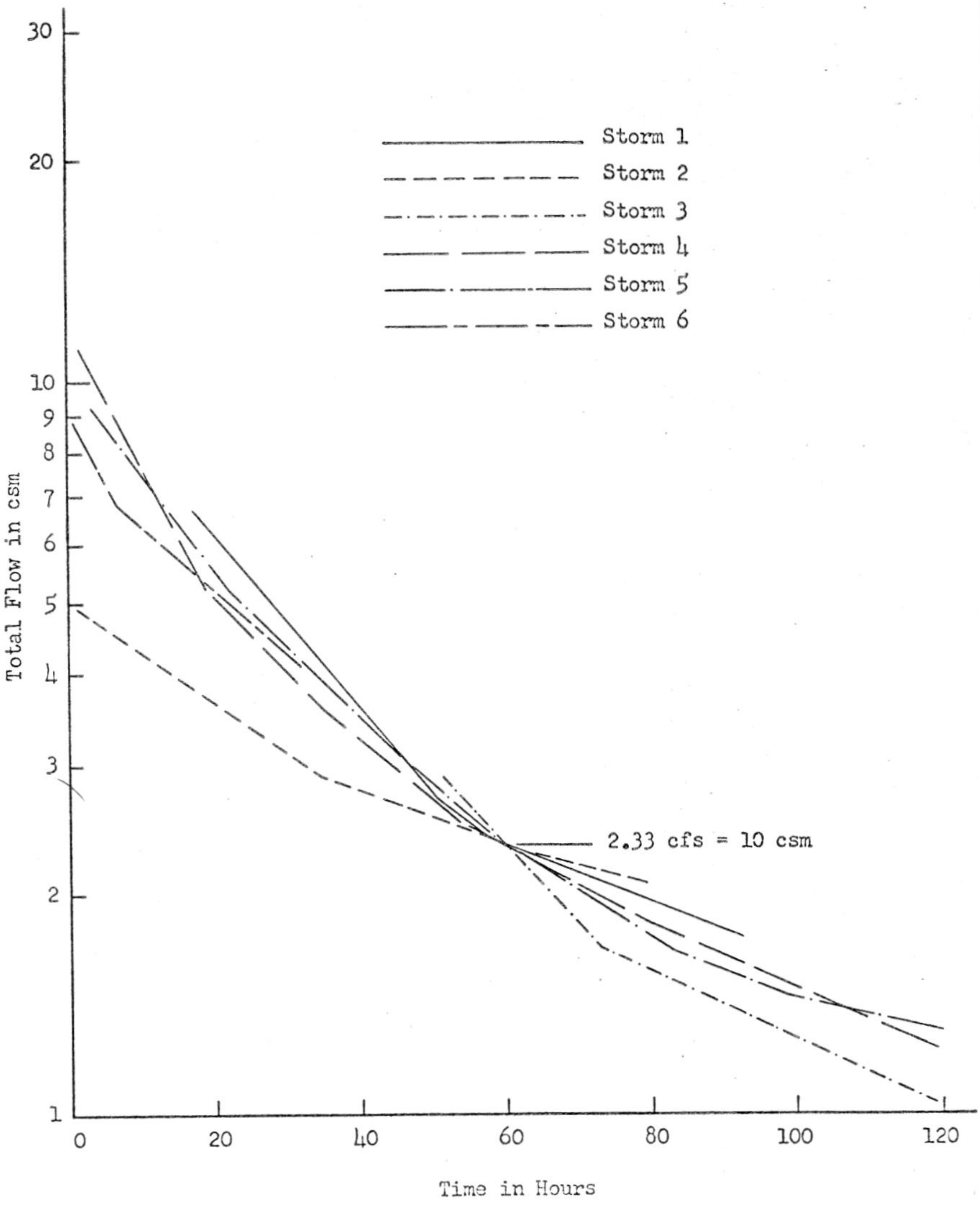


Figure 12. Hydrograph recessions of Watershed #3.

