Debris-Flow Hazards in the Blue Ridge of Central Virginia

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ABSTRACT

The June 27, 1995, storm in Madison County, Virginia produced debris flows and floods that devastated a small (130 km^2) area of the Blue Ridge in the eastern United States. Although similar debris-flow inducing storm events may return only approximately once every two thousand years to the same given locale, these events affecting a similar small-sized area occur about every three years somewhere in the central and southern Appalachian Mountains. From physical examinations and mapping of debris-flow sources, paths, and deposits in Madison County, we develop methods for identifying areas subject to debris flows using Geographic Information Systems (GIS) technology. We examined the rainfall intensity and duration characteristics of the June 27, 1995, and other storms, in the Blue Ridge of central Virginia, and have defined a minimum threshold necessary to trigger debris flows in granitic rocks. In comparison with thresholds elsewhere, longer and more intense rainfall is necessary to trigger debris flows in the Blue Ridge.

INTRODUCTION

During the last week of June, 1995, a series of unusually intense, wet, tropical storms struck parts of the Virginia Piedmont and Appalachian Mountains. These storms initiated debris flows and floods in several widely separated parts of the Blue Ridge (Figure 1). Scattered individual debris flows occurred between Buena Vista and Glasgow and a single debris flow was noted near Front Royal. Numerous debris flows were found along the North Fork, Moormans River, west of Charlottesville (Morgan and Wieczorek, 1996). More abundant, damaging debris flows were triggered throughout northwestern Madison County, where storm-related debris flows caused one fatality, destroyed buildings, bridges, and roads, killed livestock, and inundated crops (Wieczorek et al, 1996; Morgan et al., 1997).

The Madison County area affected by the June 27, 1995 storm is within the upper drainage basins of the Conway, Rapidan, and Robinson rivers on the eastern flank of the Blue Ridge Mountains (Figure 2). The main valleys are broad, up to 500 m wide, consisting of flood plains flanked by alluvial fans and terraces (Morgan et al., 1999a). The higher topography is irregular with many subsidiary ridges extending several miles from the Blue Ridge and separating well-defined hollows with small tributaries. The crest of the Blue Ridge in this area rises to a rather uniform elevation of about 1,100 m.

Land use in northwestern Madison County is predominantly rural and agricultural with farming of corn, hay and livestock on or adjacent to the flood plains. Farming has been continuous in this area since the late 1700s. Undeveloped areas are generally covered with a forest of oak, hickory, red and sugar maple, black locust, and tulip poplar, with spruce, hemlock and pines at higher elevations. The area was extensively logged from 1880 to about 1920 and the oldest forest trees are about 70 years old. Shenandoah National Park encompasses much of the land along the crest and adjacent ridges of the Blue Ridge. The population density of Madison County is likely to increase greatly in the next several decades as the suburbs of Washington D.C. and Charlottesville expand.

Although substantial moisture is delivered to the Blue Ridge by prevailing continental westerly winds, violent summer storms are caused by moist tropical air masses that move inward from the Gulf of Mexico, the Caribbean Sea and the Atlantic Ocean. Higher elevations of Madison County, such as Big Meadows along the crest of the Blue Ridge, receive an average of about 1,300 mm of annual precipitation (1969–1990; Virginia State Climatology Office, written communication, 1998). Precipitation is fairly evenly distributed during the year, although September and October are somewhat wetter months and January somewhat dryer. During the hot, humid summers much of the rain falls during thunderstorms, which can deliver decimeters of rain in only several hours. Snow falls occasionally in the cold winters, but soon melts. Low daily temperatures at higher elevations drop below freezing during the months of November through March.

The geology of Madison County was mapped and described by Allen (1963). More recent summaries of the

