Rainfall thresholds for triggering a debris avalanching event in the southern Appalachian Mountains

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ABSTRACT

In early November 1977, a storm system that formed in the Gulf of Mexico moved northeastward into the Appalachian Mountains. It produced intense (as much as 102 mm/hr) and heavy (200-300 mm) rainfall that set off debris avalanching in steep terrain of the Pisgah National Forest, North Carolina. Antecedent rainfall during September and October was 177 percent of normal and the wettest on record for these 2 months. The storm began on 2 November, and rainfall was relatively continuous and even (20-50 mm/day) for the next 3 days. The long-duration rainfall was capped by intense convective downpours the night of 5-6 November when debris avalanching occurred. Peak intensities measured at 15 gauges near Asheville, North Carolina, ranged from 21 to 102 mm/hr, with nearly half exceeding 75 mm/hr. Return intervals for peak intensity rainfall in the range of 75 to 102 mm/hr are 50 to 200+ yr. Total storm rainfall for these gauges ranged from 35 to 250 mm, with peak 24-hr rainfalls of 30 to 180 mm. Rainfall intensities for 1-, 3-, 6-, 12-, and 24-hr periods at a gauge near one avalanching site were 69, 137, 159, 164, and 180 mm, respectively.

Development of the storm was monitored by GOES infrared satellite imagery in real time, and flash flood warnings were issued. Debris avalanching and high stormflow produced peak stream flows with return periods ranging from 20 to 100+ yr. The largest debris avalanches occurred on steep slopes (70% +), started at high elevations (900-1,100 m) in shallow residual soils (less than 1 m deep), had tracks commonly greater than 700 m, and carried a volume of material averaging 2,500 m$^3$ per avalanche.

INTRODUCTION

A number of recent studies have improved understanding of the climatic and geomorphic processes that trigger debris avalanches. These studies have investigated the physical properties of failed slopes, the effects of slope angle and pore water pressure, the mechanism of debris avalanche movement, and the properties of the resulting deposits (Fisher, 1971; Hutchinson and Bhandari, 1971; Scott, 1972; Williams and Guy, 1973; Swanston, 1974; Campbell, 1975; Hollingsworth and Kovacs, 1981; Istok and Harward, 1983). Failures usually begin with sufficient rainfall to bring the entire soil mantle to field capacity. Then rainfall with an intensity exceeding percolation and interflow rates saturates the soil above some slowly permeable stratum. As the piezometric head in this stratum increases, the frictional component of the shear forces holding the soil on-slope decreases. This, combined
with decreased cohesion due to water displacing air in soil inter-
stices, reduces the shear resistance force enough to produce slope
failure. Conditions that aggravate this process include a thin soil
mantle, steep slopes, concentrated drainage, shallow-rooted vege-
tation, and high clay content in the soil mantle. Prior and current
land use, such as roads, logging, farming, and construction, can
aggravate slope instability (Megahan and Kidd, 1972; Greswell
and others, 1979; Swanston, 1979; Swanston and others, 1981).

Eschner and Patric (1982), in their report on known cases of
debris avalanching in forested regions of the eastern United
States, noted some common characteristics of these slope failures.
Within forests of this region, debris avalanches occur irrespective
of vegetative cover. In contrast, logging aggravates slope failures
in Pacific coast mountains (O'Loughlin, 1974; Swanston and oth-
ers, 1981). Scott (1972) mentioned clear-cutting in his study of
1,700 debris avalanches in the Appalachian Mountains, but did
not report evidence that clear-cutting was a major factor contrib-
ting to eastern debris avalanching.

The storm events triggering debris avalanching in the East
appear to have a threshold of 125 mm in 24 hr and occur from
May through November (Fig. 1; after Eschner and Patric, 1982).
These are the months when high-intensity, convection, and cy-
clonic storms are most abundant in the East. Eschner and Patric
(1982) estimated a general return period of 100 yr for storms
producing debris avalanches. However, few studies of historic
debris avalanching episodes in the eastern United States have had
sufficient data to analyze in detail the rainfall conditions that trig-
ger slope failure.

We have elaborated a November 1977 debris avalanching
event in western North Carolina, also reported by Eschner and Patric (1982). Some of the information on this event, particularly
the characteristics of the storm that triggered the slope failures, is
among the most complete for an event of this type. This chapter
describes the antecedent moisture conditions, storm development,
and rainfall intensities and amounts that contributed to the most
recent episode of slope failure in the southern Appalachian
Mountains.