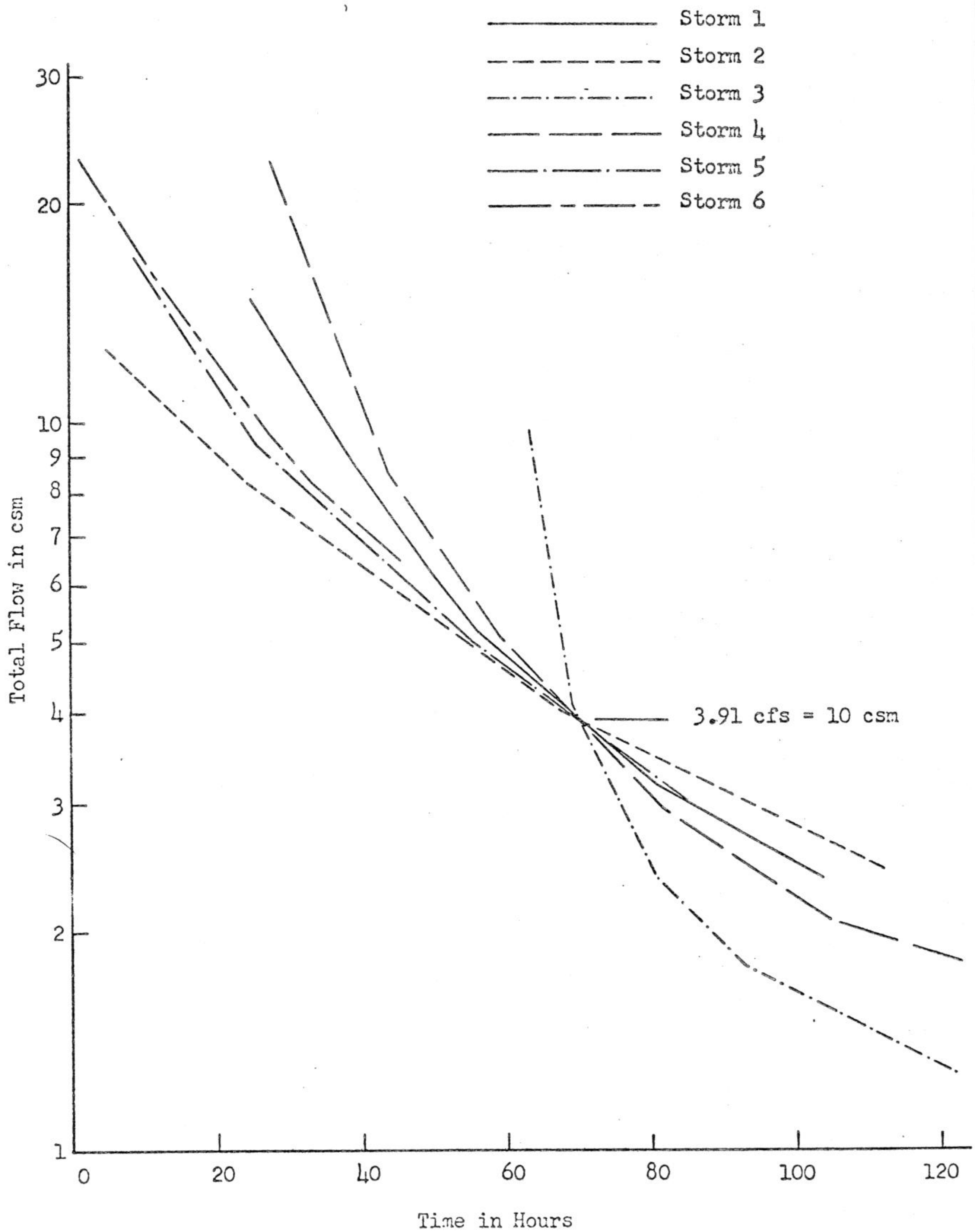


TABLE 6

SIX HOUR RECESSION COEFFICIENTS

Storm	Watershed #1			Watershed #2			Watershed #3		
	20 csm	15 csm	10 csm	20 csm	15 csm	10 csm	20 csm	15 csm	10 csm
1	0.79	0.81	0.88	0.85	0.87	0.94	0.82	0.84	0.89
2	0.86	0.87	0.89	0.90	0.92	0.95	0.88	0.90	0.93
3	0.56	0.71	0.73	-[a]	-	0.83	-	-	0.75
4	0.65	0.76	0.83	0.86	0.88	0.93	0.83	0.83	0.86
5	0.83	0.85	0.88	0.87	0.88	0.90	0.88	0.89	0.90
6	0.72	0.84	0.91	0.89	-	-	0.89	-	-
Average	0.735	0.807	0.853	0.874	0.888	0.910	0.860	0.865	0.866
Maximum/Minimum	1.54	1.23	1.25	1.06	1.06	1.14	1.09	1.08	1.24
Five Storm Average[b]	0.770	0.826	0.878	0.874	0.888	0.930	0.860	0.865	0.866
Five Storm Max./Min.	1.32	1.14	1.10	1.06	1.06	1.06	1.09	1.08	1.08

[a]Where data is missing, the storm recession did not extend through this range.

[b]Average of all storms except storm 3. In several cases it is actually a four storm average because of missing data.

Figure 13 indicates a closer overall correlation between recession coefficients for Watersheds #2 and #3 than between #2 and #1. There also appears to be a significant difference in slope between the two lines, i.e. the recession coefficients of Watershed #1 increase at a faster rate with respect to the recession coefficients of Watershed #2 than do those of Watershed #3. This means that during the early portion of the recession the discharge of Watershed #1 decreases at a much faster rate than the other two watersheds, then flattens out, approaching the recession rates of Watersheds #2 and #3.

Figure 13 indicates a closer overall correlation between recession coefficients for Watersheds #2 and #3 than between #2 and #1. There also appears to be a significant difference in slope between the two lines, i.e. the recession coefficients of Watershed #1 increase at a faster rate with respect to the recession coefficients of Watershed #2 than do those of Watershed #3. This means that during the early portion of the recession the discharge of Watershed #1 decreases at a much faster rate than the other two watersheds, then flattens out, approaching the recession rates of Watersheds #2 and #3.

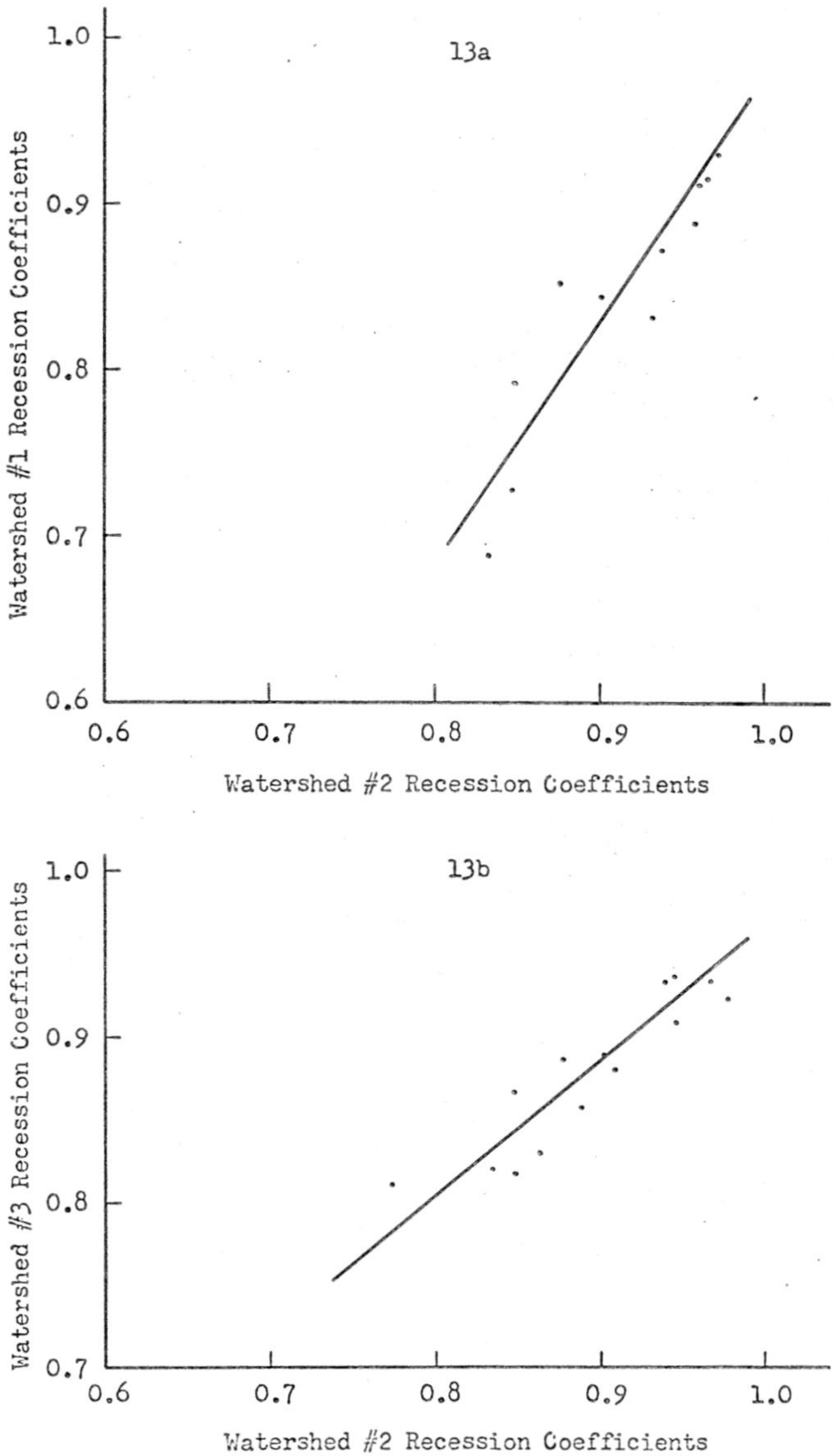


Figure 13. Comparison of six hour recession coefficients.

