



An Examination of Selected Historical Rainfall-Induced Debris-Flow Events within the Central and Southern Appalachian Mountains of the Eastern United States

By G.F. Wieczorek, L.S. Eaton, B.A. Morgan, R.M. Wooten, and M. Morrissey

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Conversion Factors

Multiply	By	To obtain
Length		
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square meter (m ²)	0.0002471	acre
square kilometer (km ²)	0.3861	square mile (mi ²)
Volume		
cubic meter (m ³)	264.2	gallon (gal)
Flow rate		
meter per second (m/s)	3.281	foot per second (ft/s)
meter per hour (m/hr)	3.281	foot per hour (ft/hr)

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Abstract

Generally, every several years, heavy amounts of rainfall trigger a large number of debris flows within the central and southern Appalachian Mountains of the Eastern United States. These types of landslides damage buildings, disrupt infrastructure, and occasionally injure and kill people. One of the first large debris flows was described in Pennsylvania in August 1779. The most destructive event occurred during August 19–20, 1969, in Nelson County, Va. During a period of 8 hours, 710 to 800 millimeters of rain triggered more than 3,000 landslides, killing more than 150 people. As the population increases in this region, future storms will likely increase the risks of property damage and loss of life. We provide a general overview of debris flows in the Appalachians, using a compilation of 19 storm events for which rainfall, duration of the storm, and descriptions of the resulting landslides have been substantially documented.

Introduction

Landslides, including debris flows, have occurred throughout mountainous areas of the United States, triggered by rainfall, earthquakes, or volcanoes. The steep slopes and poor slope stability associated with regions of the Colorado Plateau, the Appalachian Highlands, the Coast Ranges of California, and the Southern Rocky Mountains produce the greatest concentration of landslide prone areas and a variety of landslides (Radbruch-Hall and others, 1982; Wieczorek and Leahy, 2008). In the Appalachian region, landslides result primarily from heavy rainfall. Rainfall from hurricanes, cloudbursts, and thunderstorms can generate rapidly moving debris flows that are among the most dangerous and damaging type of landslides. In this publication, we explore the nature and occurrence of debris flows in the central and southern Appalachian Mountains, which extend from central Pennsylvania to Georgia.

A debris flow is a moving mass of fragmented rock and soil in which more than half of the particles are greater than sand size (Costa, 1988). Because a debris flow moves rapidly and with great force, it is capable of destroying almost everything in its path. Debris flows are most frequently generated on steep slopes during heavy rainfall and often travel along preexisting drainages and streams. The soils and poorly consolidated material on these slopes may become saturated during rainfall, lose coherence, and begin

moving downslope in a flowing stream, drawing in and transporting additional soil, rocks, and vegetation as the flow rapidly moves through the drainage network (Campbell, 1975).

The first debris flow described in the Appalachian region occurred in 1779, about 16 km northwest of Carlisle, Pa. The event was observed by David Rittenhouse in a letter he was writing to Benjamin Franklin (Delano and Potter, 1997; Potter and Delano, 1997). Ground failure resulted in a debris flow that mobilized rocks and trees that were carried downslope about 800 meters (m) in a channel 1 to 4 m deep and 9 to 30 m wide.

A valuable summary of debris-flow events within the Appalachians south of the glacial border was compiled by Clark (1987a). He provided a bibliography and a location map of 51 debris-flow events resulting from rainstorms that occurred between 1844 and 1985. More recently, several large-scale, storm-induced debris-flow events that occurred since 1987 have been documented in this region by Jacobson (1993), Morgan and Wiczorek (1996), Morgan and others (1999), Wiczorek and others (2000), and Wooten and others (2008a, b). Many debris-flow events have occurred in isolated areas with few inhabitants, so that valuable information on affected slopes, number of ground failures, rainfall, and duration of rainfall is lacking. We have compiled data in table 1 for 19 events within this region for which we have substantial information. The geographic locations of these data, combined with findings from Clark (1987a), are plotted on figure 1; the debris flows listed in table 1 are shown as small asterisks and are numbered.

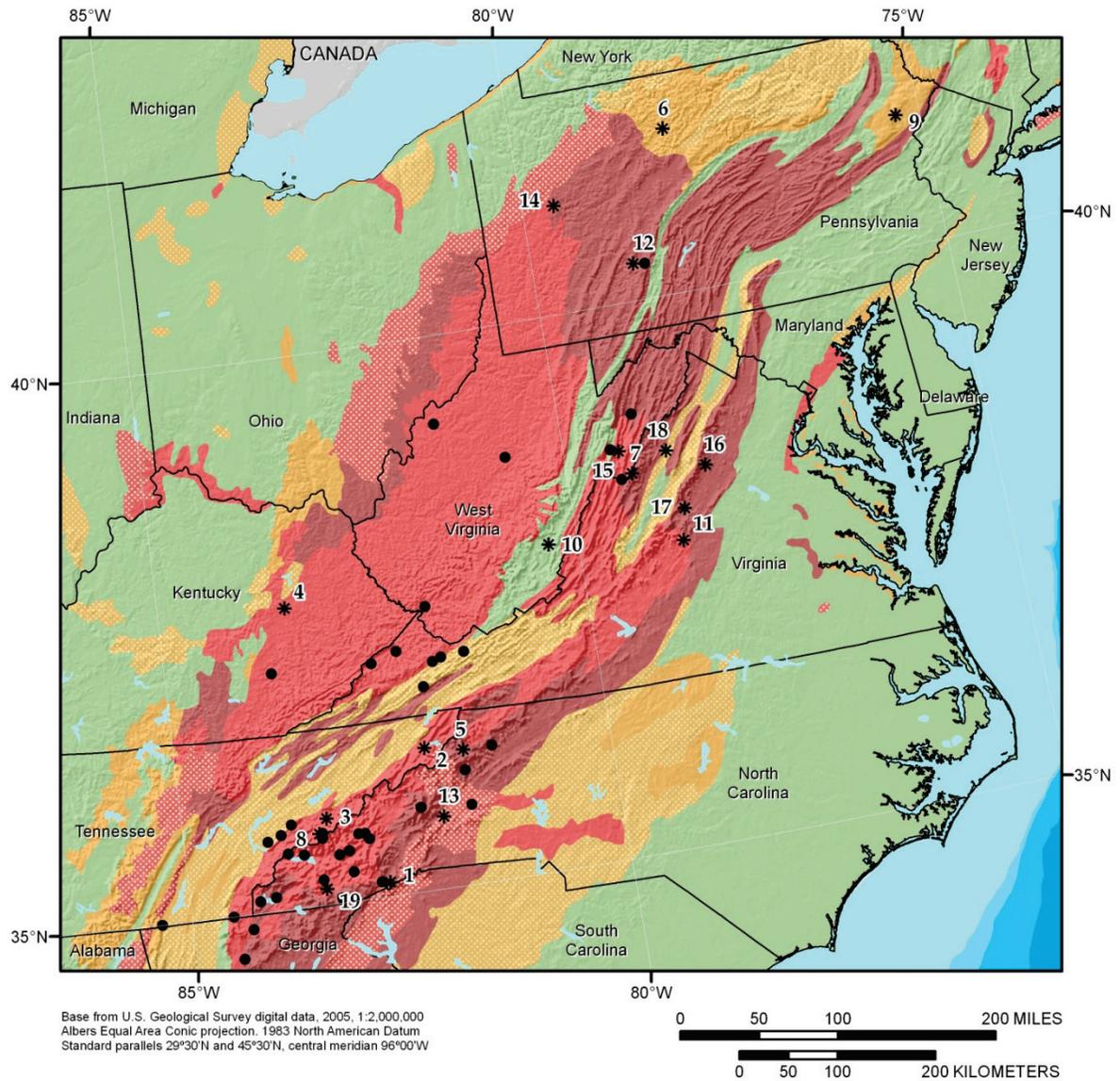


Figure 1. Distribution of debris flows within the Appalachian Mountains of the Eastern United States (Clark, 1987a; Radbruch-Hall and others, 1982).

