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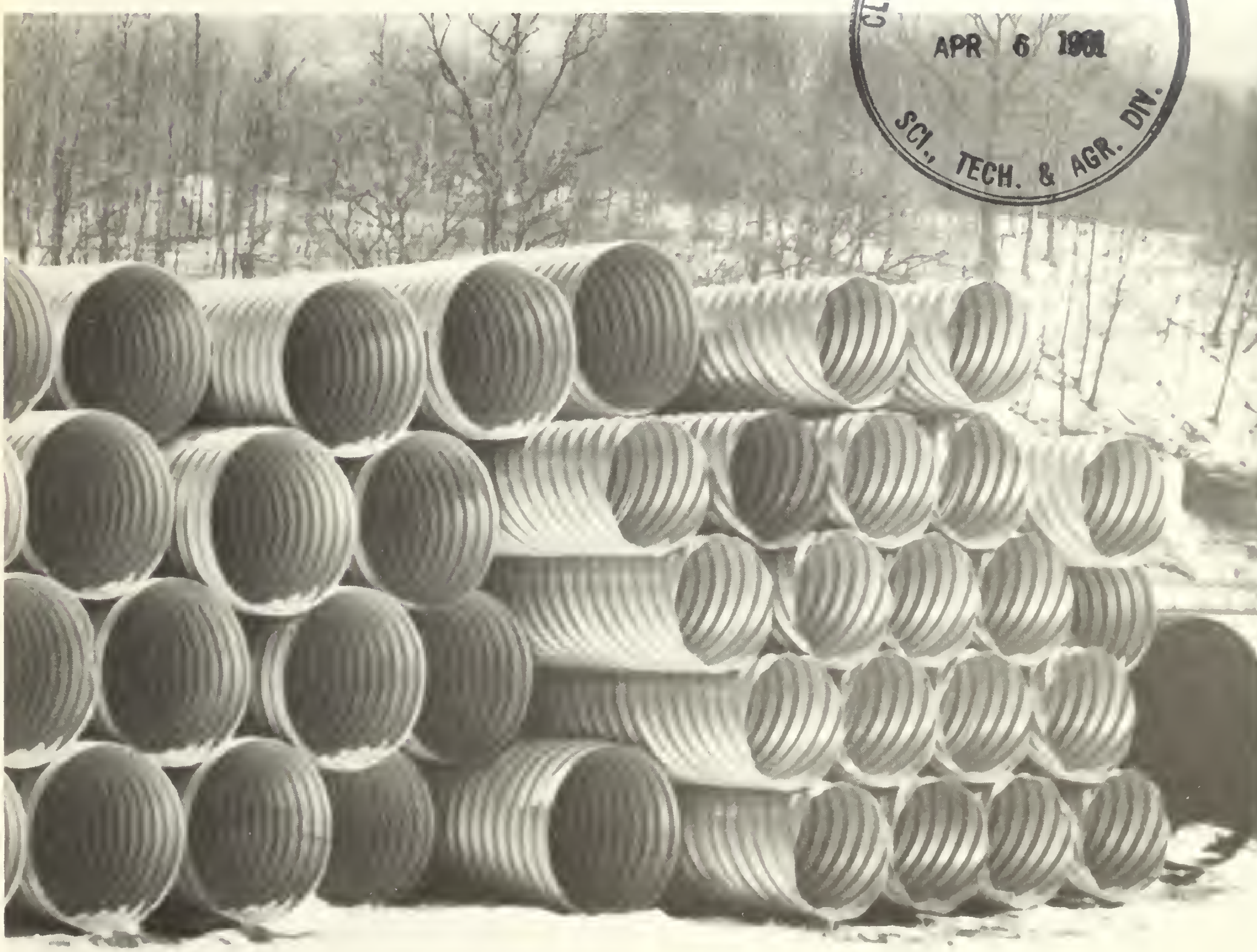
Flood Frequency and Culvert Sizes Needed for Small Watersheds in the Central Appalachians

by J. D. Helvey



The Author

J. D. HELVEY is a research hydrologist at the Timber and Watershed Laboratory, Northeastern Forest Experiment Station, Parsons, West Virginia. He received a B.S. degree in forestry at West Virginia University and an M.S. degree in forest hydrology from the University of Georgia. He joined the Forest Service in 1959.