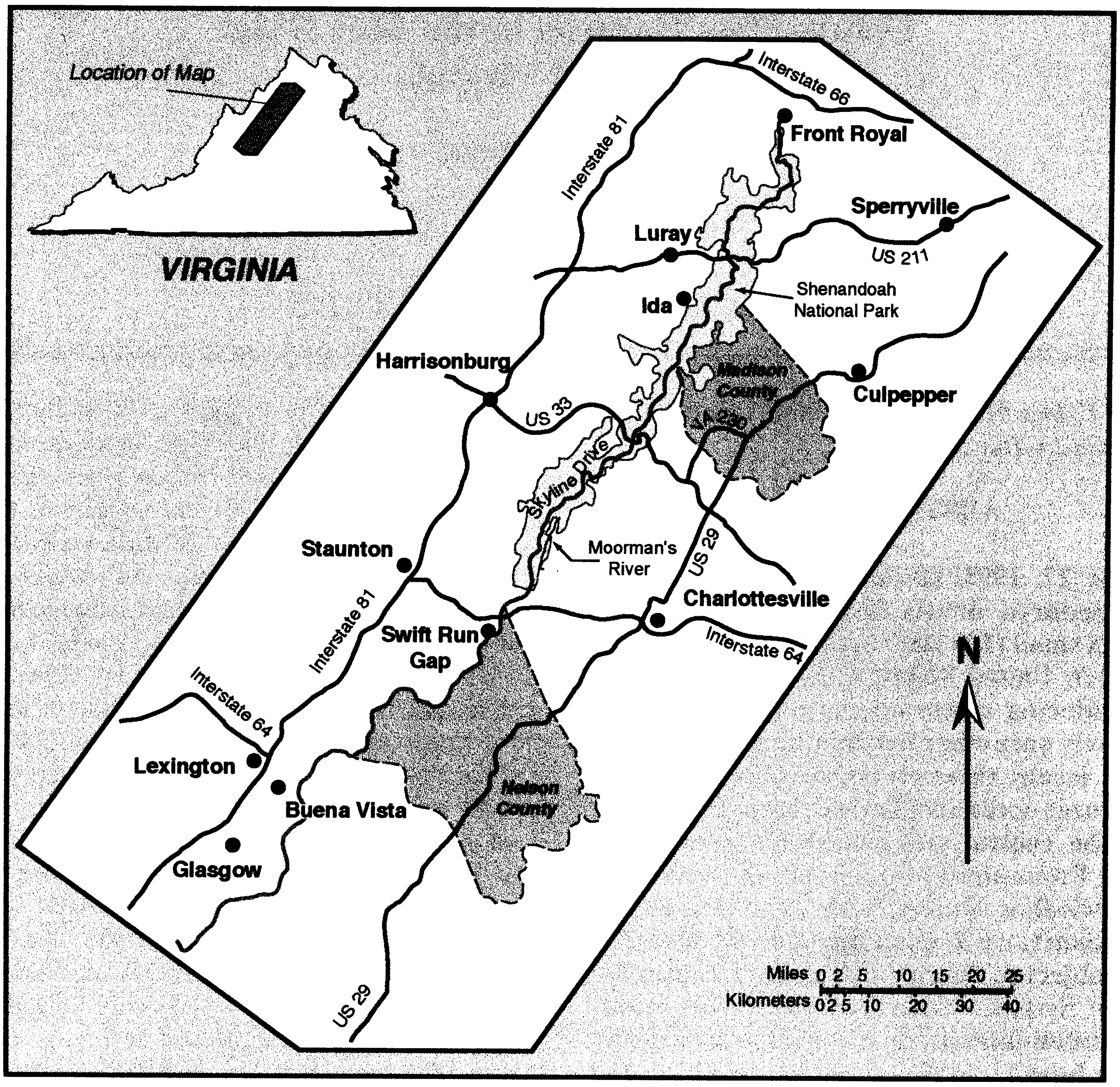


Figure 1. General location map of Blue Ridge in central Virginia, with the Moormans River west of Charlottesville, Madison and Nelson counties (dark shading), Skyline Drive, and Shenandoah National Park (light shading). Inset of State of Virginia.

geology of the underlying rocks have been published by Gathright (1976) and by Rader and Evans (1993). The area affected by the June 27 storm is underlain mainly by granitic rocks. These rocks originated as igneous intrusions and were deformed and recrystallized during the Grenville orogeny, about 1 billion years ago. About 570 million years ago these granitic rocks were intruded by diabase dikes which presumably acted as conduits for the volcanic flows of the Catoctin Formation which crops out to the west along the summit of the Blue Ridge. All of the rocks were altered more recently by metamorphism and deformation about 250 million years ago during the Paleozoic Era. The effects of the later deformation are mostly confined to a few well-defined faults and shear zones.