Table 1. Examples of historical rainfall-induced landslides within Appalachian Mountains of the Eastern United States.

Map location of debris flows on figure 1	Rainfall total (millimeters)	Time of most severe rainfall	Type of rainfall storm	Number of reported landslides	Landslide dates (month/day/year)	General landslide locations
1	564	24 hrs	Hurricane	45	7/15–16/1916	Transylvania County, North Carolina (Wooten and others, 2003)
2	380	2 days	Thunderstorm	~100	6/13/1924	Carter County, Tennessee (Scott, 1972)
3	305	4 hrs	Cloudburst	> 100	8/4 5/1938	Webb Mountain, Tennessee (Scott, 1972)
4	508	2 days	Thunderstorm	4 on photo, but total not reported	7/4–5/1939	Wolfe and Breathitt County, eastern Kentucky (Schrader, 1945)
5	254	6 hrs	Hurricane	2,099	8/10–17/1940	Watauga County, North Carolina (Wooten, 2008a)
6	782	4.5 hrs	Thunderstorm	numerous	7/18/1942	Elk, McKean, Potter, & Cameron Counties, north-central Pennsylvania (Scott, 1972)
7	400	1 day	Cloudburst	466	6/17 18/1949	Augusta & Rockingham Counties, Virginia/Highland County, West Virginia (Hack and Goodlett, 1960)
8	116	1 hr	Cloudburst	100	9/1/1951	Mt. Le Conte, Great Smoky Mountains National Park, Tennessee (Scott, 1972)
9	254	2 days	Hurricane Diane	4	8/18–19/1955	Brodhead Creek, northeastern Pennsylvania (Scott, 1972)
10	635	8 hrs	Hurricane Camille	1,584	8/19–20/1969 9/5–6/1969	Spring Creek, Greenbrier County, West Virginia (Schneider, 1973)
11	710–800	8 hrs	Hurricane Camille	3,793	8/19–20/1969	Nelson County, Virginia (Willams and Guy, 1973)
12	300	9 hrs	Thunderstorm or cloudburst	Several hundred	7/19–20/1977	Johnstown area, western Pennsylvania (Pomeroy, 1980)
13	320	5 days	Storm	72	11/6–7/1977	Buncombe County, North Carolina (Neary and Swift, 1987)
14	115	14 days	Thunderstorm	62	8/14/1980	East Brady, along Allegheny River, northern Pennsylvania (Pomeroy, 1984)
15	350	3 days	Hurricane Juan	3,000	11/3–5/1985	Pendleton County, West Virginia/Highland County, Virginia (Jacobson and others, 1993)
16	770	14 hrs	Storm	629	6/27/1995	Madison County, Virginia (Wieczorek and others, 2000)
17	635	1 day	Storm	61	6/27/1995	Albemarle County, Virginia (Morgan and Wieczorek, 1996)
18	513	1 day	Hurricane Isabel	6	9/18–19/2003	Shenandoah Valley, Virginia (Wieczorek and others, 2004)
19	700	11 days	Hurricanes Frances and Ivan	400	9/7–17/2004	Western North Carolina (Wooten and others, 2008a)

Summary of Historical Rainfall-Induced Debris Flows

We will describe the 19 debris-flow events listed and located in table 1 and figure 1, respectively, as well as other less well-documented flows, by each of the several States in the region. These descriptions will provide the basis for a summary of the general conditions that cause these devastating landslides. We will conclude with a discussion of research that could increase the ability of Federal and State agencies to predict and mitigate the risk posed by debris flows.

Georgia

The latter half of the month of August 1967 was excessively rainy throughout the north Georgia mountains (Scott, 1972). During most of the period, a stationary front was just to the north of the area, producing highly unstable atmospheric conditions, with periods of steady rain, as well as numerous heavy showers and thunderstorms. Small groups of debris slides and flows occurred at several widely separated sites in apparent response to local concentrations of exceptionally heavy precipitation. The primary rainfall center appears to have been located about 13 to 14 kilometers (km) south of the town of Blue Ridge, where an estimated 305 to 381 millimeters (mm) or more of rain fell during the period of August 19–27. Here, within an area of a few square kilometers, approximately 10 debris flows occurred on undisturbed slopes located largely within the Chattahoochee National Forest. The three largest slides had multiple sources or heads, and considerable bedrock was exposed along their paths. The largest of these slides was over 900 m long and was initiated at three sources.

On the evening of August 17, 1982, a low pressure system stagnated over northwest Georgia and southeast Tennessee and produced an excessive amount of rainfall (Wilson, 1983). Two hundred-fifty to three hundred mm of rain fell in a 12-hour period in parts of Dade County in Georgia, and Marin and Hamilton Counties in Tennessee. Debris flows were triggered along the steep (greater than 30 degrees) slopes of the Cumberland Plateau Escarpment in an area of about 84 square kilometers (km²). These debris flows were triggered within 8 to 10 hours from the onset of the rainfall. Most of the flows began as translational slides within colluvium overlying a variety of bedrock types. The thickness of the colluvium contributed to the initial failure site, and the interface between the bedrock and the soil formed the basal failure surface. The ensuing flash floods and landslides caused over 8 million dollars in property damage and resulted in 4 deaths (Wilson, 1983).

North Carolina

In early July, 1916, a storm passed over western North Carolina, producing nearly 250 mm of rain but no recorded slope movements. Shortly afterwards during July 15–16, a hurricane struck the counties of Transylvania, Henderson, and Buncombe, greatly affecting the towns of Brevard, Hendersonville, and Asheville. Heavy rains associated with this second storm caused much flooding and damage from slope movements that probably numbered at least in the hundreds, if not thousands, over a large area affecting five States (Wooten and others, 2003). The Tennessee Valley Authority (TVA, 1964) recorded 564 mm of rainfall in 24 hours near Altapass, N.C., during the storm. Residents reported over 45 landslides on the mountain sides around Brevard, N.C. (Wooten and others, 2003). At least three people were killed near Brevard as a direct result of these debris flows.

During the month of August 1940, the southeastern United States experienced two major hurricanes that caused damages of about \$30 million. The first and larger of these two storms occurred during the week of August 10–17, 1940, and the southeastern States of Georgia, Tennessee, North Carolina, and Virginia experienced severe damage. The track of the storm was highly erratic, coming

ashore near Savannah, Ga., passing through Atlanta, then swinging in a broad arc west of Knoxville, Tenn., and finally easterly across North Carolina and southern Virginia. The center of the storm, with intense rainfall, passed between the cities of Boone and Wilkesboro, N.C., between 6:00 a.m. and 12:00 noon on August 14. This event dropped a maximum of 254 mm of rain within 6 hours at Laurel Springs, N.C., and had been preceded by 86 mm of rain on August 13. In western North Carolina, flooding in many rivers was at an historical maximum. In this area, 26 people were reportedly killed, including 1 from a debris flow. Of these, nine were killed in the Stony Fork Township near Deep Gap in eastern Watauga County (Witt and others, 2007). One of the most significant features associated with this storm was the large number of shallow debris flows that traveled down steep, forested slopes into small valleys along the Blue Ridge. The source of these flows was from thin, saturated soils overlying bedrock on steep slopes. According to field observations, the size of debris flows varied from about 2 m wide and from 12 to 15 m long, to 60 to 90 m wide and 400 to 800 m long, with a maximum track length of 2,097 m measured from aerial photography flown in 1940 (Witt and others, 2008). Many of the larger debris flows continued down the slopes into the stream valleys removing trees and structures in their path. Over 2,000 debris flows and debris slides occurred (Wooten and others, 2008b) of which 763 debris flows were in the Deep Gap area of Watauga County (Wieczorek and others, 2004).

A second storm struck southwestern North Carolina during August 28–31, 1940, with the heaviest rainfall of 241–305 mm reported over a 24-hour period in the headwaters of the Tuckasee River in Jackson County (TVA, 1940; U.S. Geological Survey, 1949). Because of the concentration of high-intensity rainfall within a small area, more than 200 debris flows occurred in an area of only 388 km² (U.S. Geological Survey, 1949). Debris slides and flows triggered by this storm claimed six lives in the Tuckasee River and upper Pigeon river areas of Jackson and Haywood Counties (TVA, 1940).

