INFLUENCE OF TOPOGRAPHY AND SOIL-DEPTH ON RUNOFF FROM FOREST LAND

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Introduction

It has been recognized that topography, size, shape, vegetation, and soil-profile differ for individual drainage-areas. These inherent properties of watersheds together with climatic factors are the principal causes for variations in the hydrologic characteristics of different drainage-areas. These properties account for the differences in unit-tributary contributions to the runoff of the larger streams. Few watersheds are uniform within themselves as regards topography, vegetation, and soil-profile, but small watersheds show less variability in these properties and are, therefore, most useful in the study of contributions of tributaries to runoff of larger streams. They are also more useful in the study of the complete water-cycle, and of the changes within the water-cycle resulting from changes in conditions of vegetation and soil brought about through different land-use practices.

Watershed-studies requiring measurements within the water-cycle are now in progress on the Coweeta Experimental Forest in Western North Carolina. The Forest of 4,200 acres ranges in elevation from 2,200 to 5,200 feet, and contains 30 small drainages with continuous flow. Average annual rainfall ranges from 70 to 80 inches depending on elevation and is distributed throughout the year. Mean annual temperature is 55°F at the elevation of 2,200 feet. Natural growth is composed of deciduous forest with abundant shrubs and minor vegetation. Topography is favorable to the establishment of small independent experimental watersheds.

Results to date indicate that watersheds at the Coweeta Experimental Forest may be roughly classified on the basis of elevation. Watersheds lying largely below an elevation of 3,000 feet are characterized by a soil-profile common to the intermountain areas of the Appalachian Region and Piedmont Plateau. The soil-profile shows deep sub-soil horizons. Shallowest soils occur on the upper slopes, but even here depths of soil of four to six feet are common.

Watersheds above 3,000 feet in elevation are typically more steep. On the slopes, depths of soil are generally less than two feet. However, at the foot of these slopes, and along stream courses, there is an accumulation of a large amount of angular rock-talus and finer material.
These differences in the soil-profile between the lower and higher elevations markedly influence runoff. Characteristics of storage of the deep soil-profiles found on the Coweeta Experimental Forest have been previously discussed [see 1 of ‘References’ at end of paper]. Under natural forest-conditions, infiltration-values are well in excess of occurring rainfall-intensities. The soil-profiles store large quantities of water both as retained soil-moisture and as groundwater. Stream-flow from such areas is subject to a large degree of regulation. A characteristic winter storage of ground-water takes place which sustains ground-water flow well into the growing season. Because no surface storm-flow other than channel-precipitation occurs, peak-rates are comparatively low.

On the higher watersheds, the shallow soils on the slopes have a lower total storage-capacity which is compensated for in part by the high unit-storage of the talus-deposits. Although the latter generally cover only a small portion of any drainage, they contribute considerable storage-capacity. When the soil on these watersheds is wet to field-capacity, water moves down the slope and is stored in the talus-fill. Outflow from this storage occurs at rapid rates because of steep slopes and large voids in the fill-material. This outflow represents a dynamic form of subsurface storm-water and contributes appreciably to the hydrograph during the course of the storm. It is the form of water that accounts for the high unit-rates of storm-discharge that frequently have been reported from mountain forest land.

Higher rates of storm-discharge may be recorded at gaging-stations on the major streams even though the gages are at lower elevations, but these rates are produced by discharge from the tributaries located at high elevations. These upper tributaries not only receive more rainfall, but have less capacity to retain or store rainfall as it occurs. This is illustrated by the peak-discharges recorded at stations Nos. 8 and 9, which gage the two major streams on the Coweeta Experimental Forest (Fig. 1). Total drainage-areas above these gages are 1,677 and 1,788

![Fig. 1--The Coweeta Experimental Forest photographed from 12,000 feet (outside boundaries of the forest and of the drainage-areas discussed, are shown in white (photo by Tennessee Valley Authority))](image-url)
acres, respectively. For the general storm of December 27-29, 1942, the peak-discharge at gage No. 8 was 56 second-feet per square mile, and at gage No. 9, 55 second-feet per square mile. Tributary-drainages that are at the lower elevation, produced peaks of only 23-31 second-feet per square mile. Working with a hydrograph produced by this general heavy storm from gage No. 8, it might appear logical to assign the peak to the whole drainage-area. Actually, a proportionally much greater rate of discharge occurred from the tributaries at higher elevations. To assign a high unit-discharge based on the entire drainage above gage No. 8 to the lower watersheds would lead to a very erroneous analysis of the hydrologic characteristics of tributaries within different ranges of elevation.