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Abstract

Estimates of peak discharge from small watersheds (<100 acres) within the Central Appalachians are presented for recurrence intervals of 5, 10, 20, and 50 years. Drainage area was well correlated with estimated peak discharge for each recurrence interval. Peak discharge was significantly greater from two watersheds that had been farmed for many years than from the drainages of similar size that had never been cultivated. Culvert sizes needed to carry the expected flow rates also are presented.

Introduction

Douglass (1974) analyzed records from several small watersheds at the Coweeta Hydrologic Laboratory near Franklin, North Carolina, to determine peak discharge for various recurrence intervals. He presented equations and a graph which indicated that peak discharge for a given recurrence interval is a function of drainage area and elevation of the highest point on the drainage basin. These results provide information necessary to ensure that a culvert or bridge opening is large enough to carry the expected flow rate during the life of the structure, but not larger than needed. To install an undersized structure risks the loss of a section of road at the stream crossing during high flow; oversized structures waste finances.

The relationships presented by Douglass have not been tested at other locations within the Appalachian mountains. These guidelines are needed in the Central Appalachians, where hundreds of miles of logging roads are built and thousands of culverts are installed each year.

The objectives of this paper are to (1) analyze streamflow data from forested watersheds in north-central West Virginia and compute flood frequencies for these areas, and (2) present culvert sizes needed to carry the expected peak discharge for various drainage areas and computed flood frequency.

The Study Area

This study includes data on nine watersheds from two general locations near Parsons, West Virginia: The Fernow Experimental Forest (Fernow Watersheds 1-7) and the headwaters of Clover Run (Clover Watersheds 8 and 9). Both areas are within the Allegheny Mountain Range of the Appalachian Plateau.

The Fernow watersheds

The Fernow Experimental Forest is located about 4 miles southeast of Parsons at latitude 39°03′N and longitude 79°38′W. The soil type is predominantly Calvin silt loam (USDA Soil Conservation Service 1970). underlain by fractured sandstone and shale. Soil depth ranges from about 3 to 5 feet; the humus layer averages about 2½ inches; and infiltration and permeability of the undisturbed soils are high (Reinhart et al. 1963). Elevation ranges from 2,100 to 2,850 feet above mean sea level. Slope averages 30 percent but about a fifth of the area exceeds 40 percent.

When the research program began in 1951, the area supported an uneven-aged mixture of hardwood species including red oak, chestnut oak, white oak, sugar maple, yellow poplar, black cherry, and American beech. The area was never cleared for agriculture, but it was heavily logged between 1905 and 1910. Wildfire and grazing by domestic animals have not occurred at least since 1930.

All of the Fernow watersheds except number 4 have received cutting prescriptions ranging in intensity from light selection to clearcutting (Kochenderfer and Aubertin 1975). Possible effects of this cutting on peak discharge will be discussed later.

The Clover watersheds

The Clover watersheds are located about 9 miles northwest of Parsons at latitude 39°07′N and longitude 79°48′W. The soil series is predominantly Calvin but parts of the area are occupied by the Dekalb and Gilpin series. Soil depth varies from 2 to 4 feet; infiltration capacity is low when the soil is wetted; and permeability is moderate (Lima et al. 1978). Elevation ranges from 2,350 to 2,850 feet. Slope averages about 36 percent but a fourth of the area exceeds 40 percent.

Lima et al. (1978) attempted to reconstruct the history of land use on the Clover watersheds. Their description indicates that land use in the area was typical of a large part of the Appalachians. The forest was cleared in the mid- to late 1800's. Crops were grown year after year without the application of soil conservation practices. Severe erosion and depletion of soil nutrients continued until productivity was too low to produce a crop.

According to Lima et al. (1978): "An aerial photograph taken in 1933 indicates that once-cultivated fields were predominantly in grass; they also contained small trees and other pioneer vegetation. Apparently this farm had been abandoned before 1930." The area was purchased by the USDA Forest Service in 1941 and in 1956 it was selected for study of the relationship of natural reforestation of abandoned farmland on hydrologic parameters.

An analysis of water yield trends indicated that annual streamflow between 1958 and 1970 did not change during these years as a result of the natural revegetation (Lima et al. 1978). The authors concluded that the area was fully recovered in terms of evapotranspiration losses before the measurements began in 1958.