During November 3–7, 1977, a storm produced intense and heavy rainfall triggering debris flows on the steep slopes of the Pisgah National Forest, N.C. Total precipitation in the Asheville area ranged from 53 to 320 mm (Neary and Swift, 1987). There were at least 72 major debris flows that occurred near the end of the storm in the Bent Creek area of Buncombe County (Pomeroy, 1991). The debris flows generally ranged from 655 to 810 m long, with the largest maximum runout of at least 1,235 m (Neary and Swift, 1987).

During 2004, Hurricane Frances (September 7–8) and Hurricane Ivan (September 16–17) swept through western North Carolina. Precipitation in Macon County from Hurricane Frances at Mooney Gap (elevation 1,364 m) totaled approximately 205 mm and at Coweeta (elevation 685 m) totaled approximately 118 mm (Wooten and others, 2008a). Hurricane Ivan produced precipitation totals in Macon County ranging from 100 to 125 mm in the north to 250 to 300 mm in the south. Mooney Gap received an additional approximately 204 mm of precipitation, and another 114 mm of rain fell at Coweeta. Short-duration rainfall rates of 90–230 millimeters per hour (mm/hr) were measured during this period, and an average rainfall rate and duration of 25 mm/hr for 4.65 hours occurred just prior to two debris flows where the initiation times were known (Wooten and others, 2008a). At least 400 ground failures, including debris flows, resulted from these storms in North Carolina (R.M. Wooten, written commun., 2009), and a few additional landslides were also reported in Tennessee, West Virginia, Ohio, and Pennsylvania. The Peeks Creek debris flow began at an elevation of 1,347 m on the northeast side of Fishhawk Mountain, probably as a debris slide, measuring approximately 23 m wide, 100 m long, and about 1 m thick. This slide translated into a debris flow and traveled 3.6 km downslope to the Cullasaja River, killing 5 people, injuring 2 seriously, and destroying 16 houses, making this the most devastating of all landslides during the September 2004 storms. Calculated estimates of peak velocity [14.8 meters per second (m/s)] and discharge [(1,275 to 1,980 cubic meters (m³))] explain why this debris flow was so destructive (Latham and others, 2005, 2006). Figure 2 shows the known

locations of slope movements triggered by rainfall from Hurricanes Frances and Ivan on September 7 to 17 in the western North Carolina region (Latham and others, 2007). Detailed observations of rock slides were made at several specific times (R.M. Wooten , written commun., 2008). For example, during September 6–8, one slide of fresh rock and two slides of weathered rock occurred during rainfall from the remnants of Hurricane Frances; during September 6–17, one slide of weathered rock was triggered from rainfall from the remnants of Hurricane Frances or Ivan. During September 16–17, one rock slide, two slides of weathered rock, one composite debris rockslide, and one rock fall were triggered by rain from remnants of Hurricane Ivan. Residents in the Peeks Creek community reported that a debris flow occurred during Hurricane Ivan on September 16, 2004 (fig. 3).

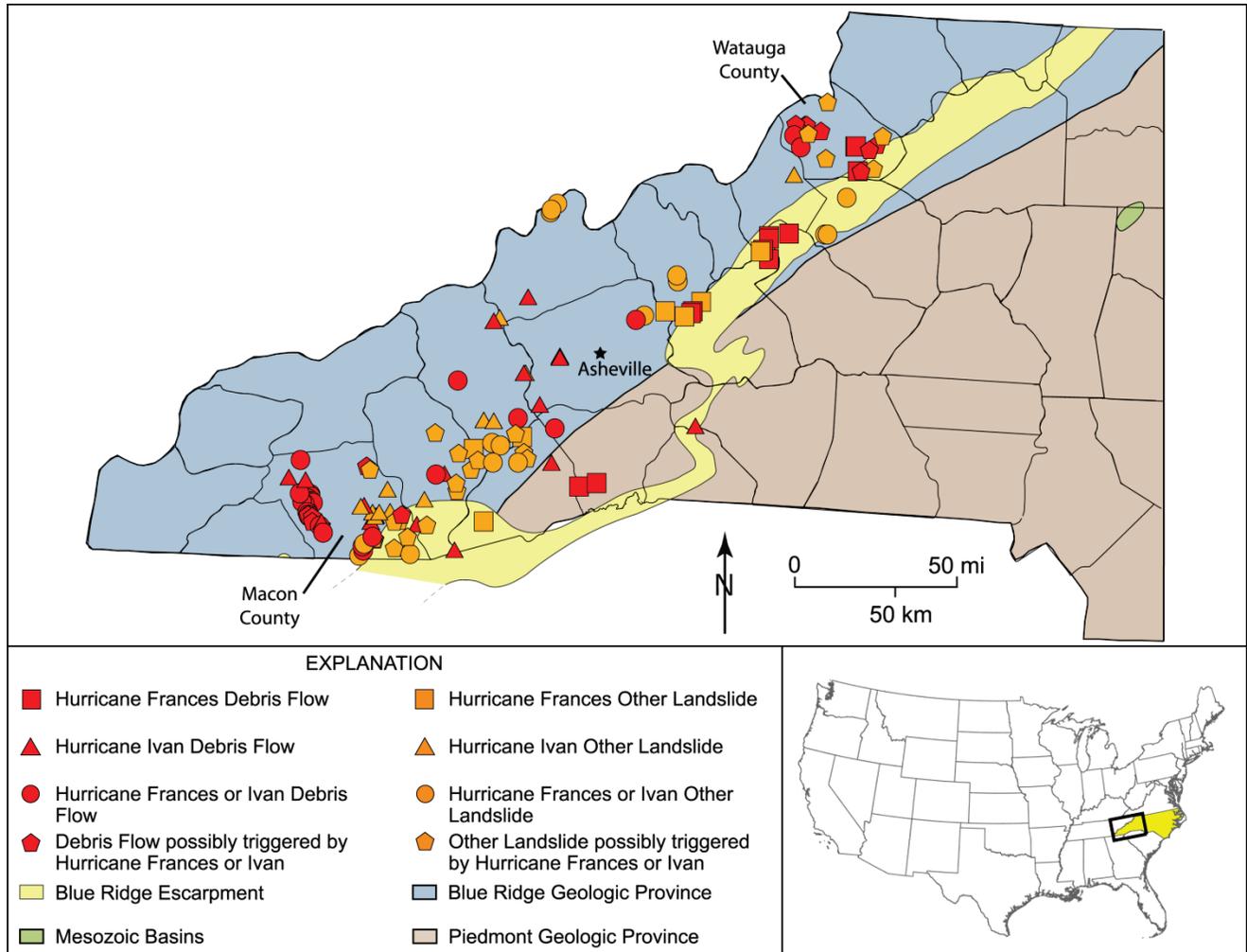


Figure 2. Map showing locations of slope movements triggered by rainfall from Hurricanes Frances and Ivan September 7–17, 2004, in the western North Carolina region (Latham and others, 2007).



Figure 3. A. Peaks Creek landslide and debris flow in Macon County, N.C., that occurred on September 16, 2004. B. Buildings destroyed by the debris flow at Peaks Creek, September 16, 2004. (Photos by R.M. Wooten, N.C. Geological Survey).

Tennessee

On June 13, 1924, in Carter County, eastern Tenn., a thunderstorm brought 380 mm of rainfall within 2 days and triggered approximately 100 landslides. Near the center of the storm, a substantial number of these failures were debris slides and flows. At least 11 people were killed by the storm and its accompanying slope failures. At Carden's Bluff, two small houses were demolished and nine occupants killed (Scott, 1972).

During August 4–5, 1938, a severe storm produced 305 mm of rain within 4 hours, resulting in about 100 landslides, including debris flows. Within the Great Smoky Mountains National Park, the areas of severe rainfall extended from the general vicinity of Calderwood, located on the Little Tennessee River, northeastward to near Cosby, on the Pigeon River, a distance of approximately 80 km (Scott, 1972). Along the Little Tennessee River, there were numerous small landslides, and at least one modern bridge near Calderwood Dam was destroyed, as well as many small bridges and buildings (Koch, 1974).