Debris flows have occurred repeatedly during historical time in the Blue Ridge. Clark (1987) documented 51 historical debris-flow events between 1844 and 1985, about one event every three years, south of the glacial border in the Blue Ridge and Valley and Ridge Provinces from Georgia to Pennsylvania. Numerous debris flows occurred in the Little River Basin of western Virginia in June 1949 as a result of intense storms (Hack and Goodlett, 1960). Nelson County, about 90 km south of Madison County on the eastern flank of the Blue Ridge, was subjected to catastrophic debris flows and floods, largely responsible for 150 deaths (Williams and Guy, 1973), triggered by heavy rainfall that accompanied the later stages of Hurricane Camille in August 1969 (Kochel, 1987; Gryta and Bartholomew, 1989). Heavy rains of November 3–5, 1985, produced extensive debris flows in the Potomac and Cheat river basins in West Virginia and Virginia (Jacobson, 1993). There is no historic record of debris flows in Madison County, which was first settled in the early 18th century. Floods occurred in April 1937, October 1942, June 1972 (Orange County Review, 1995) and from Hurricane Fran during September 1996, but the associated storms were not reported to have caused debris flows in Madison County.

Debris flows have been actively shaping the landscape of the central Blue Ridge throughout the Holocene and late Pleistocene (Clark, 1992). Deposits exposed in channels scoured by debris flows and extensive runoff during the June 27 storm in Madison County, attest to repeated episodes of debris-flow activity. In addition, the recent debris flows exposed soil, colluvium, saprolite and bedrock. Exposures of colluvium display a rich history of fossil soils, gley horizons with abundant organic remains, and prehistoric debris-flow deposits. Carbon-14 from deposits of prehistoric debris flows yield ages that range from 2,200 years to greater than 50,000 yr BP (Eaton and McGeehin, 1997). Extensive clast weathering and rubification of debris in some of the older debris-flow deposits suggest ages that are in excess of 50,000 years. In studies in nearby Nelson County, Kochel and Johnson (1984) and Kochel (1987) concluded that at least two prehistoric episodes of activity (6,340 and 10,500 yr BP) preceded the 1969 Hurricane Camille event. Paleo-debris flows in Madison and Nelson counties indicate the persistence of debris flows in the Blue Ridge of central Virginia during the Holocene and late Pleistocene.

The study reported here summarizes the meteorologic, geologic, hydrologic and topographic characteristics of recent debris flows in Madison County. We use measurements of rainfall intensity and duration to define a minimum threshold for triggering debris flows. We use detailed maps of Madison County depicting rainfall, debris flows and areas affected by floods to develop a methodology incorporating GIS techniques for evaluating areas elsewhere in the Blue Ridge subject to debris-flow hazards.

STORM OF JUNE 27, 1995

The intensity and distribution of rainfall during a series of storms which struck central Virginia during late June 1995 influenced the areal extent and magnitude of debris flows and floods in Madison County. In and around Madison County, antecedent rainfall during the 5 days preceding the June 27 storm ranged from 75 to 170 mm (Figure 3) increasing the moisture content in thin surface soils and shallow weathered rock. A cold front stalled east of the Blue Ridge Mountains where a moist southerly tropical air mass met a northerly polar air mass (Goldsmith et al., 1995). From early morning to mid afternoon of June 27, very strong rainstorms developed over Madison County. The high topography of the Blue Ridge Mountains enhanced updrafts and turbulence and the storm cells intensified and stalled, producing exceptionally heavy rainfall.

According to local residents, the rain began about 2 a.m. on June 27 and persisted until 6 a.m.; after a brief respite, a continuous heavy rain resumed around 10 a.m. and lasted until 4 p.m. During these 14 hours, rain fell with exceptional intensity for several hours, triggered approximately a thousand debris flows in an area of about 130 km^2, and raised the Conway, Rapidan, and Robinson rivers above flood stage. The track of the storm, a mapped inventory of debris flows, and documented times of debris flows are shown by Morgan and others (1999a).

Smith and others (1996) analyzed the National Weather Service WSR-88D (Weather Surveillance Radar-1988 Doppler) radar data to determine the track of this storm cell and the meteorological characteristics of the storm. Due to a lack of official weather measurements by federal, state, or local agencies in this region, and because radar data underestimated the total rainfall by a factor of 3 (Smith et al., 1996), we conducted an informal survey of measurements made by local residents and determined the distribution of rainfall shown on Figure 2A. The maximum storm total of 770 mm was reported by two different observers near Graves Mill, the junction of the Rapidan River with Kinsey Run (Figure 2; Morgan et al., 1999a).