Precipitation on both study areas is well distributed during most years; monthly averages over a 20-year period range from 3.6 inches in October to 5.4 inches in June and July. Winter storms are typically long in duration with intensity generally below 0.5 inch per hour. Approximately 10 percent of annual precipitation falls as snow, but snowmelt rarely causes significant flooding in these headwater streams. Summer storms often are showers of short duration that are caused by convective clouds which produce intensities up to 2 inches per hour for short periods.

Because of fairly shallow soils and steep slopes, flow is closely correlated with precipitation, especially in the dormant season when available space for soil moisture storage is limited. On the average, water yield is greatest in March and least in September.

Methods

Streamflow is measured with 120° V-notch weirs and FW-1 water level recorders. This analysis begins with computer output data that list the magnitude and date of the maximum instantaneous flow rate from each watershed during each year. The first step in the analysis was to test for changes in peak discharge associated with the watershed treatments. This was done by developing a simple regression for the period of record before treatment using the concurrent peak on the control watershed as the independent variable. If the measured peak after treatment was significantly greater ($P = 0.05$) than the value predicted by the regression, it was adjusted to the expected value.

Log Pearson and Gumble methods

Several methods are available for evaluating recurrence intervals of floods from measured peak discharge data. The Water Resources Council (1976) recommended the Log Pearson Type III procedure when record length exceeds 10 years. Douglass (1974) followed the recommendation of Dalrymple (1960) and used the Gumble distribution (1941) to determine the recurrence interval of peak flows. He then tested the data for homogeniety and defined the relationship between peak discharge and drainage area. Both the Gumble and Pearson methods are used in this analysis and the results compared and evaluated.

For both methods, the first step is to list the annual maximum discharge for each watershed for the period of record. For the Gumble distribution, the next step is to rank the tabulated values from highest to lowest and assign the largest value 1, the next largest 2, etc.; the smallest annual peak is assigned the number equal to the number of years of record. Next, the recurrence interval (T) for each annual peak is computed by the formula:

$$T = \frac{n + 1}{M} \qquad (1)$$

where n is the number of years of record and M is the rank number, i.e., the largest value = 1, the second largest = 2, etc. Finally, a plotting is made with T as the independent variable and flow rate as the dependent variable. When all of the points have been plotted, an eye-fitted line is drawn through them as suggested by Douglass (1974). He stated that:

> "The graphical mean has been found to be more stable and dependable than the arithmetic mean because, with graphical means, greater weight is given to medium-sized floods than to extreme floods. Furthermore, the graphical mean is not adversely influenced by the chance inclusion or omission of a major flood."

Flow rates for selected recurrence intervals are read from the graph.

The second step in the Log Pearson analysis is to compute a skew coefficient for each watershed from the tabulated peak discharge values. The skew coefficient (G) is defined as:

$$G = \frac{N^2 (\Sigma X^3) - 3N (\Sigma X) (\Sigma X^2) + 2 (\Sigma X)^3}{N (n - 1) (n - 2) S^3} \qquad (2)$$

where X is the logarithm of annual peak flows, N is the number of years of record, and S is the standard deviation of logarithms.

The logarithms of peak discharge for selected recurrence intervals are computed by the equation:

$$\text{Log}_{(10)} Q = \overline{X} + KS \qquad (3)$$

where K is a tabulated value which is a function of the computed skew coefficient (G) and the desired flood recurrence interval, S is as defined above, and $\overline{X}$ is the mean of the logarithms of peak discharge. For this analysis, floods with recurrence intervals 5, 10, 20, and 50 years are computed.