A cloudburst on September 1, 1951, in the Mount Le Conte-Sugarland Mountain area of the Great Smoky Mountains National Park resulted in numerous debris flows and related flood damage (Bogucki, 1976). The affected area is predominantly steep and is covered with virgin forest. Slide-head elevations range from 1,280 to 1,920 m (Scott, 1972). Slide-head slopes have a mean of 40 degrees, with a range of 35 to 44 degrees, with an average of 38 degrees (Bogucki, 1976). Sixty-three percent of the known slides occur on slate of the Anakeesta Formation and 37 percent on metasandstone. The largest slide in the Alum Cave Creek watershed (Slide SB-10) has a slope area of 10,500 m², with an estimated regolith removal of 3,400 m³ (Bogucki, 1976).

Virginia

In August 1969, Hurricane Camille made landfall with great destruction on the Gulf Coast and moved inland in a large north-to-northeastern arc into the Appalachian region of West Virginia and Virginia. In the area around Nelson County, Va., the eastward movement of the remnants of the hurricane stalled against a high pressure system, resulting in at least 710 mm of rainfall during an 8-hour period during the night of August 19–20 (Williams and Guy, 1973). The U.S. Weather Bureau, after conducting bucket surveys, confirmed 800 mm of rainfall at one point and 635 to 686 mm in several other places (Simpson and Simpson, 1970). A careful review of the available rainfall data was conducted by Morgan and others (1999) resulted in an isohyetal map of rainfall in the central area of the storm that is consistent with the known data (fig. 4). The affected bedrock was metagranite and granitic gneiss. More than 3,793 debris flows occurred in the Nelson County area, identified by aerial photography taken immediately after the storm (Morgan and others, 1999). The heavy rain fell during the night, which contributed to the estimated 150 deaths from debris flows and flooding. Small road bank slides began occurring as early as 10:00 p.m., and, according to one resident, large debris flows began by 11:00 p.m. in Polly Wright Cove, a few miles north of Lovingston. By 1:00 a.m., the debris flows were occurring in large numbers and continued to do so until about 4:00 a.m. The ground failures usually began at an elevation of about 550 m on slopes averaging 32 degrees. The average of many debris flows was 775 m long and 14 m wide (Scott, 1972).

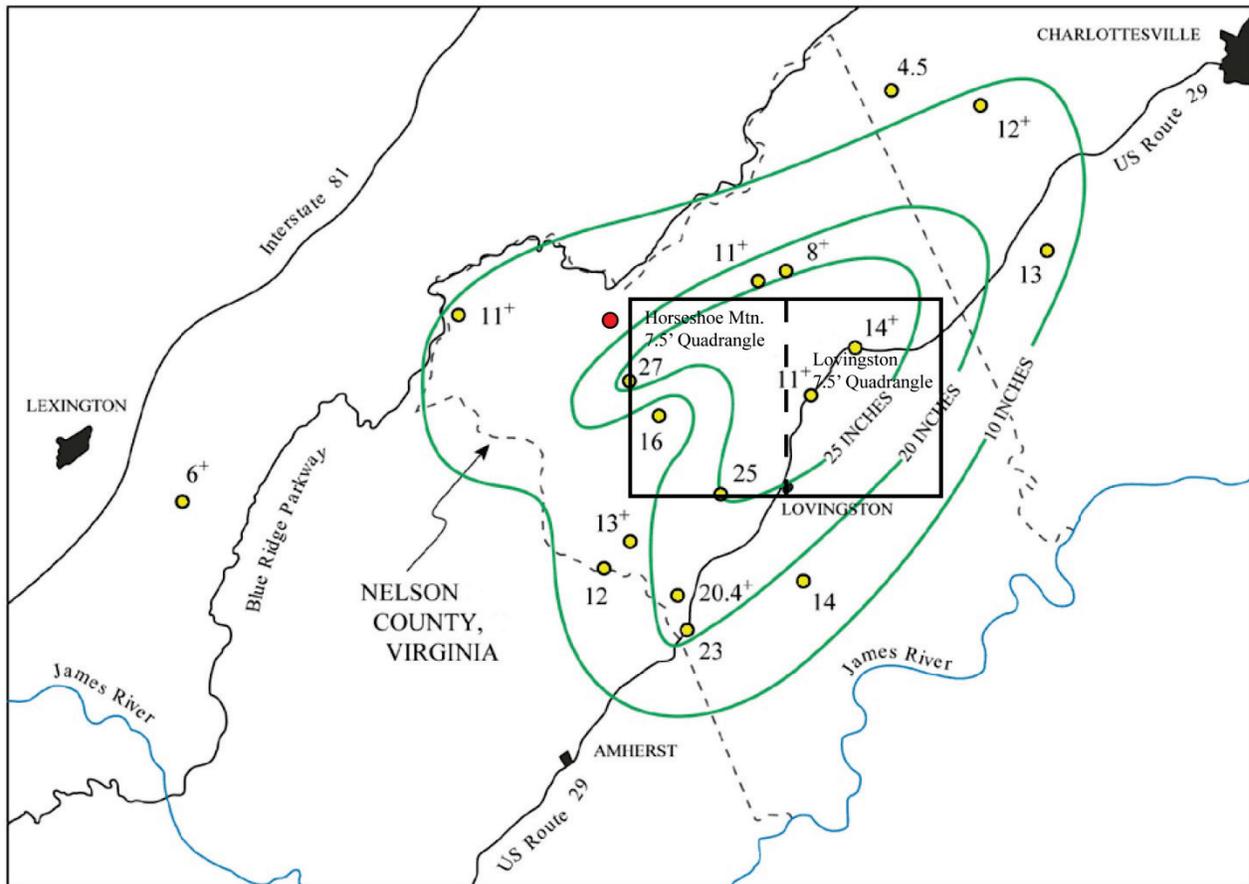


Figure 4. Isohyetal map of rainfall resulting from Hurricane Camille, August 1969, in the Lovingson and Horseshoe Mountain 7.5 minute quadrangles Nelson County, Va. (Morgan and others, 1999). Rainfall data marked with a “+” sign indicates rain gages that overflowed; they represent values that are necessary but not sufficient to determine the isohyetal contours (scale 1:500,000).

Nearly 30 years later, as much as 770 mm of rain fell in a restricted area near Graves Mill, Madison County, Va., between 10 a.m. to 1 p.m. on June 27, 1995. Antecedent rainfall during the 5 days preceding the major June 27 storm ranged from 75 to 170 mm, increasing the moisture content in thin regolith and weathered bedrock. The storm was tracked by the U.S. Weather Service and a detailed analysis was published by Smith and others (1996). Bucket surveys of rainfall data enabled researchers to develop isohyets (lines of equal precipitation), and extensive interviews of residents in the area provided valuable information on the timing of debris flows and rainfall totals that could then be correlated with the location of the storm and the rate of rainfall at the time of the debris flow (Wieczorek and others, 2000). A detailed map of the debris flows and flooding was compiled based on infrared aerial photography taken 6 weeks after the storm (Morgan and others, 1999a). This map also included isohyets and the track and timing of the storm. At least 629 debris flows were mapped within a relatively small area of 130 km². The debris flows were generated on slopes averaging 30 ± 3.7 degrees and an elevation of approximately 350 m. Debris slides were generated in weathered granitic and gneissic rock. Downslope, these usually became fluid within a few tens of meters and entrained as much as 90 percent of their final volume during their descent to the fans and flood plains of the Rapidan,

Robinson, and Conway Rivers. In the area of Graves Mill, a number of farms, as well as roads and bridges, were severely damaged (fig. 5). During this event, older debris fans were extensively incised to reveal a complex stratigraphy of debris-flow deposits interbedded with slope-wash colluvium and minor alluvium. All of the larger debris-flow deposits that were incised were found to have a composited stratigraphy, giving evidence of a history of multiple events. Figure 6 is a photograph showing scour from the July 1995 storm with lag deposits of fresh boulders from the 1995 debris flow in the bottom of the channel. Slope wash colluvium overlies at least two deeply weathered debris flows of Pleistocene age. Sufficient charcoal was obtained from similar deposits and carbon 14 (C^{14}) dates provide evidence that the area has been affected by debris flows from more than 50,000 years before present (ybp) (the limit of C^{14} determinations) to the present, with the majority of dated deposits ranging from 26,000 to 13,000 ybp (Eaton and McGeekin, 1997; Eaton, 1999; Eaton and others, 2003a). The period of intense rainfall occurred during the morning and early afternoon, and county officials were able to warn many residents of these dangerous conditions. Only one person died.