Presentation of Data

Figure 1 shows the Coweeta Experimental Forest photographed from 12,000 feet. Watersheds considered in this discussion are numbered. Watersheds 37, 28, and 22 are representative of the areas of higher elevation, whereas watersheds 1, 7, 10, and 14 represent areas of lower elevation. Differences in runoff from the two classes of drainages are illustrated by the storm of December 27-29, 1942. Rainfall of 6.78 to 10.85 inches produced a uniform pattern over the entire forest. Intensities were remarkably uniform with an average of 0.15 inch per hour. At no time did the intensity exceed 0.46 inch per hour. These rates greatly eliminated the factor of intensity as being an important factor in producing surface-runoff insomuch as all of the drainage-areas are in natural forest cover, and have surface infiltration-rates far in excess of the maximum intensities of the storm. Antecedent rainfall had been sufficient to satisfy soil-moisture deficiencies and to cause a general rise of the ground-water level. Data for drainage-area and runoff are shown on Table 1.

Table 1--Drainage-area data, storm of December 27-29, 1942, Coweeta Experimental Forest

<table>
<thead>
<tr>
<th>No.</th>
<th>Area</th>
<th>Elevation</th>
<th>Precipitation</th>
<th>Runoff</th>
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<tr>
<td></td>
<td>acres</td>
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<td>2,315</td>
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<td>14</td>
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<td>2,316</td>
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<td>37</td>
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<td>5,390</td>
<td>5,240</td>
<td>10.85</td>
</tr>
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</table>

a Above prior base, beginning of storm to midnight of January 2, 1943. b Second-feet per square mile.

Figure 2 shows the hydrographs produced by this storm for the areas mentioned, together with precipitation-data at intensity-gage No. 4, situated 3,350 feet above sea-level. Precipitation-data at other intensity-gages follow the same pattern as gage No. 4. It will be seen that the discharges for the watersheds with the deeper soil-profiles are all of the same magnitude, illustrating that they are all from the same type of storage. Peak-rates from such areas range from 22 to 31 second-feet per square mile on the tributary drainage-areas. These rates may be compared with peaks of 67 to 167 second-feet per square mile for the higher watersheds, illustrating high outflow rates from temporary storage in the talus-fills. Although the latter peaks are relatively high, the hydrographs show very definite regulation of runoff by detention-storage. Watershed 37, for which the peak was 167 second-feet per square mile, produced a discharge for the six-hour period--from 10h 00m to midnight of December 29--amounting to 0.72 area-inch at a mean rate of 77.57 second-feet per square mile. This period was well after outflow of channel-precipitation was complete. Runoff for the following day, December 30, amounted to 1.32 area-inches, a mean daily flow of 35.3 second-feet per square inch; for December 31, 0.73 inch, a mean daily flow of 19.7. This amount of water appears to have been detained in the same manner as storm-water in a detention-reservoir. The storage and comparatively rapid release of this amount of water appears to be associated with the talus-deposits on the lower slopes and in the bottoms of the ravines.

Characteristic longitudinal stream-profiles for watersheds at different elevations within the belt of high rainfall of the Southern Appalachian Mountain Region are shown in Figure 3, in which
the lower stream-reaches for the larger areas are not shown. A very rapid increase in slope takes place in the upper portion of the profile of the higher watersheds. At the base of this slope occur the beds of talus-material that appear to exhibit a definite detention-reservoir effect during storm-periods. The profile of watersheds within the lower ranges of elevation do not exhibit these steep slopes.

In the Southern Appalachians, the amount of rainfall increases with elevation. As a result, watersheds at higher elevations generally have more moisture present and consequently operate with less opportunity for storage than drainages at lower elevations. This may have been an important factor in the storm of December 27-29, but it is not the only factor to be considered. Differences in runoff shown in Figure 2 were apparently also closely related to the soil-profile on the two classes of areas, together with the associated difference in opportunity for storage.