CLIMATOLOGICAL BACKGROUND

The southern Appalachian region has one of the highest
annual rainfalls east of the Cascade Mountains of Oregon and
Washington. This wet climate and its effects on the hydrology of
forest watersheds has been studied for 50 yr at the U.S. Depart-
ment of Agriculture (USDA) Forest Service's Coweeta Hydro-
logic Laboratory (Swift and others, 1987). Mean annual rainfall
of the southern Appalachian Mountains ranges from 1,000 to
2,700 mm, but can reach 3,800 mm in wet years. Snowfall
usually accounts for less than 5 percent of total precipitation.

The characteristics of the November 1977 storm contrast
markedly with typical duration, size, and intensity characteristics
for the southern Appalachian storms. In general, the majority of
storms in this region last less than 6 hr, and only 5 percent exceed
24 hr (Fig. 2a). Thus, the storm described here is unique in that its
duration was 96 to 120 hr. Of the 133 storms that, on the aver-
age, occur yearly in the southern Appalachians, only 6 percent
exceed 50 mm (Fig. 2b), although they account for 34 percent of
the annual precipitation (Fig. 2c). Most of the storm periods have
low-intensity rainfall because rates surpass 10 mm/hr only 4
percent of the time (Fig. 2d). Rain in excess of 10 mm/hr pro-
duces 31 percent of the average total annual precipitation, where-
as only 5 percent of the precipitation comes from rainfall greater
than 50 mm/hr. The storm of November 1977 had peak intensi-
ties double the latter rate.

Antecedent conditions prior to the 1977 debris avalanche
storm were conducive to slope failure conditions. Rainfall in
western North Carolina during September and October was 177
percent of normal. Including November, this was the wettest fall
period on record (Tennessee Valley Authority, 1977). Debris
avalanches were triggered by one intense storm that comprised 70
to 80 percent of November 1977 precipitation on soils that had
two previous months of record-high moisture inputs.

METEOROLOGICAL SITUATION

The storm of 3-7 November 1977 was produced by a low-
pressure system that pulled moist air from the Gulf of Mexico.
Precipitation accompanied a slow-moving cold front on 2-3 No-
vember. A low-pressure center reformed on 4 November over the
Florida Gulf Coast along the then-stationary cold front. It moved
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Figure 2. Long-term rainfall patterns at recording gauge 6, Coweeta Hydrologic Laboratory, Otto, North Carolina, based on 40-yr record. A, storm duration; B, storm size as percentage of average of 133 storms/yr; C, storm size as percentage of total annual precipitation; D, precipitation intensity as percentage of time; E, precipitation intensity as percentage of total precipitation.
Figure 3. GOES infrared satellite imagery of southeastern United States during night of 5-6 November 1977. A, 8:30 p.m. EST; b, 9:30 p.m. EST; c, 11:31 p.m. EST; d, 12:30 p.m. EST; e, 1:30 a.m. EST; f, 3:30 a.m. EST (highest convective cells in black).
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Tennessee

Figure 4. Map of Asheville-Statesville, North Carolina, area showing precipitation (in millimeters) that caused flood of November 1977. [Map adapted from National Weather Service (Stewart and others, 1978).]

slightly westward on 5 November and then tracked north-northeast over Georgia, Tennessee, and Kentucky on 6-7 November. Rainfall began in western North Carolina in the early morning of 2 November. Precipitation was generally continual and even (20 to 50 mm/day) from 2-5 November, by which time cumulating rainfall generally exceeded 60 mm.

The long-duration rainfall before 5 November was capped by intense downpours that initiated the debris avalanching. The heavy rainfall on the night of 5-6 November was produced by convective activity in association with orographic lifting over the southern Appalachian Mountains. Development of the convective cells was simultaneously observed in near real time on GOES infrared satellite imagery. Forecasts of flash flooding were issued for the area involved using a (then) newly developed forecasting procedure (Scofield and Oliver, 1977; Heidelberger, 1977).

Intensive convective cells formed within the storm cloud around 2030 EST (8:30 p.m.) on 5 November (dark patches in Fig. 3a). These cells centered over western North Carolina, intensified, and grew in area coverage by 2130 EST (Fig. 3b). The convective cells moved slightly to the northeast by 2331 (Fig. 3c) and intensified further by 0030 EST (12:30 a.m.) on 6 November (Fig. 3d). Later satellite images showed increased area coverage at 0130 EST and continued drift to the northeast (Fig. 3e). By 0330 EST, the main convective cells were still over western North Carolina but were beginning a gradual dissipation as another cell intensified farther east over the Atlantic coastline.