Figure 5. A. Debris flow that destroyed a home in Madison County during storm of June 27, 1995. B. Damage to the home. (Photo taken August 18, 1995.)



Figure 6. Scour from June 27, 1995, debris flow in Madison County, Va., revealing older debris-flow deposits.

Later on the evening of June 27, between 9 and 11 p.m., a similar storm developed over the Moormans River area in Shenandoah National Park in western Albemarle County. At least 29 mm of rain fell during this approximate 2-hour period. No hikers were within the Park during the event, and the rain gage was near the apparent periphery of the storm; therefore, there were no direct witnesses to the storm or the ground failures. Using infrared aerial photography, a map of the area was constructed showing 61 debris-slide scars (Morgan and Wiczorek, 1996). The area is entirely underlain by

metabasalt and clay-rich saprolite. Massive debris slides developed within weathered metabasalt and were characterized by deep scarps at the head of the failures, slopes between 19 and 26 degrees, and broad, poorly defined channels, usually less than 300 m long. In addition to debris slides, there were a number of smaller slumps and soil slips. The debris slides converged into the Moormans River to create a powerful debris torrent that scoured the valley walls, creating major scarps along the thalweg and depositing a delta of debris into the downstream Charlottesville Reservoir (Morgan and Wieczorek, 1996). The rainfall in the Moormans River area exceeded 279 mm (Morgan and Wieczorek, 1996) but may have been as great as 635 mm (Eaton, 1999).

The June 1995 storm had a significant impact on a third region in the Blue Ridge. Located approximately 120 km southwest of the Rapidan Basin, the site is near Buena Vista in eastern Rockbridge County. Although no direct rainfall measurements were available from the field area, the National Oceanic and Atmospheric Administration (NOAA) estimates that approximately 213 mm of rain fell on June 27. The nearby Maury River (basin area 1,676 km²) reached a flood stage and peak flow of 19.5 ft and 37,500 ft³/s, respectively, and was the third largest flood of record since the installation of the USGS gaging station in 1936. The deluge triggered 53 individual failures, primarily debris slides and flows, within a ~50-km² area in steep, rugged topography. The majority of the debris flows initiated in zero- and first-order drainages on slopes exceeding 28 degrees. The basins are underlain by conglomerate, phyllite, metasilstone, and quartzite of the Chilhowee Group; specifically, the Antietam quartzite was the dominant rock within most of the failure zones. Sas and Eaton (2008) found evidence that possible mechanisms of the slope failures include (1) elevated rates of hydraulic recharge in fracture zones, (2) structural controls dominated by the intersections of joint and bedding planes, and (3) significant contrasts in the hydraulic conductivities between rock and regolith materials, thereby increasing pore pressures and subsequent failures. The research also found that the denudation values of two of the impacted basins were exceptionally high and were probably the result of a combination of factors, including high-storm and antecedent rainfalls; steep topography; numerous, deep-seated wedge failures; and an abundance of regolith along the debris-flow chutes.

West Virginia

On June 17 and 18, 1949, an intense convectional storm produced over 400 mm of rainfall in a 24-hour period in the North Fork Mountain area in eastern West Virginia (Hack and Goodlett, 1960). This storm resulted in floods on the South and North Branches of the Potomac River and triggered debris flows in soils derived from sandstone on the steep upper slopes of North Fork Mountain (Cenderelli and Kite, 1998). At least 8 persons were killed and about 2,400 residents were driven from their homes (Clark, 1987b). The runoff produced dozens of debris slides on the upper mountain slopes, enlarged most of the channels, reworked debris on the bottom lands of many large valleys, and, in places, removed the forest cover on the entire valley floor. The largest of the debris flows on North Fork Mountain had its head 160 feet below the ridge crest and traveled approximately 2.5 km. Its width at the head of the debris flow was 12 m and gradually increased to 43 m at its base (Stringfield and Smith, 1956). According to Cenderelli and Kite (1998), the largest debris flow had a combined length (failure zone, transport zone, and deposition zone included) of 2,600 m with a volume total of 17,300 m³ and a volume of deposited sediment of 12,000 m³.

Hurricane Camille, in addition to the devastating storm that impacted Nelson County, Va., also had a separate but major impact on August 19 and 20, 1969, in the Spring Creek drainage basin of Greenbrier County in eastern West Virginia (Radbruch-Hall and others, 1982). Debris flows and related flood damage were concentrated in an elongate pattern directly under the area of most intense rainfall, in an area of approximately 58 km², although the total area affected was approximately 94.2 km²

(Schneider, 1973). Debris flows were triggered on slopes that averaged 35 degrees, with a minimum slope of 19 degrees on clear land and 17 degrees in timberland (Schneider, 1973). As many as 1,584 debris flows and debris slides occurred in this area. According to Schneider, the volume of material removed by an individual slide ranges from 0.3 m³ to approximately 24,366 m³. The total volume of material removed was 147,684 m³. The range in maximum slide scar-head width is less than 3.7 to 160 m. The area of land disturbed at an individual site and the volume of regolith removed range from 1.9 m² disturbed and 1.9 m³ removed, to 6,029 m² and 24,369 m³ distributed and removed, respectively.

Rainfall from Hurricane Juan, November 3 through November 5, 1985, triggered numerous landslides, including debris slides and debris flows in the area of North Fork Mountain in eastern West Virginia and western Virginia (Jacobson, 1993). In this area of Pendleton County, W.V., and Highland County, Va., rainfall varied from less than 170 to more than 240 mm, resulting in more than 3,000 ground failures of all types. Most failures occurred at the northeast end of the study area where 48-hour rainfall totals were in excess of 200 mm. Most of the landslides triggered by the storm were classified as debris slumps, debris slides, earth slides, and debris flows, according to accepted landslide terminology (Varnes, 1978). Most failures were shallow, planar slides with depths rarely exceeding 2 m, and showed minor rotational movement. A smaller number of failures occurred in colluvial aprons at the base of slopes and were presumably triggered by lateral stream erosion of the slope toes. Eight large debris flows on North Fork Mountain began as sliding masses of sandstone residuum and colluvium. The masses moved down steep slopes and flowed as much as 2 km, with varying amounts of erosion and deposition. Ninety-five percent of the earth failures triggered by the November storm were slides, slide flows, slumps, or slump flows. The remaining 5 percent can be classified as debris flows and debris slides transitional to debris flows. According to Cenderelli and Kite (1998), the largest landslide was a debris flow at Twin Run with a total deposition of eroded sediment of 13,900 m³ with a total length of 2,848 m.

Kentucky

A thunderstorm on July 4 and 5, 1939, released 508 mm of rain that triggered four debris flows and many other earth failures in Wolfe and Breathitt Counties, eastern Kentucky. Flooding and slope failures resulted in 78 deaths (Schrader, 1945). Debris slides and debris flows resulted from another storm on June 21, 1956, according to Clark (1987b).

Pennsylvania

During the night and morning of July 18–19, 1942, an astonishing 782 mm of rain and hail fell in at least one locality during a thunderstorm complex in just 4.5 hours. Other localities lacked the intensity but received approximately 889 mm during a 12-hour period (Scott, 1972; Eisenlohr, 1952). The storm was centered in Elk, McKean, Potter, and Cameron Counties of Pennsylvania, and triggered numerous landslides, including debris slides and flows, although the numbers of were not recorded. One of the largest debris flows moved downslope for more than 1.6 km and was nearly 0.4 km wide at its base where it entered Kettle Creek in Clinton County (Eisenlohr, 1952).