DISCUSSION

As indicated previously, the large number of variables and the small number of observations precluded a statistical means of defining the relationship between watershed parameters and runoff characteristics. However, a number of observations can be made and a rational approach applied to these observations.

From the differences in soil depths as shown in Table 3 and Figure 3 it can be assumed that there are similar differences in the amount of available storage in the soil. (The most recent soil survey did not indicate any great difference in areas of soils with similar porosity and permeability among the three watersheds.) Therefore, it can be postulated that Watershed #1, having the least amount of available storage, will yield the greatest amount of runoff from a given storm and, its storage being filled faster, will rise at a more rapid rate during the early portion of the storm. Similarly, because of the reduced effect of storage on Watershed #1, it should reach a peak rate of flow sooner following cessation of effective precipitation and should recede more rapidly following the peak due to the lower volume of storage available to sustain flow.

The slightly greater average slope of Watershed #1 should also allow more rapid subsurface flow according to Darcy's Law,

$V = KS$, where V is velocity of flow, S is the hydraulic gradient, and K is a coefficient determined primarily by permeability.

The timing of runoff on Watershed #1 was found to be as expected, i.e., a faster rise, earlier peak, and steeper recession than on the other two watersheds. Watershed #1 produced the most runoff on five out of six storms; however, on only one storm was the volume of runoff from Watershed #1 found to be more than 10% greater than the next highest watershed.

Extending this line of reasoning, it can be further postulated that, on normal storms, Watershed #1 should have the highest peak flow. This assumes a theoretical maximum peak rate of loss to deep seepage (or percolation to a ground water aquifer) -- this rate of loss or percolation to a lower strata should approach a constant value much as surface infiltration rates do. In order to reach this theoretical maximum, a storm of sufficient intensity and duration to completely fill all available storage would be necessary. If this occurred, the hydrographs would flatten at the peak and runoff would continue at this rate until the rainfall intensity decreased or effective precipitation ceased. Under such conditions, then, differences in peak rates of flow would reflect differences in deep percolation rates rather than in available storage.

Examination of the hydrographs used in the study indicated that on none of the storms studied did peak flow reach its theoretical maximum for the rainfall intensity. Thus effective precipitation always ceased before available storage was filled. Because of its lower total storage Watershed #1 would be more nearly filled when rainfall ceased and would be expected to be flowing at a higher rate at this time and thus reach a higher peak. This was found to be the case on all six storms as Table 4 shows. The greater response of peak flow to increases in runoff volume on Watershed #1 than on the other two watersheds, pointed out earlier, could also be attributed largely to a lower detention storage on this watershed.

Although this difference in available storage would seem to give an explanation for the high peak flow of Watershed #1, it cannot be assumed to be the only causative factor. Differences in deep percolation rates could also contribute to such an effect. Although peak flow of Watershed #2 (in csm) averages slightly less than that of Watershed #3, it was greater than Watershed #3 on three of the six storms. Thus it appears that peak rate differentials may be affected by both differences in available storage and differences in percolation rates.

Available soil moisture storage may also help explain differences in interstorm variability of runoff time distribution. Watershed #2, with most storage, would exert the most control over storm runoff. Watershed #1, with the least amount of storage to affect runoff, would be most affected by storm variables such as duration, intensity, and volume. The maximum/minimum ratios, V, shown in Table 5 bear this out for Watersheds #1 and #2 but not quite so well for Watershed #3. Watershed #2 has the greatest maximum/minimum ratio of actual peak flows in csm (Table 4) due to its low peaks on small storms -- again largely a result of greater storage. Variability of peak flows expressed as percent of storm runoff is least on Watershed #2, however.

Figures 14 and 15 show storm runoff hydrographs in inches per hour and rainfall intensity by hourly averages for storms 4 and 5 and are included here to illustrate the differences in hydrographs as affected by fluctuations in rainfall intensity.

Examining storm 4 (Figure 14), it can be seen that Watershed #1 rises continuously for almost 24 hours, then peaks when rainfall intensity drops from 0.24"/hr. to 0.19"/hr. As rainfall intensity drops rapidly to less than 0.10"/hr. it recedes steeply and describes a smooth recession curve. All three watersheds are affected by the three-hour decrease in intensity (to 0.15" /hr.) from 1000 to 1300 (1:00 p.m.) on December 6. This effect takes the form of a reduced rate of rise on Watershed #1 and a two to three-hour flattening of the hydrograph on Watersheds #2 and #3. A two-hour decrease in intensity of smaller magnitude from 1600 to 1800 caused a temporary hydrograph depression on Watersheds #2 and #3, though more noticeable on #3. The next major decrease in intensity, starting at about 1900, caused a hydrograph flattening on Watersheds #2 and #3 with Watershed #3 being affected first (or at a greater rainfall intensity). Watershed #3 then peaked at 2200 and Watershed #2 at 2330 (11:30 p.m.), just one-half hour later than Watershed #1, following a brief period of increased rainfall intensity.