The general isohyetal map prepared by the National Weather Service (National Oceanographic and Atmospheric Administration, 1977) for this storm shows the distribution pattern of the rainfall (Fig. 4). Four isohyetal peaks ranging from 200 to 320 mm occurred in a southwest-northeast line along the Appalachian Mountains. The largest peak occurred in the Mt. Mitchell area. This discussion focuses on the most southwestern of the isohyetal peaks, specifically, the vicinity of Hominy Creek and Bent Creek watersheds, southwest of Asheville (Fig. 5). On these watersheds, exceptionally complete rainfall and debris avalanching data were collected. Both streams originate in the Pisgah National Forest and flow into the French Broad River. They are
Figure 5. Total precipitation (in millimeters) in vicinity of Asheville, North Carolina, for 3-7 November 1977 storm.

Separated by a forested ridgeline which exceeds 1,100 m in elevation.

Total precipitation in the Asheville, North Carolina, area during the 3-7 November 1977 storm ranged from 53 to 320 mm (Fig. 5). Rainfall in the Hominy Creek drainage was generally in the range of 190 to 216 mm, based on a survey of unofficial gauges and exposed containers made immediately after the storm (NOAA, 1977). Across the ridge to the east in the Bent Creek basin, two USDA Forest Service gauges overtopped at 188 mm sometime during the storm. Both of these basins had previously received total storm rainfalls in excess of 200 mm without occurrence of debris avalanching. However, antecedent moisture conditions predisposed the slopes to failure with sufficient rainfall loading (TVA, 1977). The unique feature of the November 1977 storm was the particularly intense burst of rainfall that culminated an otherwise normal, long-duration event. This is precisely the type of situation that Campbell (1975) described as providing the climatic conditions for slope failure.

The U.S. Geological Survey estimated return intervals for peak flows of streams in the storm area to range from 25 to more than 100 yr (Fig. 6) (U.S. Geological Survey, 1977; Stewart and others, 1978). A record flood occurred on Hominy Creek northwest of Bent Creek (Fig. 5). The stream gauge at Candler was destroyed, but high-water marks established the crest at 7.37 m, nearly 2 m above the previous record set in 1940 (TVA, 1977). Although the flow on ungauged Bent Creek is unknown, the Highway 191 bridge across the creek was washed out.

An indication of the storm sequence over the Bent Creek and Hominy Creek basins can be illustrated from the Tennessee Valley Authority recording rain gauges near Mt. Pisgah, Cedar Mountain, Roan High Knob, and Little Switzerland. Figure 7a shows that 120 mm of rain had fallen at Mt. Pisgah during the 90 hr prior to the intense rainfall the night of 5-6 November. Then, during a 6-hr period, an additional 55 mm of rain fell. Peak rainfall intensities calculated from Tennessee Valley Authority gauges around Asheville showed a range from 21 to 102 mm/hr (Table 1). At the Mt. Pisgah gauge, peak intensity was only 21 mm/hr despite its high total storm rainfall (180 mm) and high
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Western North Carolina
Area of most severe flooding
November 6-7, 1977
(Flood recurrence interval - years)

A Asheville
B Boone
C Charlotte
WS Winston Salem

Figure 6. Flooding return period in areas of western North Carolina affected by severe flooding, November 1977.

Figure 7. Recording rain gauge analog traces from Tennessee Valley Authority. Recording rain gauges 1-8 November 1977: a, Mt. Pisgah TVA gauge 254; b, Roan High Knob TVA gauge 231; c, Cedar Mountain TVA gauge 283; d, Little Switzerland TVA gauge 235.
TABLE 1. PRECIPITATION AMOUNT AND INTENSITY FOR 3-7 NOVEMBER 1977 STORM AT SEVERAL TENNESSEE VALLEY AUTHORITY GAUGES NEAR ASHEVILLE, NORTH CAROLINA