Hurricane Diane released at least 245 mm of rain in northeastern Pennsylvania on August 17–19, 1955. Four debris flows were triggered on the face of the Pocono Escarpment in the headwaters area of Brodhead Creek (Scott, 1972). Hack and Goodlett (1960) visited the area and measured one slide chute at 300 m long and 15 m wide.

Within the Johnstown area of western Pennsylvania, a thunderstorm resulted in 300 mm of rain that fell during a 9-hour period on July 19–20, 1977 (Brua, 1978). Several hundred debris slides, debris flows, slumps, earthflows, and combinations of the various types of landslides took place. The largest of

the debris flows were triggered on 40-degree slopes with head scarps as wide as 25 m and as deep as 4 m (Pomeroy, 1980).

On August 14, 1980, a thunderstorm triggered slope movements of debris slides and debris flows at East Brady, along the Allegheny River in northern Pennsylvania (Pomeroy, 1984). The highest density of earth failures was on an east-facing slope opposite East Brady with about 85 failures per square kilometer (Pomeroy, 1984). On the same slope 1 to 3 km east of East Brady, a smaller number (56 per square kilometer) was recorded. The head of one debris flow was 6 m wide and 2.5 to 3.0 m deep, and the flow was 135 m long. A minimum of 1,500 m³ of colluvium was flushed out of the channel and into the Allegheny River (Pomeroy, 1984).

Summary of Observations on Debris Flows

We summarize data on the triggering, occurrence, and effects of debris flows in the central and southern Appalachians. This account is based primarily on the well-documented occurrences noted in table 1 and field studies published in Morgan and Wieczorek (1996), Morgan and others (1999a, b), Wieczorek and others (2000), Eaton and others (2003a, b), and Wooten and others (2008a, b).

The principal conditions that must prevail to trigger debris flows are excessive rainfall, elevated terrain with steep slopes, and a susceptible supply of material.

Rainfall totals for nineteen debris-flow occurrences are given in table 1 and range widely from 115 mm to as much as 800 mm over periods of 14 days to 1 hour. The rate of rainfall appears to be more critical than the total rainfall (fig. 7). This figure indicates that critical rainfall conditions in the Blue Ridge of central Virginia range from about 20 mm/hr for a duration of 24 hours to up to 180 mm/hr for a duration of about 1 hour. Unfortunately, for most of the best described events in the Appalachian region, rainfall data are scarce. Many events took place in isolated regions with few inhabitants, and most rain gages have a maximum capacity of 12 inches. The Nelson County storm occurred in a rural area of small farms, but the great majority of rain gages overflowed and yielded only minimum values for rainfall. Contours of rainfall are available for only two of the events that occurred within Nelson and Madison Counties (shown in Morgan and others, 1999a, b). Actual rainfall patterns are more complex than the apparent bull's-eye of the contoured data. The actual trace of the Madison storm determined by Smith and others (1996) and shown plotted on the Madison storm and debris-flow map (Morgan and others, 1999a) passed over the area in a broad "U" shape so that the central area was inundated twice in a short period, giving a total of 770 mm in that location. Figure 8 shows the rate of rainfall and the time of directly witnessed debris-flow impacts at a given location for the Madison storm. These debris flows were triggered during periods of rapid rainfall-rate increases rather than just being the result of the total rainfall. Finally, we do not know what role that antecedent precipitation plays in setting the conditions for debris-flow triggering during intense rainfall. In the Madison area, antecedent rainfall 3 days before the debris-flow event ranged from 60 to 100 mm, thoroughly soaking the colluvium.

Intensity - Duration Threshold for central Blue Ridge, Virginia

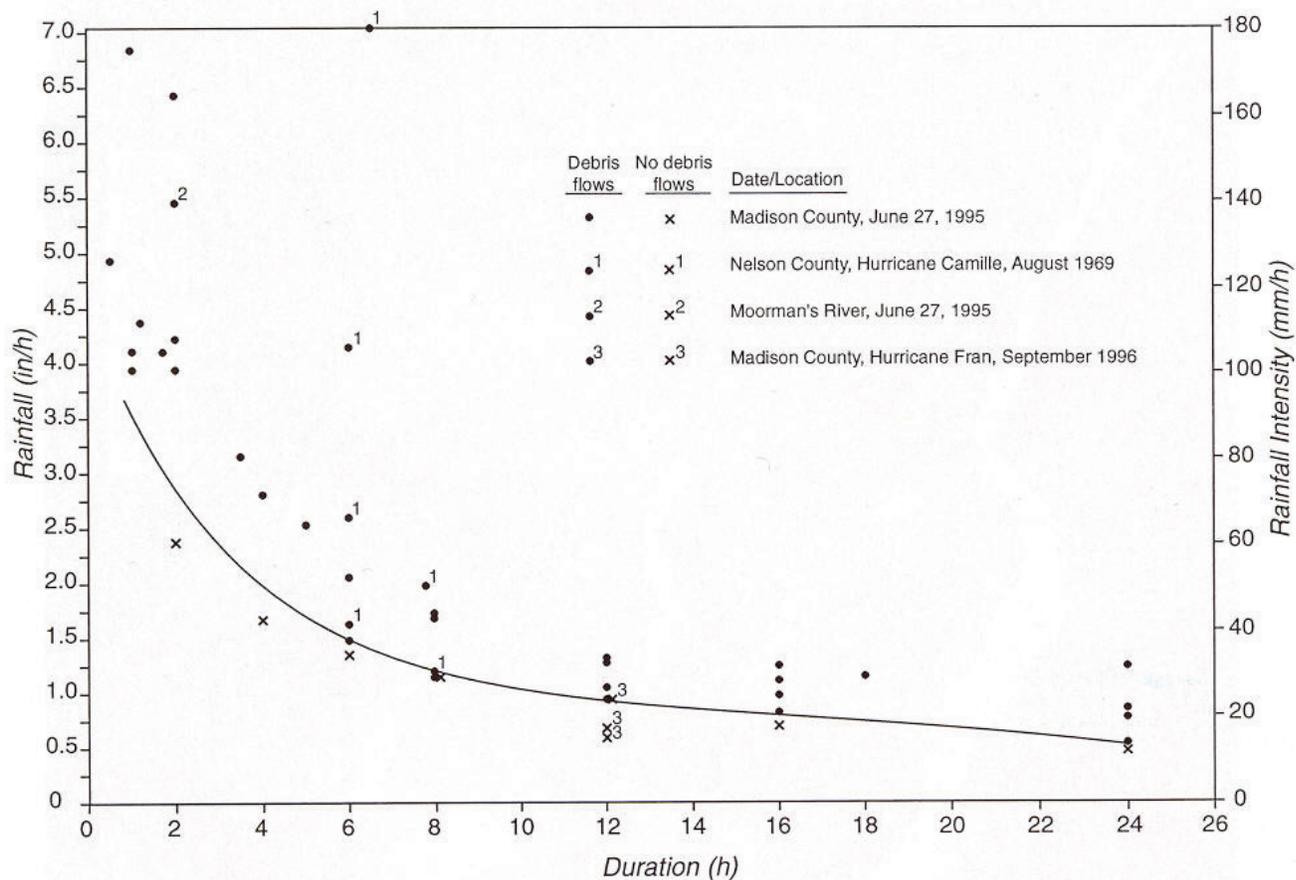


Figure 7. Rainfall intensity and duration for storms in the Blue Ridge of central Virginia. The line depicts a predicted threshold that represents minimum values necessary for triggering debris flows (Wieczorek and others, 2000).