Storm 5 (Figure 15) exhibits a fairly similar pattern of reaction to fluctuations in rainfall intensity. Again, Watershed #1 rises smoothly and, prior to the peak period, its rate of rise

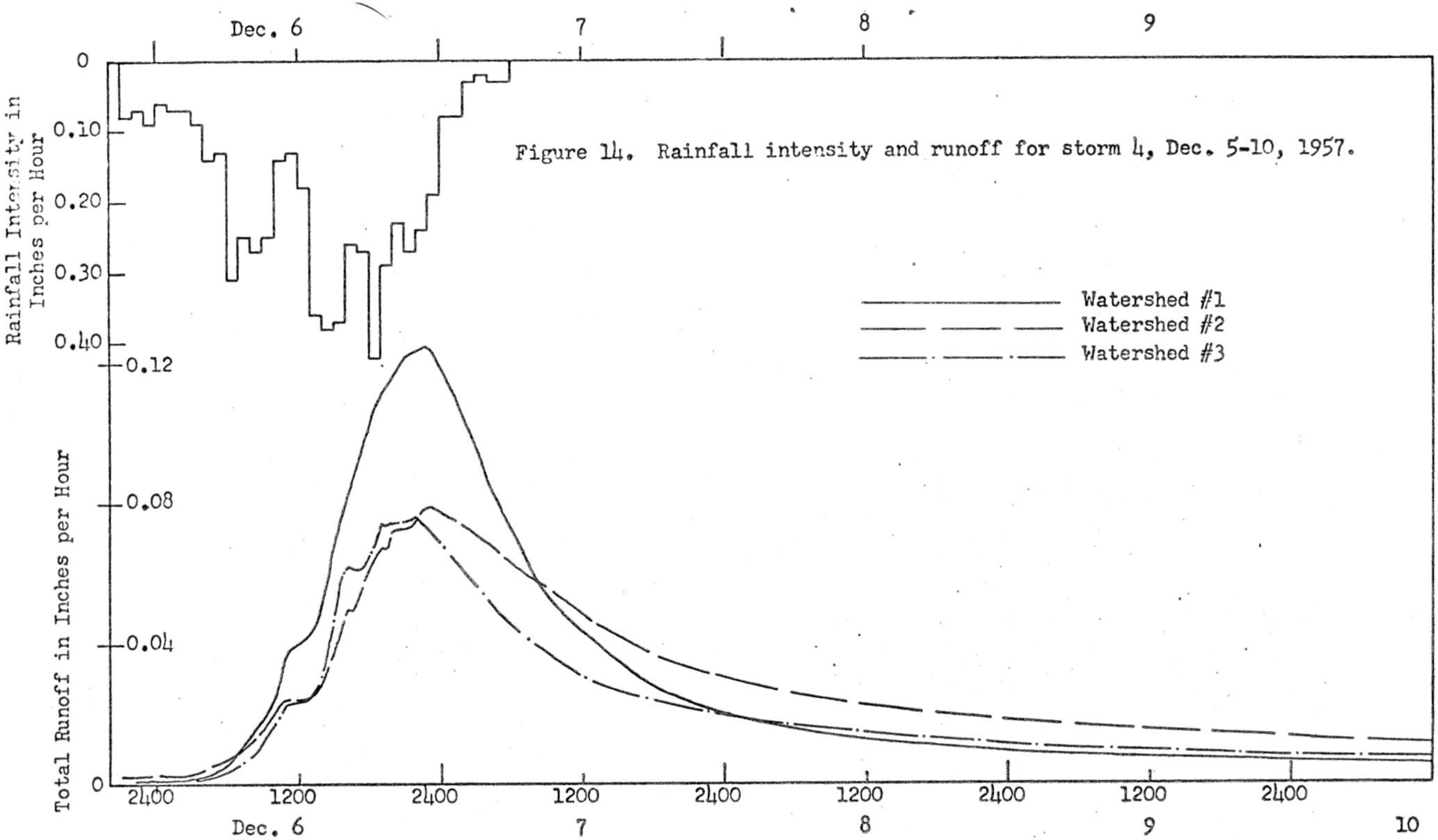


Figure 14. Rainfall intensity and runoff for storm 4, Dec. 5-10, 1957.

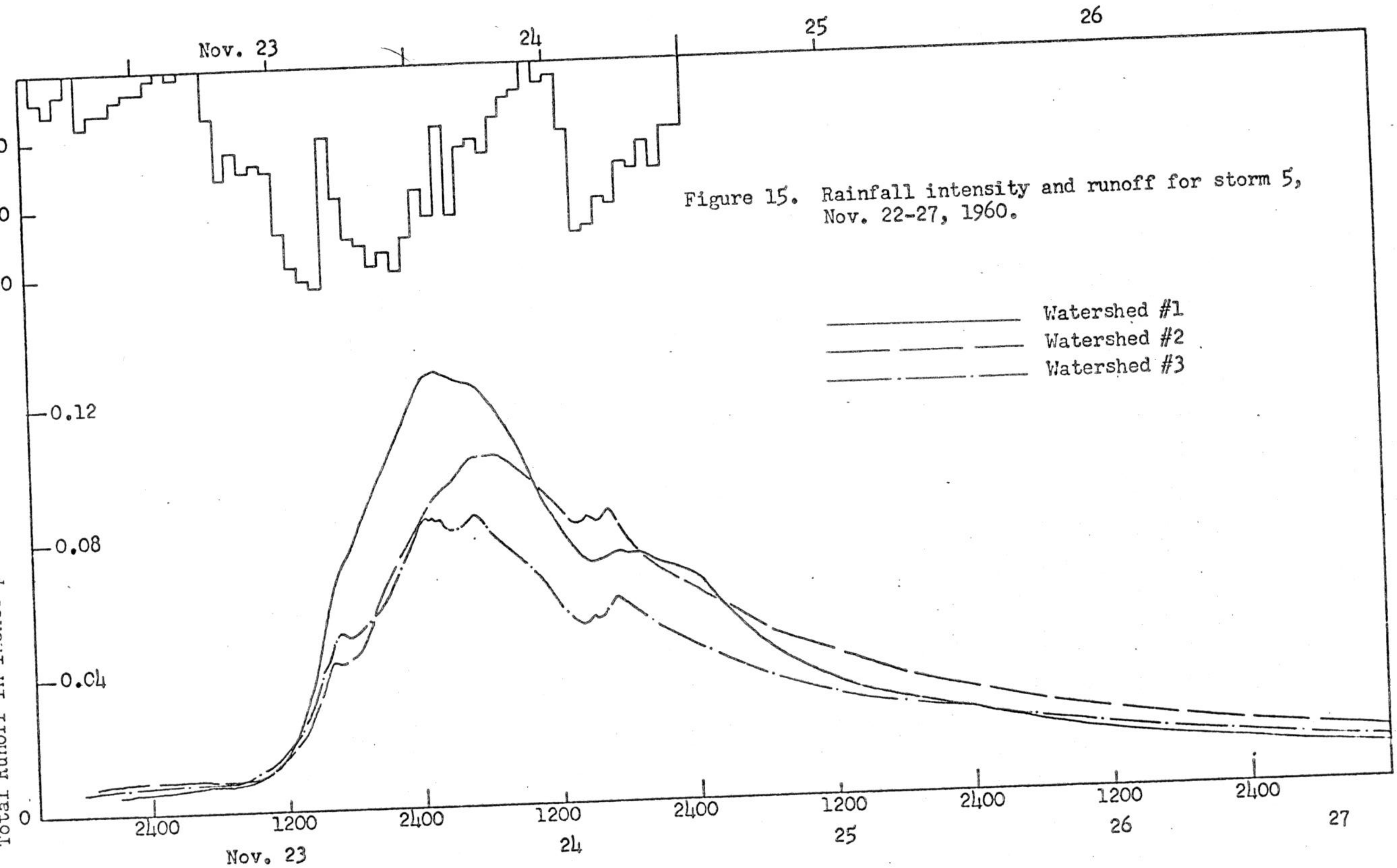


Figure 15. Rainfall intensity and runoff for storm 5, Nov. 22-27, 1960.