<table>
<thead>
<tr>
<th>Gauge Site</th>
<th>Elevation (m)</th>
<th>Storm Amount (mm)</th>
<th>Peak intensity (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cataloochee Ranch</td>
<td>1463</td>
<td>53</td>
<td>15</td>
</tr>
<tr>
<td>2. Waynesville Watershed</td>
<td>789</td>
<td>53</td>
<td>22</td>
</tr>
<tr>
<td>3. Parker Branch</td>
<td>658</td>
<td>79</td>
<td>25</td>
</tr>
<tr>
<td>4. Sassafras Mountain</td>
<td>1048</td>
<td>&gt;87</td>
<td>91</td>
</tr>
<tr>
<td>5. Laurel Mountain</td>
<td>1244</td>
<td>125</td>
<td>34</td>
</tr>
<tr>
<td>6. Gloucester Gap</td>
<td>951</td>
<td>145</td>
<td>76</td>
</tr>
<tr>
<td>7. Coxcombe Mountain</td>
<td>1274</td>
<td>154</td>
<td>24</td>
</tr>
<tr>
<td>8. Haywood Gap</td>
<td>1646</td>
<td>155</td>
<td>86</td>
</tr>
<tr>
<td>9. Roan High Knob</td>
<td>1865</td>
<td>173</td>
<td>38</td>
</tr>
<tr>
<td>10. North Fork</td>
<td>756</td>
<td>&gt;178</td>
<td>46</td>
</tr>
<tr>
<td>11. Mount Pisgah</td>
<td>1573</td>
<td>180</td>
<td>21</td>
</tr>
<tr>
<td>12. Blueridge P.O.</td>
<td>689</td>
<td>193</td>
<td>91</td>
</tr>
<tr>
<td>13. Mills River</td>
<td>610</td>
<td>195</td>
<td>69</td>
</tr>
<tr>
<td>14. Cedar Mountain</td>
<td>823</td>
<td>202</td>
<td>96</td>
</tr>
<tr>
<td>15. Little Switzerland</td>
<td>1085</td>
<td>250</td>
<td>102</td>
</tr>
</tbody>
</table>

*All gauge charts show intense rain between 2000 and 2400 EST on 5 November 1977.

The peak hourly intensities, given in Table 1, were weakly related to storm total rainfall (Fig. 8a) and were not related to altitude (Fig. 8b). Gauges entirely within the French Broad River Basin had total storm rainfall of less than 81 mm and 173 to 180 mm and had maximum intensities less than 60 mm/hr. Gauges with middle (81 to 155 mm) and upper total rainfall ranges (greater than 191 mm) recorded the most intense rainfall. These
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**Figure 9.** Storm intensity return periods for Coweeta Hydrologic Laboratory gauge 6 with storm data from 3-7 November 1977 storm (dots).

**Figure 10.** Tennessee River Basin rainfall intensity range with annual maxima for 1-, 3-, 6-, 12-, and 24-hr intensities, 1941-1984, and November 1977 rainfall intensities for Mills River TVA gauge. High and low ranges represent highest and lowest annual maximum rainfall intensities for indicated time periods and length of record.

gauges were all located along the ridges that form the southeastern boundary of the French Broad River watershed. This ridgeline is the divide for the Mississippi and Atlantic continental watersheds and also the main topographic structure for producing orographic lifting of air masses coming from the south.

Forty percent of the peak hourly rainfall intensities listed in Table 1 exceeded 75 mm/hr. Based on long-term data from the Coweeta Hydrologic Laboratory located 96 km southwest of Asheville, rainfalls greater than 75 mm/hr have return periods in excess of 50 yr (Fig. 9). Peak intensities greater than 86 mm/hr in Table 1 (Sassafras Mountain, Blue Ridge P.O., Haywood Gap, and Cedar Mountain) compare to return periods of 100 to 150 yr. The peak hourly intensity at Little Switzerland (102 mm/hr) may have been a 175 to 200-yr event. However, none of the 24-hr rainfalls were exceptional, with 24-hr precipitation less than 150 mm, approximating a 1- to 10-yr return period. The remainder (155 to 180 mm in 24 hr) were 10- to 25-yr return period rainfalls. Thus, the exceptional characteristic of this November 1977 storm was the high 1-hr peak intensities. Total storm and 24-hr rainfalls were not unusual for the area.

Indeed, in comparison to the historical range of rainfall intensities for the entire Tennessee Valley network, the maximum intensities at Mills River for the November 1977 storm fall in the middle to low range (Fig. 10). Although much higher intensity rainfalls have occurred within the Tennessee River Basin, the combination of very wet antecedent conditions on steep slopes with high-intensity, **short-duration** rainfalls created conditions especially favorable for slope failures in the southern Appalachians. Recorded intensities at several sites exceeded the 125 mm in 24-hr threshold suggested by Eschner and Patric (1982).
DEBRIS AVALANCING

The most extensive debris avalanching triggered by the 3-7 November 1977 storm occurred near Hominy Creek and Mt. Mitchell. However, the best information on the debris avalanching came from Bent Creek where a survey was conducted after the storm (Fig. 11). This basin is an experimental forest managed by the USDA Forest Service, Southeastern Forest Experiment Station.