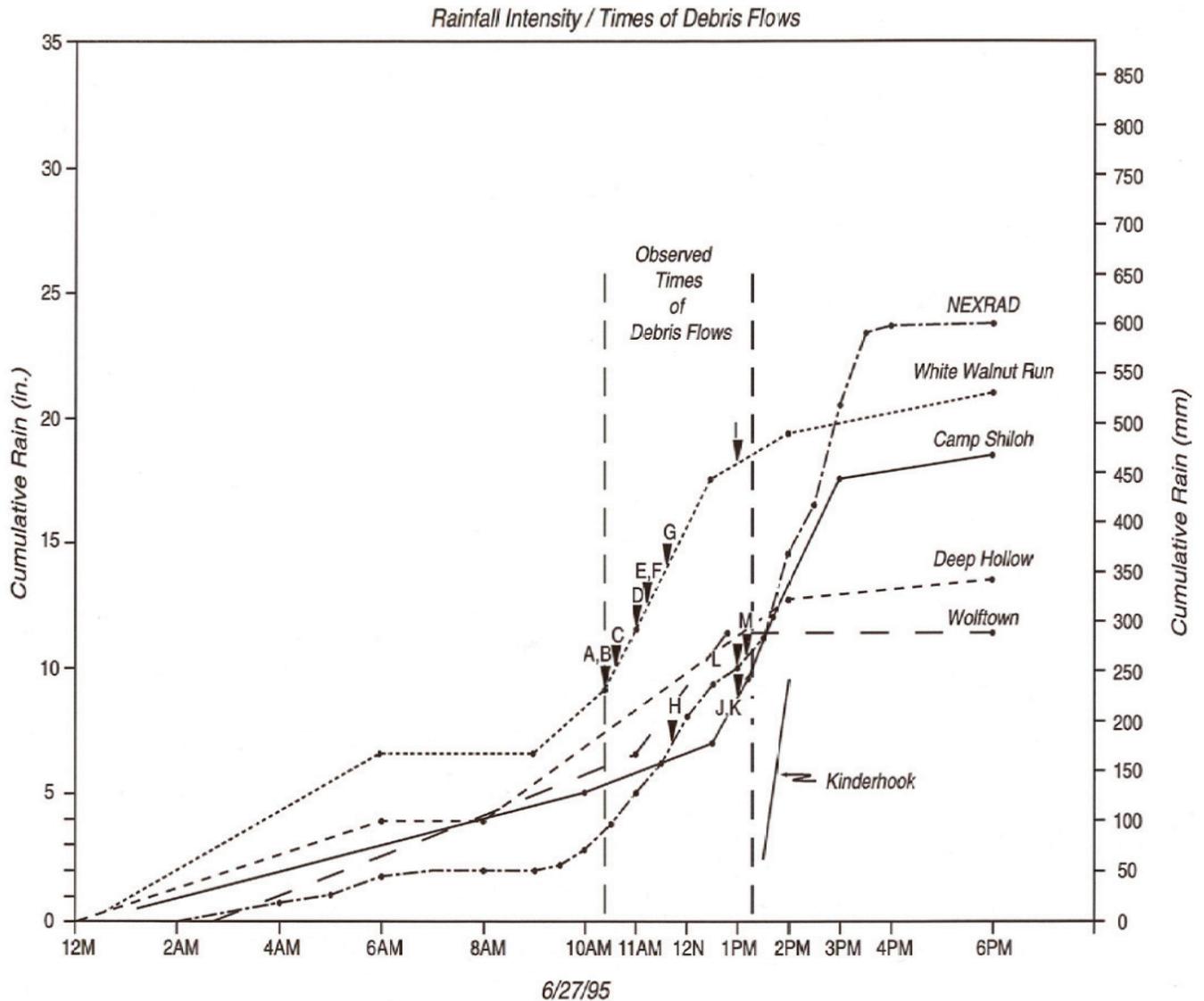


Figure 8. Rainfall and a few observed times of debris flows (shown as letters A–M) during the June 27, 1995, storm in Madison County, Va. (Wieczorek and others, 2000).

Steep slopes appear to be a critical condition for debris-flow occurrence. Clark’s 1987 map depicted in figure 1 clearly shows the relationship of debris flows to the mountains of the central and southern Appalachians. Slope measurements, where taken, confirm a steep topography, with debris flows found more frequently on slopes greater than 20 degrees and averaging about 30 degrees.

A susceptible supply of material available for debris-flow occurrence is critical, but the characteristics of that supply will vary widely, because of both the underlying bedrock of the region and its history of weathering and erosion. Areas underlain by shales and intercalated thinly bedded shales and sandstones will respond more readily to debris-flow triggering (Jacobson, 1993). For example, two locations underlain by sedimentary rocks, specifically the Allegheny River in Pennsylvania and Pendleton County, W. Va., experienced numerous slope failures from a storm that dropped 145 mm and 350 mm, respectively, over several days. In contrast, storms having similar rainfall intensities have not affected the metagranitic rocks of the Virginia Blue Ridge. Highly jointed quartzites and sandstones

proved to be susceptible lithologies in a debris-flow event near Buena Vista, Va., in 1995 (Sas and Eaton, 2008). In the Blue Ridge of central Virginia, we believe that periglacial conditions resulted in the widespread cover of loosely consolidated mountain top debris above an elevation of about 600 m (Clark, 1987a). This material is highly susceptible to mobilization during heavy rainfall.

The suggestion has been made that colluvium collects in coves along ridge crests until metastability is attained during excessive rainfall (see Hack and Goodlett, 1960; Kochel, 1987). We carefully tested this hypothesis in the Madison County area and determined that approximately two-thirds of the triggering sites were in concave or cove sites. Data from debris-flow initiation sites in North Carolina also show that about two-thirds of the sites were in concave slopes. Inspection of aerial photography in the Nelson County area revealed that many triggering sites were not in coves but along ridge crests and occasionally on convex surfaces. Triggering sites in the Moormans River area frequently occurred on convex slopes. Residual soil development and colluvial accumulation from weathered and saprolitized bedrock are slow processes. Carbon samples from saprolitized material were invariably radiometrically “dead,” indicating an age greater than 50,000 ybp. Onsite recurrence intervals appear to be much shorter, in the range of 3,000 to 5,000 years (Eaton and others, 2003a). On the basis of these data, we believe that debris-flow occurrences in the Blue Ridge are not a steady-state phenomena based on continued accumulation of colluvium and residual soils. Instead, debris-flow occurrences are the result of historical or contingency processes during which periglacial debris and surficial materials are progressively mined out of the terrain more rapidly than they can accumulate.

Ground failure at the source is almost always a debris slide characterized by a relatively planar detachment surface. Upslope migration of the failure sites was not observed in the Madison area. The debris slide evolved into a flow within 10 to 20 m downslope as evidenced by scouring of the detachment surface and development of lateral levees. Once triggered and moving, the debris flow does move directly downslope into the drainage network and loosely follows the stream channel. Long transport and substantial sediment discharge of a debris flow are dependent on entrainment of material downslope, indicating that soil saturation and the presence or absence of a perched water table along the path are critical factors. In our study of a tributary of Kinsey Run in Madison County (Wieczorek and others, 2000), we found that more than 90 percent of the sediment discharge was contributed by entrained material along the path of the flow. Super elevation of the flow above the channel (Johnson 1970, 1984) was often observed along this drainage with measured velocities of 24 m/s near the head of the scarp and slowing to 8 m/s near the depositional fan (Wieczorek, and others, 2000). The upper and steeper chutes of the debris-flow path are marked by extensive scour, lateral levees, and plunge pools; the lower gentle slopes of the path are the sites of deposition. However, multiple debris-flow surges along the same channel coming from different headward tributaries can create a complex geometry of deposition followed by scour and then later by deposition over the earlier flow sites.

Deposition of debris-flow discharged material in the Madison and Nelson Counties areas is on prominent fans bordering the larger streams and rivers in the area. These fans are irregular in map view and confined to the valley walls and have been built up by successive late Pleistocene and recent debris-flow and fluvial deposition (Kochel and Johnson, 1984). Field studies in Macon County, N.C., identified preexisting debris deposits at all of the 62 relatively recent debris-flow sites, an indication that earlier, and, in many cases, multiple debris-flow events had occurred (Wooten and others, 2008a).