is affected only slightly by a decrease in rainfall intensity. Hydrograph depressions are caused on Watersheds #2 and #3 by a decrease in intensity between 1600 and 1800 on November 23. An irregular decrease in intensity from 0000 to 0300 on the 24th causes a leveling, then a marked depression on Watershed #3 while only causing a reduced rate of rise on Watershed #2. A one-hour increase from 0300 to 0400 raises Watershed #3 to its peak at 0445. The hydrograph of Watershed #2 begins to level off at this time and finally peaks at 0615. A second discernible block of effective precipitation which begins at about 1300 on the 24th causes a sharp double peak on Watersheds #2 and #3. Watershed #1 has a smoother hydrograph through this period and recedes very slowly until precipitation ceases. Separation of runoff caused by this second "storm," as described earlier, revealed 0.50" of runoff from this storm on Watershed #1 as compared to 0.36" on both Watersheds #2 and #3. This would further support the premise of greater storage available on Watersheds #2 and #3. The evidence on the relative sensitiveities of the three watersheds to rainfall intensity fluctuations is further borne out by examination of the other storm hydrographs of the study.

From the foregoing illustrations several observations can be made:

1) During the rising limb of the hydrograph Watershed #3 requires the greatest rainfall intensity to maintain rise while Watershed #1 will continue rise with the least intensity of rainfall.

2) Reactions to major rainfall intensity fluctuations are usually reflected in the hydrograph approximately

one-half hour earlier on Watershed #2 than Watershed #3. This may be partially due to the shorter length and more compact shape of Watershed #2. Gradual decreases in intensity usually show up earlier on the hydrograph of Watershed #3, indicating that this watershed is more sensitive to minor decreases in intensity than is Watershed #2. No clear pattern of timing is evident on Watershed #1 in relation to the other watersheds. It may be surmised here that Watersheds #2 and #3 behave more nearly alike than do Watersheds #1 and #2 or #3. For example, fluctuations which greatly affect Watersheds #2 and #3 may not noticeably alter the hydrograph of Watershed #1.

3) For all three watersheds a greater rainfall intensity is needed to maintain a rising hydrograph at high flow than at low flow. This points to the necessity of a differential occurring between input to detention storage and runoff (or outflow from detention storage) in order to maintain a rise in streamflow. At higher runoff rates a greater rate of input, or rainfall intensity, is necessary to maintain a differential.

It might be inferred from such a hydrograph analysis that there is a difference in watershed infiltration capacity among the three watersheds; not surface infiltration but, rather, percolation into strata from which water is released slowly and does not appear as storm runoff. Thus Watershed #1 would have the lowest infiltration capacity and Watershed #3 the highest. It must be kept in mind that such an analysis takes into account infiltration capacity of the watershed as a whole and it cannot be assumed that a soil on Watershed #3 would have a greater rate of percolation than one on Watershed #1.

Analysis of the recession limb of the hydrograph would indicate that Watershed #2 held the greatest amount of detention storage and Watershed #1 the least amount, as evidenced by the high six-hour recession coefficients of Watershed #2 and the low recession coefficients of Watershed #1. Table 3 indicates little difference in soil depths between Watersheds #2 and #3; however, not separately accounted for are the presence and distribution of large areas of deep colluvial soils, particularly on Watershed #2. This difference in soil detention storage is further supported by the fact that summer minimum flows in csm are greatest on Watershed #2 and lowest on Watershed #1.

A difference in soil detention storage would also help account for the difference between total stream lengths in wet and dry seasons on Watershed #1 as compared to the other two watersheds (Table 2). Because of low storage on Watershed #1 many wet weather streams would be dry in summer and would not have been measured in a summer survey.

As mentioned previously, the unit hydrograph was not found to be applicable for characterizing storm runoff from these watersheds. One of the most important assumptions of the unit hydrograph is that all storms of unit duration (i.e., less than or equal to the period of rise of a unit hydrograph), regardless of their magnitudes, produce nearly identical distribution graphs.

This is because of the constancy of such factors as size, shape, slope, drainage density, etc. which control storage and transit of surface runoff. This same assumption is basic to the derivation of unit hydrographs from complex storms, i.e., that the time distribution of runoff derived from precipitation during one part of the storm is the same as the time distribution of runoff from precipitation during any other equal time period of the complex storm. Nash (32) expressed it through his theory of the instantaneous unit hydrograph in which he routs an instantaneous input of runoff-producing rainfall through the linear storage imposed by watershed characteristics. The instantaneous unit hydrograph then gave a characteristic time distribution of runoff from the watershed.

This assumption of equal time distributions of runoff does not seem to be valid for runoff derived from subsurface flow. It appears that the principal reason that unit hydrographs could not be derived from these storms was that the time distribution of runoff from three-hour storm periods was not constant throughout individual storms. It was particularly variable during the rising limb of the hydrograph. The reason for this variability can best be explained by the variation in storage through which the subsurface flow is routed and the variation in the area of the watershed which is actually contributing runoff. This is affected primarily by antecedent moisture conditions.

An example can be considered of a storm occurring when soil moisture is low. (It must be remembered that soil moisture will not be constant throughout a watershed but will be greatest in depressions, at the foot of slopes, and along stream banks.)

During the early part of this storm the only portions of the watershed contributing to storm runoff will be the channel -- through channel precipitation -- and the areas adjacent to stream channels which had a higher moisture content at the beginning of the storm and thus less available storage. As the storm continues and soil storage is gradually filled, the area of watershed contributing to runoff increases. As the contributing area increases, the time base of the runoff distribution graph will also increase because of the greater distance through which water travels under the surface. Thus the time distribution graph of runoff derived from an early portion of the storm will have a steeper rising limb, higher peak, and steeper recession than the time distribution graph of runoff from a later portion of the storm. If the storm continues for a sufficient duration, then runoff should approach a constant time distribution when all of the watershed is contributing runoff.