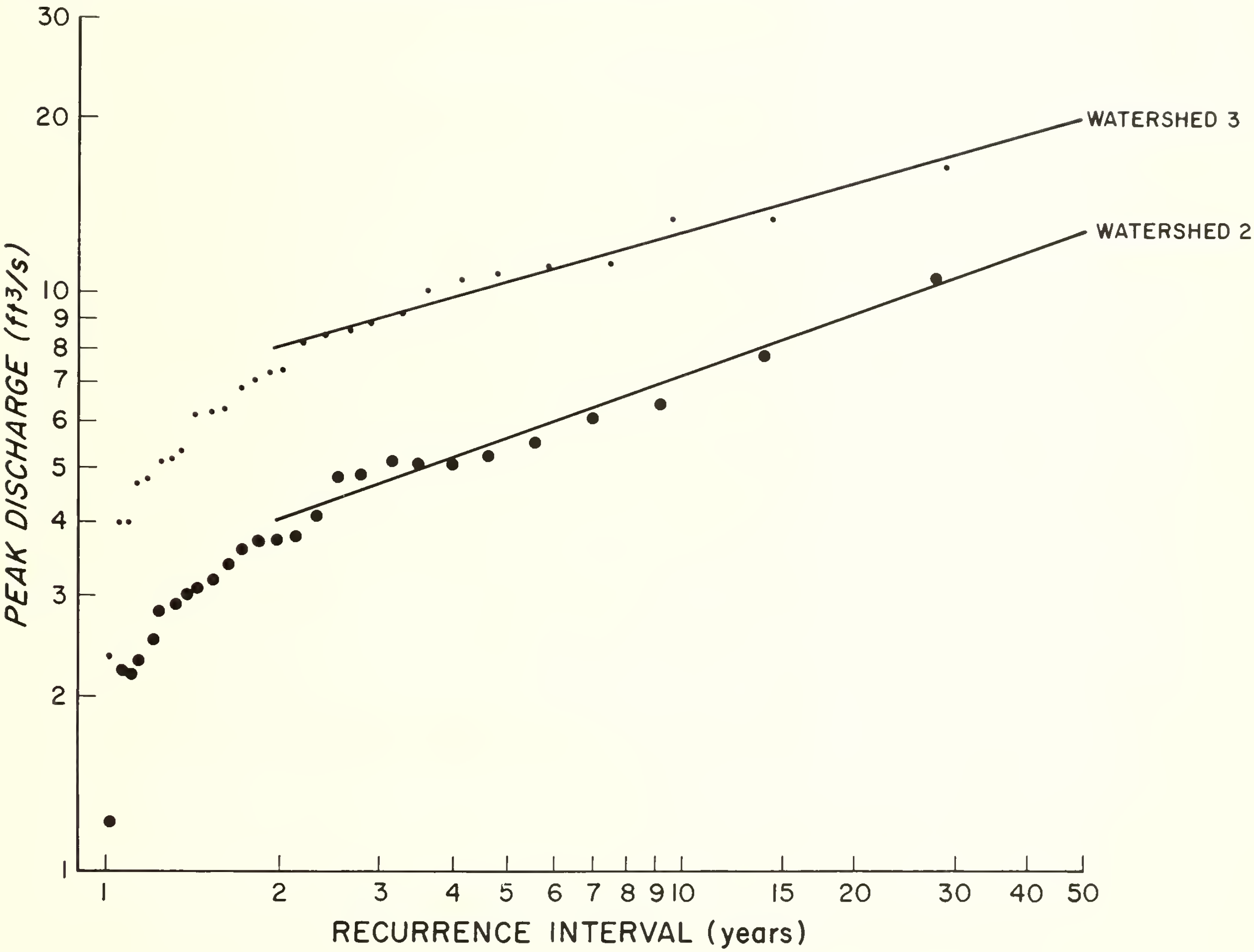
Results and Discussion

The test for changes in peak discharge after watershed treatment indicated no significant effects except on Fernow watersheds 6 and 7 when clearcutting was followed by herbicide spraying to maintain a barren condition. During this period, peak flow was significantly increased during 2 years on watershed 7, and 4 years on watershed 6. Possible changes in smaller peaks were not investigated in this study, but Patric (1973) found higher peak flows on clearcut watersheds during the growing season, especially in small storms.

The Gumble and Log Pearson Type III methods produced results that agreed well at the 5- and 10-year recurrence intervals. For all nine study watersheds, peak discharge as computed by the Gumble method exceeded that computed by the Pearson method by an average of 7 percent. Peaks calculated by the Gumble method were 16 and 36 percent higher at the 20- and 50-year recurrence intervals, respectively, than the values calculated by the Pearson method. One advantage of the Pearson method is that no personal judgement is required; that is, the Gumble method requires that flood values be estimated from an eye-fitted curve. Therefore, it is possible for two people to obtain slightly different answers from the same data set. The Pearson method, a straight forward computation procedure, produces uniform results for a data set. In spite of this advantage, the Gumble method seems to give more reasonable results for the data analyzed here. Therefore, the remainder of this paper is based on results computed by the Gumble method.