Local rainfall measurements during the storm, some of which were exceptionally high, can be used to approximate rainfall intensity. An observer near Aylor (Figure 2) measured 60 mm of rain between 10:20 and 11 a.m., equivalent to a rate of 90 mm/h; between 11 a.m. and 12:30 p.m. at this location the intensity increased to 105 mm/h. Farther west at Camp Shiloh, along the Conway River (Figure 2), observers measured a rate of 130 mm/h over a 30-minute period between 1:15 and 1:45 p.m. The highest intensity was measured near Kinderhook (Figure 2), where 180 mm fell during 35 minutes, an astonishing rate of 300 mm/h. Nearby this location and at about this time, Smith and others (1996) determined peak rainfall rates using radar data, calibrated by locally measured rainfall, which exceeded 300 mm/h for two short periods of about 6 minutes each, the interval between radar readings.

Eyewitness accounts confirmed that debris flows occurred during times of high intensity rainfall between about 10 a.m. and 1 p.m. on June 27 (Table 1). A plot of cumulative rainfall during the storm (Figure 4) indicates a temporal correlation between an increase in rainfall intensity and the observed times of debris flows. Within this period (10 a.m.–1 p.m.), debris flows occurred when rainfall exceeded about 25 to 100 mm/h as determined by measurements of nearby rain gages. About 10:30 a.m., a debris flow from Sag Top, struck, crushed, and carried away a house, killing the occupant (Madison County Eagle, 1995). Near Graves Mill at about 11:30 a.m., a family sought refuge in the second story of their house