The condition of a low antecedent moisture as indicated by base flow at the beginning of a storm is present in the case of storms 3 and 4. Storm 3 (Figure 16), with only 2.39" of precipitation and an effective duration of 11 hours, caused streamflow to rise rapidly and recede very rapidly following peak flow, the upper third of the recession being almost as steep as the rising limb. Storm 4, with 5.88" of precipitation and a 20-hour effective duration, caused streamflow to rise almost as rapidly during the early part of the storm as did storm 3. As the storm continued the rate of rise decreased and following the peak the hydrograph receded at a considerably slower rate than that of storm 3 (as indicated by the higher six-hour recession coefficients on storm 4 shown in

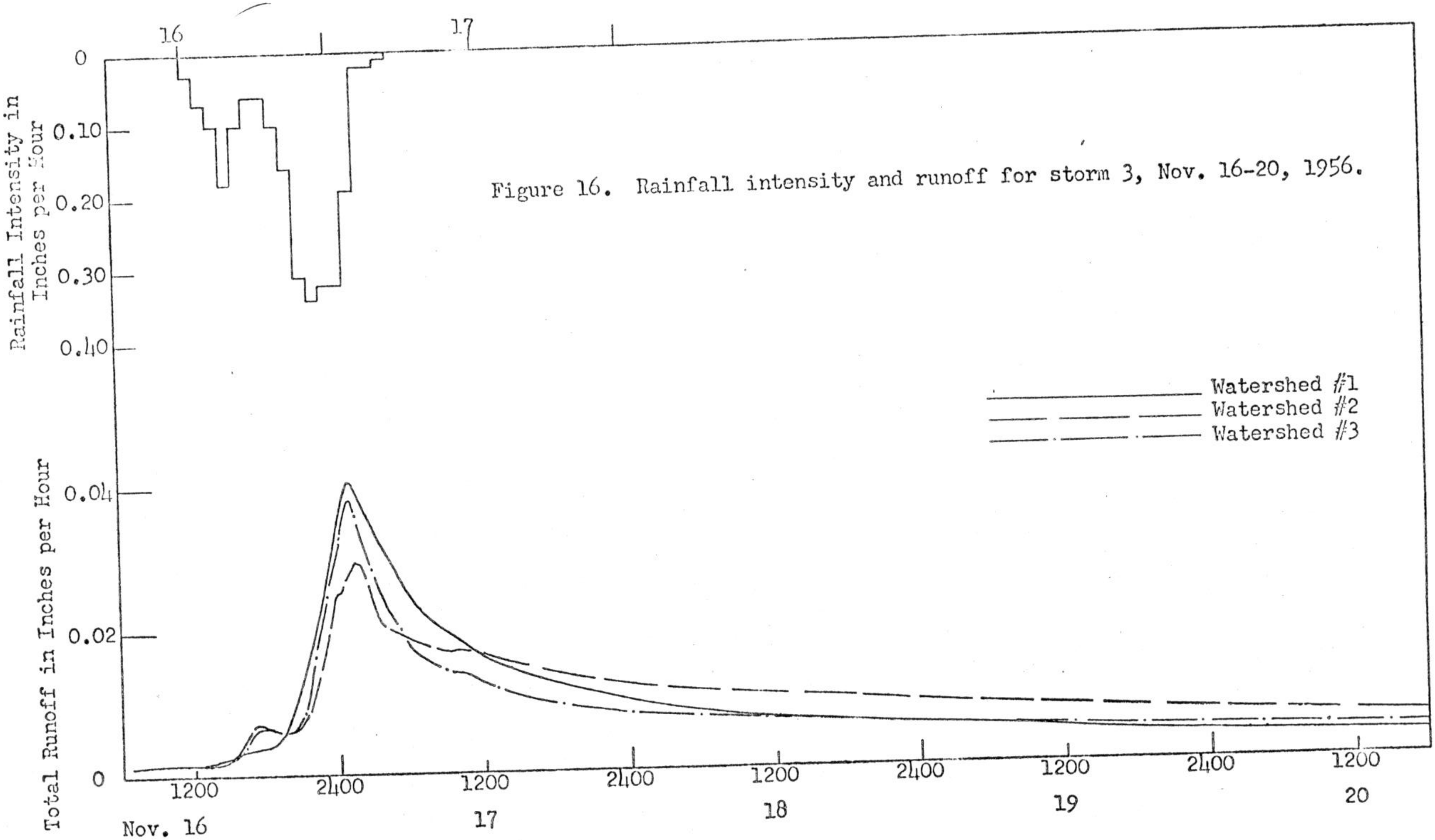


Figure 16. Rainfall intensity and runoff for storm 3, Nov. 16-20, 1956.

Table 6.) Apparently a smaller watershed area contributed runoff on storm 3 than storm 4 because of the smaller volume of rainfall available to go into storage.

Some indication of the increase in storage from storm rainfall can be obtained from the losses column in Table 4. As the table shows, losses on storm 4 are almost double those of storm 3. Storm 2, which had a rainfall volume intermediate between storms 3 and 4 (4.01"), had losses considerably lower than storm 3, yet had much higher recession coefficients than either storm 3 or storm 4. This seeming paradox can be explained by the difference in antecedent moisture as indicated by the antecedent flow, also shown in Table 4. The available moisture storage at beginning of storm 2 was greatly reduced and the accretions to storage, though considerably less than those from storms 3 and 4, raised the total storage to greater volumes and thus gave slower recessions.

Differences in recession coefficients between storms appear to be explainable largely by the factors of antecedent moisture (with antecedent flow as an index) and storm losses. The one exception is storm 6 which has an antecedent flow considerably greater than the next highest, storm 2, and losses of about the same magnitude as storm 4, yet has recession coefficients very similar to storm 2. The relationship between antecedent moisture (or available storage) and antecedent flow may not be the same for this storm as for the other storms due to the fact that 2.66" of precipitation were received in the three days prior to this storm, whereas the periods preceding the other storms were relatively precipitation free.

The relationship between storage and discharge has been developed by many writers (e.g., Riesbol (34), Hursh and Brater (26)) and is usually assumed to be a relatively fixed relationship for a watershed. Most such relationships have been determined for either ground water flow or for surface runoff and/or channel storage. However, this study did not indicate a fixed relationship between storage and discharge for subsurface flow from these watersheds. If such a relationship existed, the recessions from a given watershed would be expected to coincide closely over the same ranges of flow. This was not found to be the case as pointed out and discussed earlier.