Figure 1 shows the relationship between recurrence interval and peak discharge rate for Fernow watersheds 2 and 3 (Fig. 1). These results compare well with results by Douglass (1974) in that both the Coweeta and Fernow data show an approximately linear relationship on log-log paper for recurrence intervals greater than 2 years. Below 2 years, the relationship for both areas is strongly curved.

Figure 1.—Discharge vs. recurrence interval for two watersheds at the Fernow Experimental Forest. The lines are eye-fitted to the plotted points.



Clover vs. Fernow watersheds

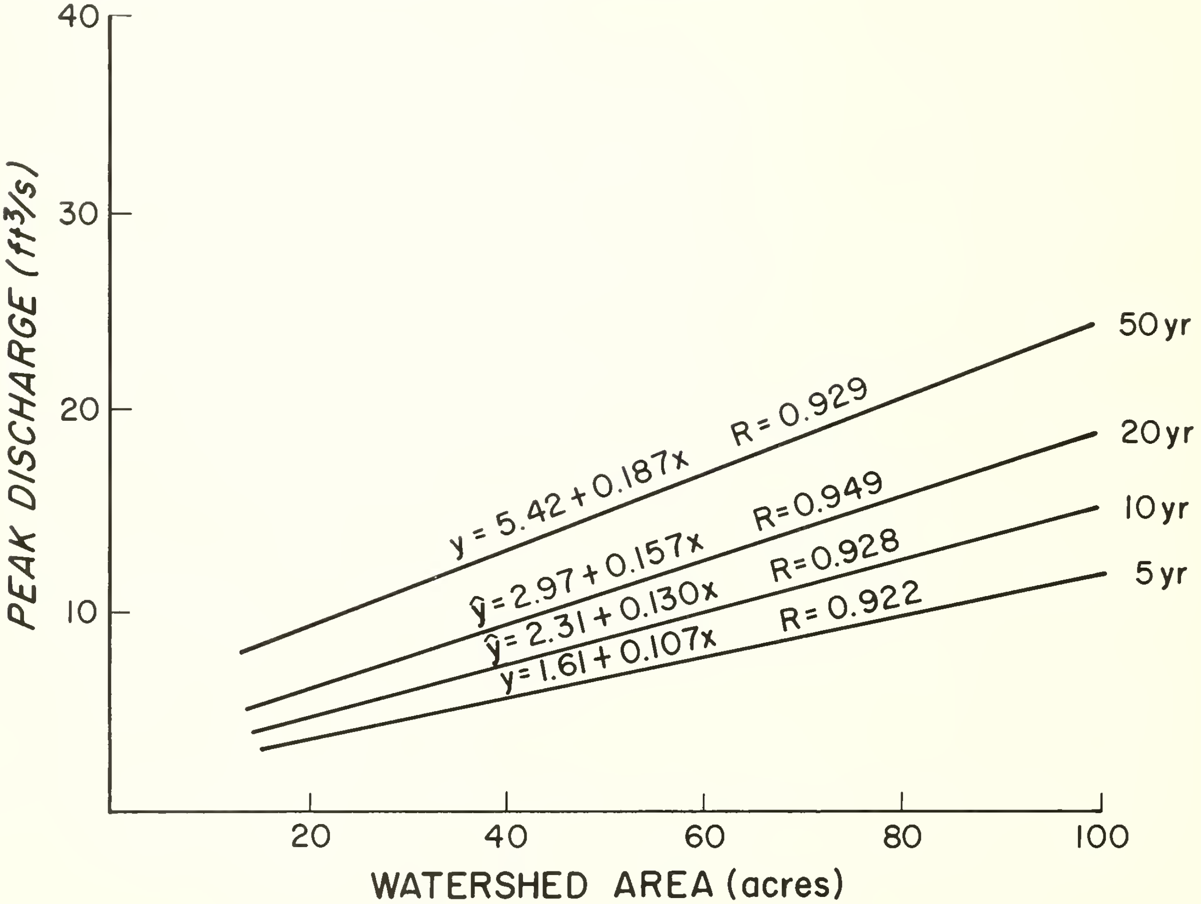
In Table 1, each of the study watersheds is listed along with estimated floods, at recurrence intervals of 5, 10, 20, and 50 years. A plotting of these data indicated that the Clover watersheds (8 and 9) produce significantly greater flood peaks for a given recurrence interval than Fernow watersheds of similar size. There are at least two possible explanations: (1) agriculture depleted the organic layer to an extent that detention storage is reduced and, (2) the hydrologically sensitive streamside area was increased during the years of cultivation when flood peaks probably were much greater than on undisturbed watersheds. Although Lima et al. (1978) could find no influence of revegetation on annual water yield, this analysis indicates that abandoned agricultural land may require larger culverts to carry streamflow than an equal area that never has been farmed. In fact, computed peak flow is almost double on the two farmed watersheds than on the watersheds that were not farmed.