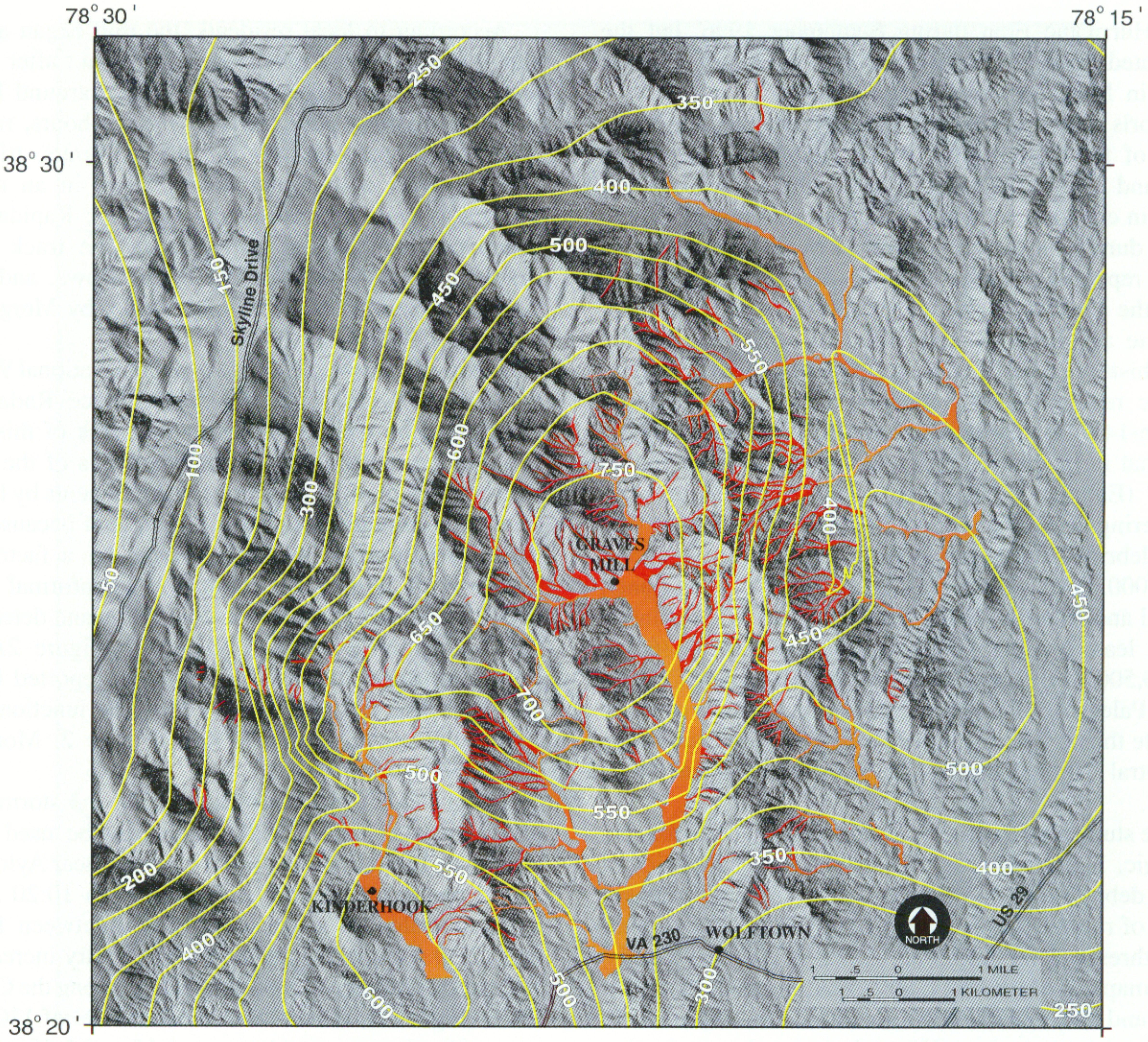


Figure 2. Digital shaded relief of the Madison County region. A) Rainfall contours (mm) from June 27, 1995 storm (yellow), areas of debris flow (red) and areas of flooding (orange).

as a debris flow pushed the house off its foundation, displacing it approximately 11 m. The timing and location of eyewitness observations (Table 1) corresponds roughly to the track of the centroid of the storm cell as determined from radar (Smith et al., 1996; Morgan et al., 1999a). Although the debris flows on the inventory map occur within the 350 mm contour of total storm rainfall (Figure 2), the timing of observed debris flows beginning at about 10 a.m. suggests that high rainfall intensity was more critical than the amount of rainfall for triggering debris flows. Debris flows probably continued to occur during intense rainfall after 1 p.m., but were not noted by observers who were probably seeking shelter from the storm and its effects.

Downstream of the confluence of the Conway and Rapidan rivers, near Ruckersville, the flood peaked shortly before 4 p.m., destroying the gaging station. The reconstructed crest of the flood on the Rapidan River in Madison County was in excess of a 500-year flood, with a discharge per unit area, 10.2 m^3s^{-1} km^{-2}, approximating the maximum historic value reported for the United States east of the Mississippi (Smith et al., 1996). This discharge was enhanced by large volumes of sediment and organic debris, i.e., tree trunks, delivered from hillsides by debris flows to the flooding streams and rivers within the Conway and Rapidan watersheds.

DEBRIS-FLOW PROCESSES

During the storm, hundreds of shallow rock, debris, or soil slides mobilized into debris flows. In this paper, we used types of slope movement as defined by Cruden and Varnes (1996). We used color infrared stereo positives at approximately 1:18,000-scale taken in August