It appears that distribution of storage is more important than total watershed storage in determining discharge. The examples cited earlier apply here also. Storms with relatively intense rainfalls may cause high discharges without greatly increasing watershed storage. The recessions of such storms then overlap with recessions of storms having come much nearer to filling the storage capacity -- thus the variation in recession rates occurs through the same range of discharges.

This situation brings into question the accuracy of using composite recession curves for subsurface flow constructed by either synthesizing individual storm recessions or by drawing envelope curves encompassing points plotted for q_o vs. q_t (both of these methods are illustrated by Linsley, Kohler and Paulhus (30)). It would seem that these complete composite recession curves would apply only to depletion of full, or nearly full, storage and therefore would have wide applicability only in the lower segments which would represent drainage from areas near stream channels -- the areas which will have their storage filled most often.

If there were an accurate method of separating ground water flow -- i.e., flow from a continuous, completely saturated medium -- from "subsurface flow" or lateral flow through the non-capillary pore space of the upper soil horizons, a more accurate and consistent recession analysis might be possible and might give results more in line with those reported for ground water or channel storage alone. Technically speaking, much of the storm runoff is probably ground water at the point where it actually enters a stream channel, as the banks and immediate areas adjacent to the stream become saturated. However, the distance through which it has traveled as ground water is probably very short. As Hewlett (17) has demonstrated, unsaturated flow in the range of field capacity can be sufficient to maintain base flow from a steep watershed. It appears likely that most of the stream bank ground water tables are fed during storm periods by unsaturated flow from upslope areas in the range between field capacity and saturation. The continuous "hydraulic pathways" created by biological activity, as described by Hursh and Fletcher (27), are probably quite important in increasing the speed of this flow.

The nature of the apparent percolation into base flow feeding strata which affects hydrograph reactions to rainfall fluctuations is a matter of conjecture. It seems unlikely that it is strictly a vertical movement. A possible explanation is percolation into the deep colluvial deposits present on Watersheds #2 and #3. Percolation rates (both vertically and laterally) would be the determining factor here rather than volume of storage available in the deposits.

As pointed out earlier, lag time seemed to be relatively independent of storm characteristics; however, it could not be shown to be related to the watershed parameters commonly used for predicting lag time of surface runoff. Again, it appears that the factors controlling subsurface flow and their interrelationships are different than those controlling surface flow, and that formulas and methods of analysis developed for use with surface runoff should be used with caution where storm runoff is derived from subsurface flow.

One factor not evaluated, but probably of considerable significance, is the distribution of soils (deep, shallow, and bare rock) and of slopes. Langbein (29) has pointed out that the distribution of slopes, channel segments, and storage areas is often more important hydrologically than total or mean values. It is quite probable that this holds true here -- that this factor makes interpretation of the effect of other factors more difficult and may account for some of the unexplainable differences in runoff characteristics.

SUMMARY AND CONCLUSIONS

This study analyzed data from experimental Watersheds #1, #2, and #3 of the H. J. Andrews Experimental Forest in west-central Oregon to determine runoff characteristics from winter storms, which produce the only flood runoff of consequence in this area. The watersheds are small in size, being 237, 149, and 250 acres, respectively, but are fairly representative of large areas of undisturbed Douglas-fir forests on the western slopes of the Cascade Mountains in Oregon. Topography is steep and rough; soils and parent material are of volcanic origin and have a complex history and pattern of distribution. Predominant soil textures are clay loams, silty clay loams and clays. Of especial importance to this study is the occurrence of deep colluvial deposits, often alternating with thin-soiled steep slopes.

Precipitation and runoff were analyzed for six winter storms varying from 2.39 to 7.67 inches of rainfall. Storm runoff as separated from base flow varied from 0.57 to 4.59 inches.

Composite distribution hydrographs were constructed for each watershed using interstorm average distribution percentages for three-hour periods. Average time from beginning of effective precipitation to peak was used for time placement of these hydrographs. Recessions of total flow were plotted on semi-log paper and six-hour recession coefficients computed for straight line segments of the recessions. Other methods of analysis used included comparisons of storm runoff with precipitation and peak flow with storm runoff, plus a comparison of reactions to fluctuations in rainfall intensity.

Data relating to a number of watershed characteristics including slope, drainage density, and soil depths was analyzed and an attempt made to interpret the effect of some of these characteristics on storm runoff.

The major results and conclusions reached can be summarized briefly as follows:

1) Watershed #1 had the highest peak flows -- both in csm and in distribution percentage, usually peaked first, and had the steepest recessions. Watershed #2 had the lowest peaks and the most sustained recessions. Watershed #3 was intermediate but more closely resembled Watershed #2 in timing of runoff. The differences seem to be attributable primarily to differences in soil moisture storage capacity -- Watershed #2 having the greatest amount of storage and Watershed #1 the least.
2) Interstorm variability in time distribution of runoff was least on Watershed #2 and greatest on Watershed #1. The influence of subsurface storage in regulating storm runoff is suggested as the most probable reason for this difference.
3) There is an apparent difference in percolation capacities to base flow feeding strata which causes Watershed #3 to be the most sensitive to fluctuations

in rainfall intensity and Watershed #1 to be least affected. Exact cause of this hydrograph reaction could not be isolated.

4) Recession analysis did not indicate a fixed storage-discharge relationship for subsurface storm flow. Differences in antecedent conditions and the changing area of watershed contributing to recession flow are believed to be the reason for the varying relationship.

5) In view of the above factors, the unit hydrograph was not found to be applicable for characterizing storm runoff derived from subsurface flow. The unit hydrograph assumption of identical time distributions of runoff from all unit storms was not met -- a consequence of differences in moisture conditions.

6) Lag time was found to be relatively constant for each watershed. However, watershed characteristics commonly related to lag time of <u>surface</u> runoff and used for prediction purposes could not be related to lag time for <u>subsurface</u> runoff. This finding emphasizes the limitations of using regionally developed empirical correlations for predicting storm runoff characteristics in areas where stormwater travels largely beneath the soil surface, and also the need for accurate information on the extent and characteristics of subsurface flow.

In order to better understand the process of water movement beneath the surface, more actual measurements of this flow and determination of the factors which control it are needed. Such information, in combination with hydrograph analysis, may lead to more accurate methods of predicting storm runoff, whether for the purpose of evaluating effects of watershed treatment on runoff or for other purposes.

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APPENDIX

Soil Series Descriptions*

The following is a brief summary of the soil series mapped on the experimental watersheds by a Forest Service soil survey team in 1962. The classification (series names) is strictly provisional at the present time. Watershed #3 was mapped in greatest detail because of impending logging operations as part of the planned treatment and Watershed #1 was mapped in least detail. Because of this difference in mapping intensity, the soil map is not included here. The series are listed in order of decreasing area within the experimental watersheds.