Except for one debris avalanche, all the major slope failures occurred along the ridge between Bent and Hominy Creek. Seven major avalanches were identified. A large number of smaller slope failures occurred, some of these associated with roads (asterisks in Fig. 11). Most of the avalanches originated on undisturbed forest slopes. The heads of the seven largest slope failures were located between elevations of 945 and 1,100 m on slopes of 70 percent and greater (Table 2). Four of these debris avalanches had multiple scarps. Exact runout lengths were difficult to establish because debris avalanche material merged into existing stream bottom colluvium, alluvium, and other debris. Most of the easily identifiable debris avalanche tracks were estimated to be from 655 to more than 810 m long.

Some of the avalanches entrained a considerable amount of woody material. Most of this debris was deposited on lower gradient slopes, old debris fans, or terraces formed by roads. Measurements of debris avalanche volumes were not conducted at Bent Creek. A report by the National Forest in North Carolina indicated that 24 major debris avalanches occurred on federal land in the Bent Creek basin and the Beaverdam drainage of Hominy Creek (USDA Forest Service, 1979). These avalanches covered a total area of 12 ha. If an average failure depth of 0.5 m in the source area is assumed (based on visual and photographic review of most avalanches), then a conservative estimate of the average volume per debris avalanche was about 2,500 m$^3$. This value is in the middle of the range of slope failure volumes reported by Swanson and others (1981).
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TABLE 2. CHARACTERISTICS OF SEVEN MAJOR DEBRIS AVALANCHES, BENT CREEK EXPERIMENTAL FOREST, BUNCOMBE COUNTY, NORTH CAROLINA, STORM 3-7 NOVEMBER 1977

<table>
<thead>
<tr>
<th>Debris Avalanche Head</th>
<th>Elevation (m)</th>
<th>Slope (%)</th>
<th>Character</th>
<th>Runout Length (m)</th>
<th>Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1055</td>
<td>80</td>
<td>Multiple</td>
<td>1235+*</td>
<td>N</td>
</tr>
<tr>
<td>2</td>
<td>1035</td>
<td>80</td>
<td>Multiple</td>
<td>700+</td>
<td>NE</td>
</tr>
<tr>
<td>3</td>
<td>1100</td>
<td>120</td>
<td>Single</td>
<td>655+</td>
<td>SE</td>
</tr>
<tr>
<td>4</td>
<td>990</td>
<td>80</td>
<td>Multiple</td>
<td>810+</td>
<td>SE</td>
</tr>
<tr>
<td>5</td>
<td>1035</td>
<td>60</td>
<td>Single</td>
<td>700+</td>
<td>SE</td>
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<tr>
<td>6</td>
<td>975</td>
<td>60</td>
<td>Multiple</td>
<td>700+</td>
<td>SE</td>
</tr>
<tr>
<td>7</td>
<td>945</td>
<td>80</td>
<td>Single</td>
<td>760</td>
<td>SE</td>
</tr>
</tbody>
</table>

*Minimum track length; actual length is impossible to determine because of track coincidence with major stream channels.

of some stream channels suggests that even larger amounts of material were moved. More details on the debris avalanching can be obtained from Neary and others (1986).

CONCLUSIONS

This study examines the conditions that produced an episode of debris avalanching in forests of the southern Appalachian Mountains. All the classical conditions of antecedent moisture (177 percent above normal), heavy rainfall (more than 125 mm over 3 days), intense downpours (as much as 102 mm/hr), steep slopes (35 to 80 percent), and shallow soils (depth to bedrock less than 2 m) were present. Although slope stability is not recognized as a general problem in mountainous areas of the East, debris avalanching is a major contributor to long-term erosion rates and influences formation of some of the more productive forest soils. Long-return periods of 100 to more than 200 yr for these destructive events obscure the perception of their importance as an erosional process. Peak hourly rainfall intensities of 90 to 100 mm/hr approached the suggested 24-hr threshold for initiating debris avalanches in mountainous regions of the humid East. These high hourly intensities were the key to triggering slope failure in well-drained and highly permeable forest soils of the southern Appalachians.

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