**Discussion**

By far the greatest amount of land-area in the Southern Appalachian Region is less than 3,000 feet above sea-level. Under natural forest conditions, this land generally contributes only small amounts of storm-runoff to stream-tributaries. When depleted and misused for agriculture and grazing, however, both opportunities for infiltration and storage are greatly reduced, and drainage-areas with these same soil-profiles may produce measured peaks of 800 to 1200 second-feet per square mile for watersheds of 10 to 20 acres.

Most of the land-areas below 3,000 feet in the Southern Appalachian Region are pastured or cultivated, or because of their accessibility have been heavily cut over for wood products, and hence there is very little undisturbed forest-cover. At the higher elevations, however, which are in effect the headwater-areas for the streams, there is much less farming. Particularly the steep slopes have not been used for agriculture because of the shallow soils and difficult cultural technics. In addition, the accumulations of talus, or rock-bars as they are locally called, cannot easily be logged, and consequently trees are more likely to be present, giving the appearance of a heavy forest-cover. Because vegetation has been little disturbed, runoff-characteristics of
streams draining such areas have been considered to represent the effects of a forest-cover. However, on many of these headwater-areas, the geologic factors are expressed in the thin soils and deep talus-slopes in the ravines may be far more important than effects of vegetation. Vegetation actually does have a tremendous influence on the thin soil-profiles on such areas, being directly responsible for the organic material which protects the mineral soil on extremely steep slopes. Without this organic development, it is conceivable that no soil whatever would remain on the steep slopes in the Southern Appalachians and that the talus-fills would be rendered less efficient in producing the controlling effect they now exert. On forested watersheds where peak-discharges are now high, the principal consideration is not the present magnitude of the peaks, but rather what would be the actual runoff-rates if no vegetation were present. In making a comparison of the effect of different land-use types upon runoff, it is obviously necessary that the studies under consideration all be carried out on watersheds of the same general hydrologic characteristics with regard to the nature of the soil-profile.

The remarkable similarity of the unit-discharge rates from watersheds at the lower elevation shown by Figure 2 indicates that these watersheds, although differing in size, shape, and aspect, are controlled principally by the uniform soil-profile type and associated natural forest-cover. Soil and topographic conditions similar to those at the lower elevations of the Coweeta Experimental Forest may be found throughout the Southern Appalachian Mountains and Piedmont Plateau. Preliminary observations indicate that wherever the same general conditions of soil and vegetation-cover exist, there occur similar conditions of high infiltration and storage of rainfall during prolonged storms, such as have been recorded at the Coweeta Experimental Forest. This suggests that the results of studies obtained on the Coweeta Forest at an elevation below 3,000 feet may have a wide application to the land-use problems throughout the deep, red-clay soils of the Southeastern and Middle Atlantic States. The results obtained from watersheds above 3,000 feet apply principally to steeper mountain ranges of the Southern Appalachian Region.

Summary

This paper is a report of tributary-contributions from small drainage-areas to the runoff of larger streams within the Coweeta Experimental Forest. Storm-runoff is discussed for the storm of December 27-29, 1942. This storm—6.78 to 10.85 inches—produced the same general rainfall-pattern over the entire forest. Average intensities were quite low—0.15 inch per hour with maximum 0.46 inch per hour. Small tributary drainage-areas—40 to 212 acres in size—produced maximum peaks of 22 to 32 second-feet per square mile. For drainage-areas of similar size, but with elevation well above 3,000 feet, peaks of 68 to 167 second-feet per square mile were recorded. Difference in peaks is assigned in part to greater rainfall at higher levels, but it is also related to soil-depth, topography, and hydrologic characteristics associated with the different elevations.

References


DISCUSSION

WALDO E. SMITH (U. S. Soil Conservation Service, Washington, D.C.)—The authors have presented, in a very interesting and instructive manner a picture of the influences of topography and soil-profile on runoff from a given rain in the forested Coweeta Area. An additional column in Table 1, showing the retention of the rain on all watersheds, would have been revealing, and is shown in Table A.