1. Limberlost series:--Regosols intergrading to Brown Podzolic soils formed in colluvium from greenish tuff and breccia bedrock. Texture is a gravelly clay loam to heavy clay loam with 30-60% gravel and stones by volume. Structure is strong fine subangular blocky in upper horizons grading to weak very fine subangular blocky in the C horizon. This soil is well drained and has a moderately rapid permeability. Depth is 2 to more than 10 feet. It occurs on ridges, steep and dissected slopes, and colluvial toe slopes. It is mapped as occupying most of Watershed #1 plus large areas in mid to lower Watersheds #2 and #3.

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*Information provided by C. T. Dyrness, Soil Scientist with Pacific Northwest Forest and Range Experiment Station.

2. Budworm series:--Yellowish Brown Lateritic to Brown Podzolic soils formed in residuum and colluvium from greenish tuff and breccia bedrock. Texture grades from a gravelly clay loam to heavy clay and silty clay loam (in lower horizons) with 0-30% gravel and stones. Structure is strong fine subangular blocky grading to massive. This soil is moderately well drained and has a moderate permeability. Depth is three to more than six feet. It usually occurs on uneven side slopes and ridges. It occupies a small area on Watershed #1 and relatively large areas on mid portions of Watersheds #2 and #3.

3. Flunky series:--Lithosols to Brown Podzolic soils formed in colluvium and residuum from basalt. Texture is a very gravelly loam to clay loam with gravel and stones comprising 50-90% by volume. Structure is moderate to weak fine and very fine subangular blocky. This soil is well drained with a moderately rapid permeability. Depth to bedrock is ten to thirty inches. Its occurrence is on steep smooth side slopes and ridges. This soil is mapped in small areas along the upper ridge of all three watersheds.

4. Frissell series:--Regosols to Brown Podzolic soils formed in colluvium from reddish breccia. Texture is a gravelly loam to gravelly light clay loam with 40-60% stones and gravel. Structure is strong medium granular grading to massive. This soil is well drained with moderately rapid permeability. Depth is 1½ to more than 10 feet (average of 4 feet). It is found on steep side slopes, dissected slopes, and colluvial toe slopes. It is mapped on the lowest portion of Watershed #1.

5. Slipout series:--Reddish Brown Lateritic Podzolic soils formed in residuum and colluvium from greenish tuff and breccia bedrock. Texture is a light clay loam to silty clay loam and silty clay with 10-40% gravel and stones. Structure is moderate fine angular blocky to massive. This soil is imperfectly drained with moderately slow permeability and marshes are often present. It occurs on uneven side slopes and is mapped on two small areas of Watershed #3.

6. Andrews series:--Reddish Brown Lateritic to Brown Podzolic soils formed in residuum and colluvium from reddish breccia bedrock. Texture is a gravelly loam to heavy silty clay loam with 10% gravel to 50-60% tuffaceous and basalt stones. Structure is strong medium granular and moderate fine subangular blocky grading to massive. This soil is well drained and has moderately slow permeability. Depth is 4 to greater than 10 feet. It occurs on side slopes, ridges, and landflows. It is mapped as occupying a small area on Watershed #3.

Table 7

Bulk Density and Soil Porosity
From Three Sites on Watershed #3

Site No.	Depth Class (inches)	Bulk Density	Total Porosity		Capillary Porosity (inches)	Non-capillary Porosity (inches)
			%	inches		
6	0-12	0.87	67.2	8.1	3.9	4.2
	12-24	1.04	60.7	7.3	5.7	1.6
	24-48	1.06	60.0	14.4	12.4	2.0
	Total			29.8	22.0	7.8
9	0-12	1.02	61.5	7.4	4.8	2.6
	12-24	1.15	56.6	6.8	5.4	1.4
	24-48	1.09	58.8	14.1	12.6	1.5
	Total			28.3	22.8	5.5
11	0-12	0.97	63.4	7.6	4.7	2.9
	12-24	1.00	62.3	7.5	5.1	2.4
	24-48	1.16	56.2	13.5	13.4	0.1
	Total			28.6	23.2	5.4

Total porosity computed from bulk density; capillary porosity computed from soil moisture-tension data. Data furnished by R. L. Fredriksen, Research Forester, H. J. Andrews Experimental Forest.

Vegetation

Common and scientific names of species mentioned in text.

Scientific Name	Common Name
Trees	
Acer macrophyllum	big-leaf maple
Alnus rubra	red alder
Castanopsis chrysophylla	chinquapin
Cornus nuttalii	dogwood
Libocedrus decurrens	incense cedar
Pseudotsuga menziesii	Douglas-fir
Taxus brevifolia	Pacific yew
Thuja plicata	western redcedar
Tsuga heterophylla	western hemlock
Shrubs	
Acer circinatum	vine maple
Berberis nervosa	Oregon grape
Gaultheria shallon	salal
Rhododendron macrophyllum	rhododendron
Vaccinium parvifolium	red huckleberry
Forbs	
Coptis lacinata	goldthread
Linnaea borealis var. *Americana*	twinflower
Oxalis oregana	oxalis
Polystichum minitum	swordfern
Xerophyllum tenax	beargrass

From soil survey report by Wollum (49).

Abstract of Thesis

STORM RUNOFF CHARACTERISTICS OF THREE SMALL WATERSHEDS IN WESTERN OREGON

This study was undertaken to characterize and compare storm runoff from three small watersheds in the Douglas-fir region of western Oregon and to account for differences in these runoff characteristics through watershed characteristics. Runoff and precipitation were analyzed for six winter storms on the experimental watersheds of the H.J. Andrews Experimental Forest. The watersheds range in size from 149 to 250 acres and are characterized by steep and rough topography with shallow soils on the steeper slopes, often alternating with deep, bench-like colluvial deposits.

In order to characterize storm runoff, composite distribution hydrographs were constructed for each watershed using interstorm average distribution percentages by three hour periods. In addition, recessions of total flow were plotted on semi-log paper and six hour recession coefficients computed for straight line segments of the recessions. Further analysis included comparisons of storm runoff with precipitation and peak flow with storm runoff, plus a comparison of reactions to fluctuations in rainfall intensity. Available data on soil depth, slope, and several other watershed characteristics was analyzed and an attempt made to interpret the effect of some of these characteristics on storm runoff.

The major findings and conclusions were as follows:

1. Differences in peak flow -- in csm and in percent of total, time to peak, and rate of recession were attributed primarily to differences in soil moisture storage capacity as indicated by relative areas of deep and shallow soils.