Table 1.—Peak discharge for selected recurrence intervals computed by the Gumble method

Watershed	Area (acres)	Recurrence interval (years)			
		5	10	20	50
		ft^3/s			
1	74	9.8	12.0	15.9	20.0
2	38	5.6	7.2	9.3	13.0
3	85	10.0	12.2	15.0	19.0
4	96	10.6	13.2	17.2	22.5
5	90	13.0	15.8	19.2	25.0
6	54	7.1	8.8	11.0	15.0
7	59	8.0	9.8	12.0	16.0
8	47	11.4	16.0	22.0	34.0
9	29	5.3	7.8	11.5	19.0

The relationship of estimated flood from undisturbed watersheds at 5, 10, 20, and 50 years recurrence intervals are plotted in Figure 2 as a function of drainage area. This

Figure 2.—The relationship of peak discharge and drainage area for four recurrence intervals; peak discharge is estimated by the Gumble Method.



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Estimates of peak discharge from small watersheds (<100 acres) within the Central Appalachians are presented for recurrence intervals of 5, 10, 20, and 50 years. Drainage area was well correlated with estimated peak discharge for each recurrence interval. Peak discharge was significantly greater from two watersheds that had been farmed for many years than from the drainages of similar size that had never been cultivated. Culvert sizes needed to carry the expected flow rates also are presented.

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Keywords: Floods, small watersheds, hardwood forest, Central Appalachians

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figure can be used to predict the maximum flow rate for areas similar to the Fernow watersheds for selected recurrence intervals if drainage area is known. A topographic map or aerial photograph can be used to estimate drainage area above a potential stream crossing where a culvert or bridge will be installed.

After the expected peak discharge has been determined, the next task is to determine the culvert size or bridge opening needed to carry this flow. Several variables must be evaluated before a determination can be made. These include channel slope, which determines stream velocity, whether flow is controlled at the culvert entrance or outlet, and the expected life of the structure. Since flow rate in volume per unit time is the product of cross-sectional area and stream velocity, a sluggish stream on a gentle gradient will require a larger culvert or bridge opening than the same flow rate on a steep gradient where velocity is higher.

The expected life of the structure should be considered in conjunction with computed flow rates at the various recurrence intervals. For example, if a culvert has a probable life of 25 years, does it make sense to make it large enough to carry a 50- or even 100-year flood? What will be the damage to the road and water quality if a 50-year flood occurs where the design capacity of culverts was only 25 years? What are the cost differences of a larger culvert versus the environmental consequences of an overtopped culvert? For an excellent discussion of these questions, see Valentine (1974).

The culvert sizes listed in Table 2 were derived from the following assumptions: (1) maximum depth of water at the upstream end of the culvert is equal to the culvert diameter, (2) the downstream end of the culvert is not submerged, and (3) culvert slope ≥ 2 percent.