The first group of watersheds, lying at the lower elevations, all had uniformly high retention as compared with the second group as a whole. However, within the second group there is great variation, and on the largest watershed of the group (No. 28) the retention was the greatest of all the watersheds listed. However, the general trend—relatively low retention on the steep upper watersheds, more on the lower and flatter ones—conforms to the findings of flood-control studies made in the Department of Agriculture to determine the relative retentive qualities of various soil-profiles in the Southeast.
Table A

<table>
<thead>
<tr>
<th>Watershed No.</th>
<th>Area (acre)</th>
<th>Retention determined from Table 1 (inch)</th>
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</table>

Rain-gage No. 4, with a total rainfall of about 8.3 inches (Fig. 3), corresponds quite closely with the average rainfall of 8.37 inches on Watershed 22 (Table 1). It is of interest to note that the peak-rate of runoff from Watershed 22 was 68 second-feet per square mile—about 0.1 inch per hour. The rainfall for an hour near the end of the storm just preceding the peak was about 0.3 inch, thus indicating that a balance between rainfall and runoff had not been reached and that detention plus retention was increasing at a rate of about 0.2 inch per hour, or somewhat more, since the peak-rate of runoff did not occur until after the termination of the rainfall-rate of 0.3 inch per hour.

By extrapolation, the rainfall-rate on Watershed 37 during the high hourly rate shortly preceding peak-flow was about 0.39 inch per hour. The peak-rate of runoff was 167 second-feet per square mile—about 0.26 inch per hour. Thus, detention plus retention was increasing at a rate of about 0.13 inch per hour, or somewhat more as explained above. From the rapid subsequent outflow it appears that this should probably be classified as detention, and had the rates of rainfall that preceded the peaks by about an hour continued for an hour or so more, the resulting peaks would have closely approached the rates of rainfall.

Figure 3 suggests that instead of using elevation as a basis for classification of watersheds, the longitudinal profile might be used to better advantage. Profiles for Watersheds 1, 7, 10, and 14 all tend toward parallelism although their elevations are quite different. Watershed 22, which apparently has no more area above 3,000 feet than Watershed 10, has much steeper slopes, which is an influence in the difference in performance. If one is to use a classification based on elevation, judging from Figure 3 one might say that 3,500 feet would be a better dividing elevation than the 3,000 feet used by the authors.

The authors made no mention of the number of rain-gages from which the average depths of rainfall shown in Table 1 were determined, or anything concerning their exposure. Because of the substantial variation in amount of precipitation, this is important. In a paper presented before the Section of Meteorology on the subject "A comparative study of rain-gages," the authors, H. C. STOREY and E. L. HAMILTON, who are connected with the San Dimas (California) Experiment Station of the Forest Service, raised again the old question of accuracy and significance of records of rainfall in mountainous country. The discussion brought out that a rain-gage with its top parallel to the slope and otherwise satisfactorily exposed would be a measure of the catch on the inclined area. It would appear to the writer that while this may be correct, the vertical angle of the falling rain may theoretically be used with the degree of slope to correct the catch in a rain-gage set with its top in a horizontal plane in order to get the average catch in the horizontal projection of the inclined area (see Fig. 1).

Referring to Figure 1, if rain is falling at an angle $\alpha$ with the vertical, and $M$ is the catch in a rain-gage installed with its top in a horizontal plane, then $M'$, the corrected value for the catch on the horizontal projection of the slope is $M' = M[(L + H \tan \alpha)/L] = M(1 + \tan \theta \tan \alpha)$, in which the sign is plus if the slope is exposed, as shown in Figure 1, and negative if sheltered.

If the rain falls in a vertical plane that is perpendicular to the axis of a symmetrical watershed, however, the deficiency of rain below the average on the sheltered side of the watershed tends to be compensated for by excess above the average on the exposed side. But if the rain falls in a vertical plane that tends to parallel the axis of the watershed, the error tends to be greater. Studies should demonstrate whether or not the theoretical correction outlined applies to the usual type of measurements of precipitation in mountainous country, and should be of great help in determining correct quantitative measurements of rainfall on steep slopes and mountain watersheds.