In the Moormans River area, and possibly along Davis Creek in Nelson County, debris slides and small debris flows converged into a river in a full-flood state, creating a hypoconcentrate flow or debris torrent (Costa, 1988). In the Moormans River, this torrent moved with great erosive force, cutting away banks and, in a series of successive surges, carrying debris downstream and filling nearly one-half

of the Charlottesville Reservoir. Davis Creek in Nelson County was also probably the site of a debris torrent and was the site of the greatest loss of life for any of these events, with 50 casualties in that area.

Future Research

Figure 7 is an algorithm depicting critical rainfall rates and duration necessary to trigger debris flows in the Blue Ridge of central Virginia. Similar algorithms have been developed for other areas and are shown in figure 8 (Wieczorek and others, 2000). This figure documents that the weather conditions necessary to trigger flows in the Blue Ridge are more extreme than those in other areas that have been studied. We believe that this is mainly a function of sediment supply. The Virginia Blue Ridge is a mature landscape, with a protracted erosion history, and is underlain by highly competent metaigneous rocks and metasedimentary rocks with a relatively thin carapace of soils, saprolite, and mountain top colluviums (Clark, 1987a). Apparently, these characteristics combine in such a way that a high level of activation energy is required to initiate debris flows in the Blue Ridge in central Virginia. We have no reliable information necessary to develop a similar algorithm for other geologic provinces in the central and southern Appalachians. Areas underlain by sandstones and shales in western Virginia, West Virginia, and much of Pennsylvania could respond with very different thresholds for ground-failure triggering.

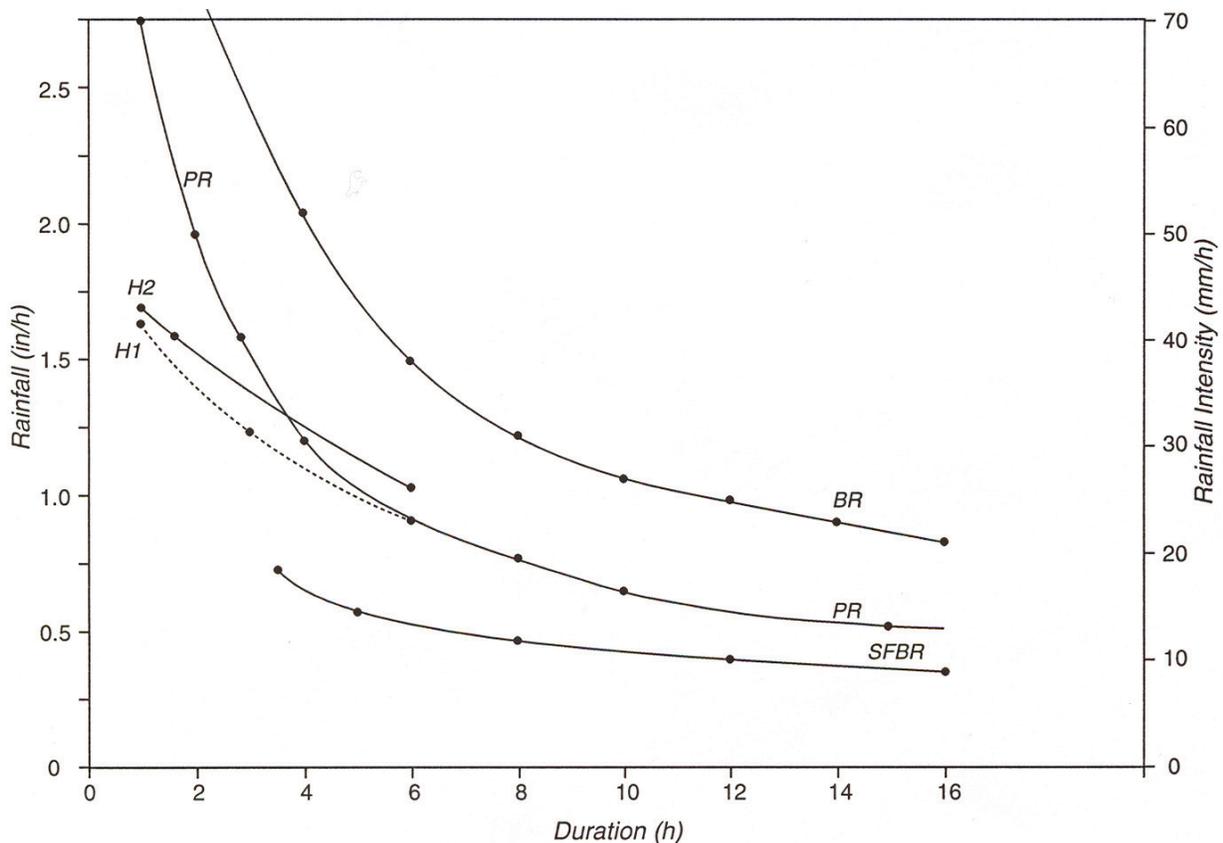


Figure 9. Rainfall intensity-duration for debris-flow thresholds for Blue Ridge (BR); Hawaii (H1, H2) (Wilson and others, 1992); San Francisco Bay Region (SFBR) (Cannon and Ellen, 1985); and Puerto Rico (PR) (Jibson, 1989; Larsen and Simon, 1993).

Factors leading to the saturation by rainfall of surficial materials leading to the loss of cohesion and internal friction are not well understood. These include the role of antecedent rainfall in preparing the ground before a major rainfall, the nature of the regolith, especially the clay content and permeability, and the role of bedrock, including the extent of jointing and other planar characteristics, such as bedding, cleavage, and foliations.

Sedimentological experiments and computer modeling have been used to develop predictive tools. These have been increasingly applied over the past decade, and an extensive literature has been published. These include experimental studies by Iverson and others (1994) and modeling studies applied to the Nelson County storm (Morrissey and others, 2001, 2008). An extensive survey of landslide hazards in western North Carolina is being undertaken, and computer modeling is a standard application in this effort to delineate areas of potential hazard (see Wooten and others, 2008b). Increased sophistication of these modeling programs, coupled with new remotely sensed mapping of surficial features, including side-looking radar and Light Detection and Ranging (LIDAR), offers a promising avenue for investigation of landslides in remote locations and broad areas of the Appalachians.

Recurrence intervals for debris-flow activity at a given site are almost completely unknown. Using the historical record, large areas, such as Virginia, appear to have a recurrence interval of about 15 years, whereas, for western North Carolina, the interval appears to be much shorter, perhaps as little as 3 years. Witt (2005) reported that the recurrence of debris-flow events averages 16 years for the French Broad watershed in North Carolina (over 7,000 km²); for small watersheds (<10 km²), Wooten and others (2008a) reported recurrence could be on the order of decades. A more accurate determination of the recurrence interval for a given site can be obtained through investigation of prehistoric debris flows with ages determined by C¹⁴ (Kochel, 1987), and Eaton and coworkers (Eaton and McGeehin, 1997; Eaton and others, 2003a, b) have undertaken an exhaustive study of prehistoric debris flows dated by the age window for C¹⁴. For the Madison area, Eaton concluded that the recurrence interval was approximately 3,000 years. A similar conclusion was reached, on a much shorter time interval, by Kochel (1987) working on Davis Creek in the Nelson County area. Recurrence intervals, of course, are a function of scale, with the interval decreasing as larger areas are considered. Research is needed to determine the recurrence intervals for debris flows in the Ridge and Valley Province or in the highlands of North Carolina.

Warning the public of potential or impending debris-flow hazards will require a concerted effort by local, State, and Federal Governments. A network of rain gages that records rainfall in real time is available in parts of the southern and central Appalachian Mountains and could become more widely developed in the region. To be effective as a hazard-warning system, the rain-gage network should be integrated with radar precipitation data, hillslope monitoring information, and radio, television, and Internet communications for State Emergency Response Centers and public and emergency managers in areas of concern. If a set of algorithms similar to those in figure 7 can be developed for the several geologic provinces of the Appalachians, the rainfall-time thresholds indicated by these algorithms can provide the basis for hazard alerts. Long-range mitigation of debris-flow hazards can be improved by careful placement and strengthening of roads (Collins, 2008) and bridges and by the selection of sites for new construction that are away from areas most susceptible to landslide failure and subsequent inundation by debris flows.

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