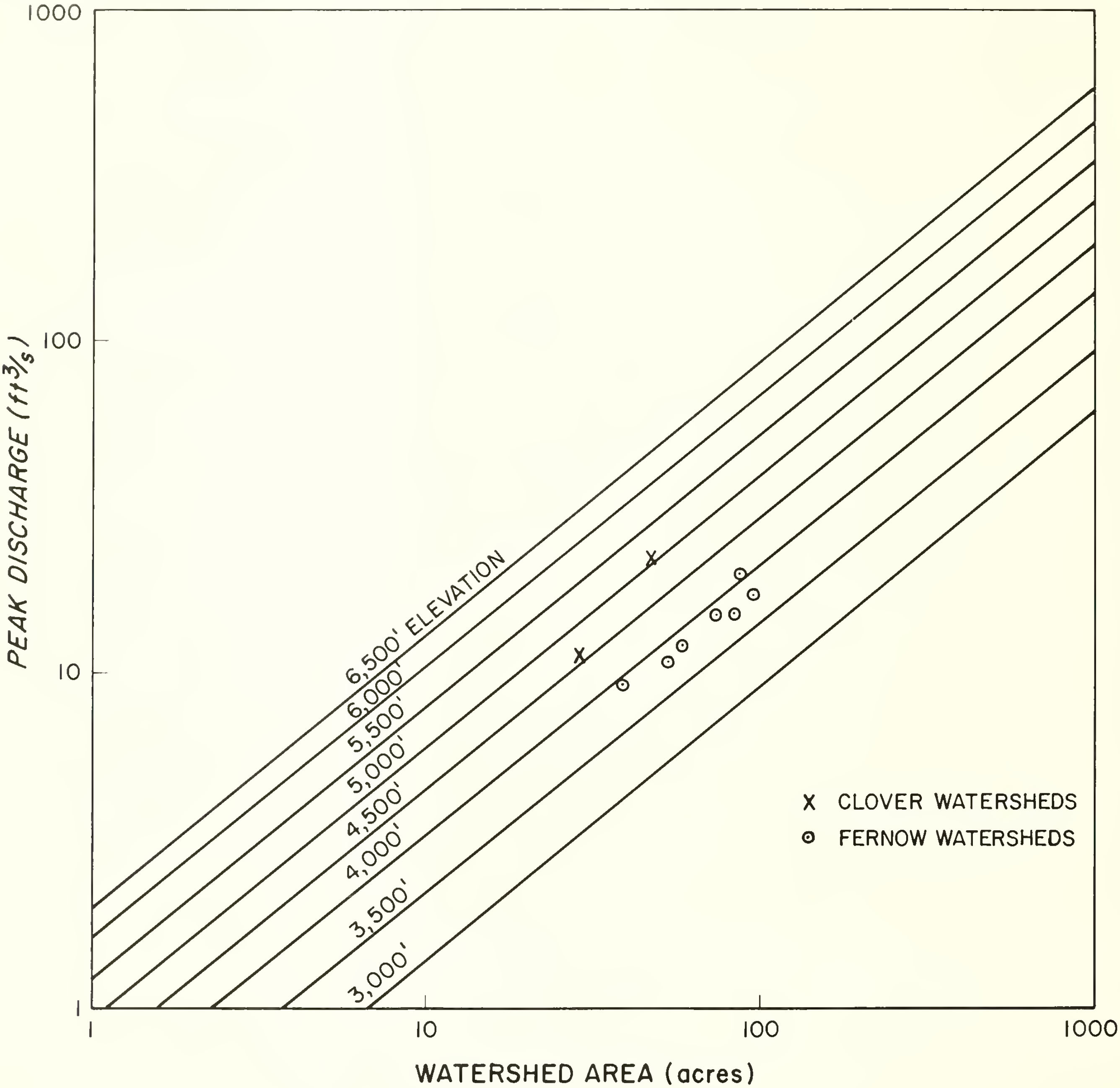
Table 2.—Estimated culvert diameters needed to carry flood water from forested areas ranging from 30 to 100 acres and at recurrence intervals of 5 to 50 years

Area (acres)	Recurrence interval (years)			
	5	10	20	50
	Inches			
30	16	18	20	22
40	18	20	20	24
50	20	20	22	24
60	20	22	22	26
70	22	22	24	26
80	22	24	26	28
90	22	24	26	28
100	24	24	26	30

Coweeta vs. Fernow data

Figure 3 illustrates the comparison of the Coweeta, Fernow, and Clover Run data. Although the maximum elevation at Fernow—Clover Run is 2,850 feet, flood peaks at the 20-year recurrence interval plot slightly below the 4,000-foot curve derived from the Coweeta data. Using Figure 3 and the actual elevation of the study watersheds, the 20-year peak from a 100-acre drainage is estimated at less than 9 ft^3/s. Our analysis (Table 1) indicates an actual peak of about 20 ft^3/s for the undisturbed watersheds. The reasons for these contrasting results cannot be determined with certainty, but the most obvious ones are associated with soil depth. Soils on the Coweeta watersheds are at least twice as deep as the Fernow—Clover Run soils. Therefore, more storage space is available during flood-producing storms.

Figure 3.—Peak discharge for the Fernow and Clover watersheds compared with predicted discharge for watersheds in the Southern Appalachians. (Adapted from Figure 4 in Douglass 1974.)



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