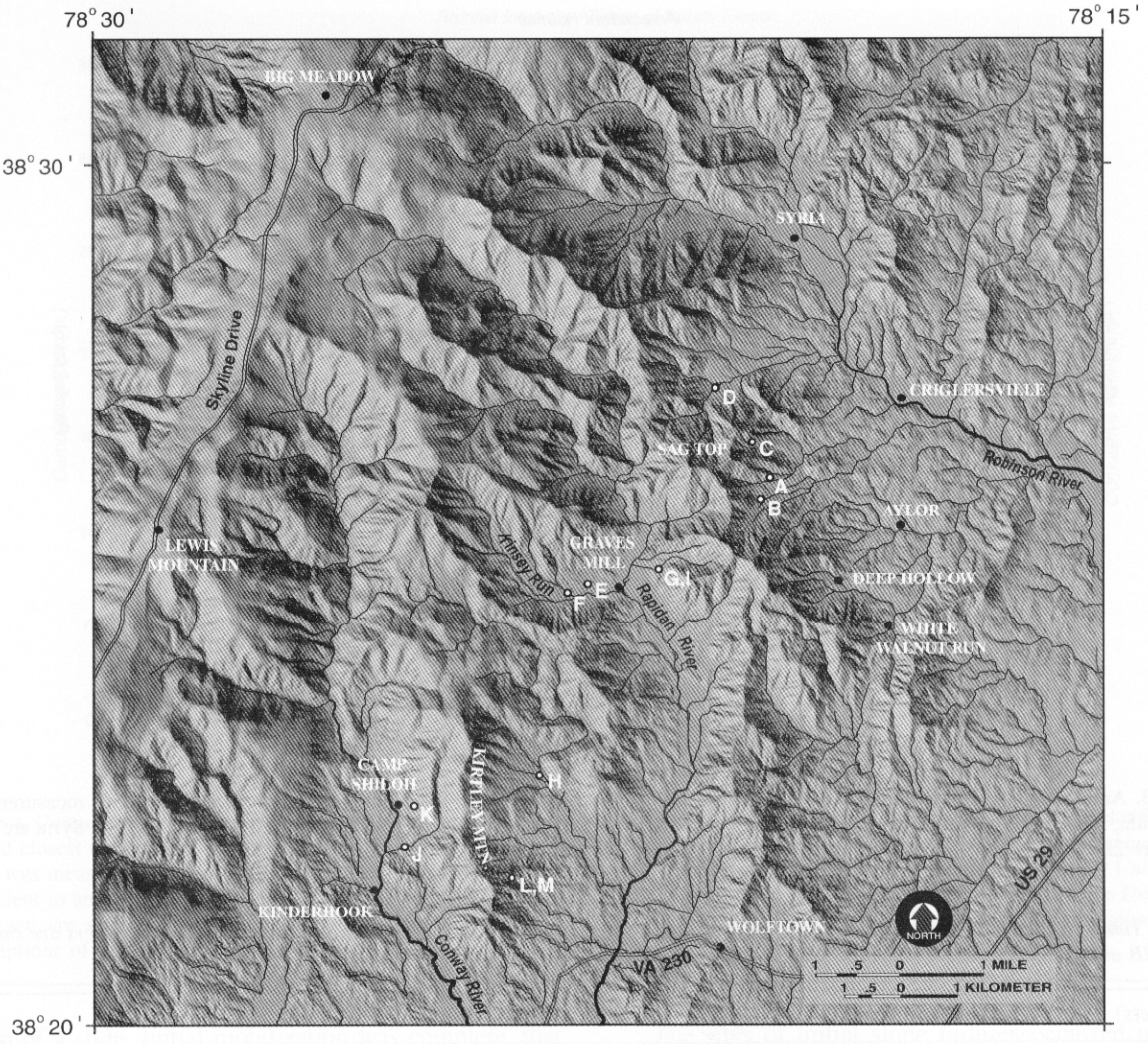


Figure 2. B) Conway, Rapidan, and Robinson river drainages (west to east) and sites of debris flows (dots with letters) observed by eyewitnesses (Table 1).

1995 to prepare a map of debris flows and flooding at a scale of 1:24,000 (Morgan et al., 1999a). Taken about 2 months after the storm, but without any intervening storms, the photographs display details of the initial slides, debris-flow channels and deposits on fans (Figure 5A). We conducted field studies to verify mapping and to characterize debris-flow features on about half of the mapped sites. We measured various features of debris flows, including dimensions of initial slide, slope steepness, deposit thickness, and size of median and largest boulders at 220 debris-flow source areas, 148 channel sites, and 86 sites on depositional fans (Morgan et al., 1997). Debris-flow deposits were distinguished from flood deposits on the basis of deposit morphology and sedimentology, especially the fabric of coarse- and fine-grained particles lacking grading or sorting according to size as in stream or flood deposits (Costa, 1984; Keaton et al., 1988; and Major et al., 1997).

Hillside Initiation of Slides and Debris Flows

The mobilization of debris flows from slides is a complex process that depends upon the imposed stresses, water content, and whether the initial soil is in a loose or dense condition. In terms of soil mechanics, loose soils with high void ratios have fabrics that tend to contract or collapse under shear stresses, and under undrained conditions lead to rapid debris flows. Dense soils, with low void ratios, expand during shearing, and if additional inflow of water is available, can transform into slow-moving debris flows (Ellen and Fleming, 1987; Lee et al., 1988).

In Madison County we noted that soil, rock, and debris slides initiated debris flows leaving distinct scars high on the hillslopes. Retrogressive slope failure, or progressive upslope failure, played a minor role; only rarely were small slides, slumps or ground cracks found above the

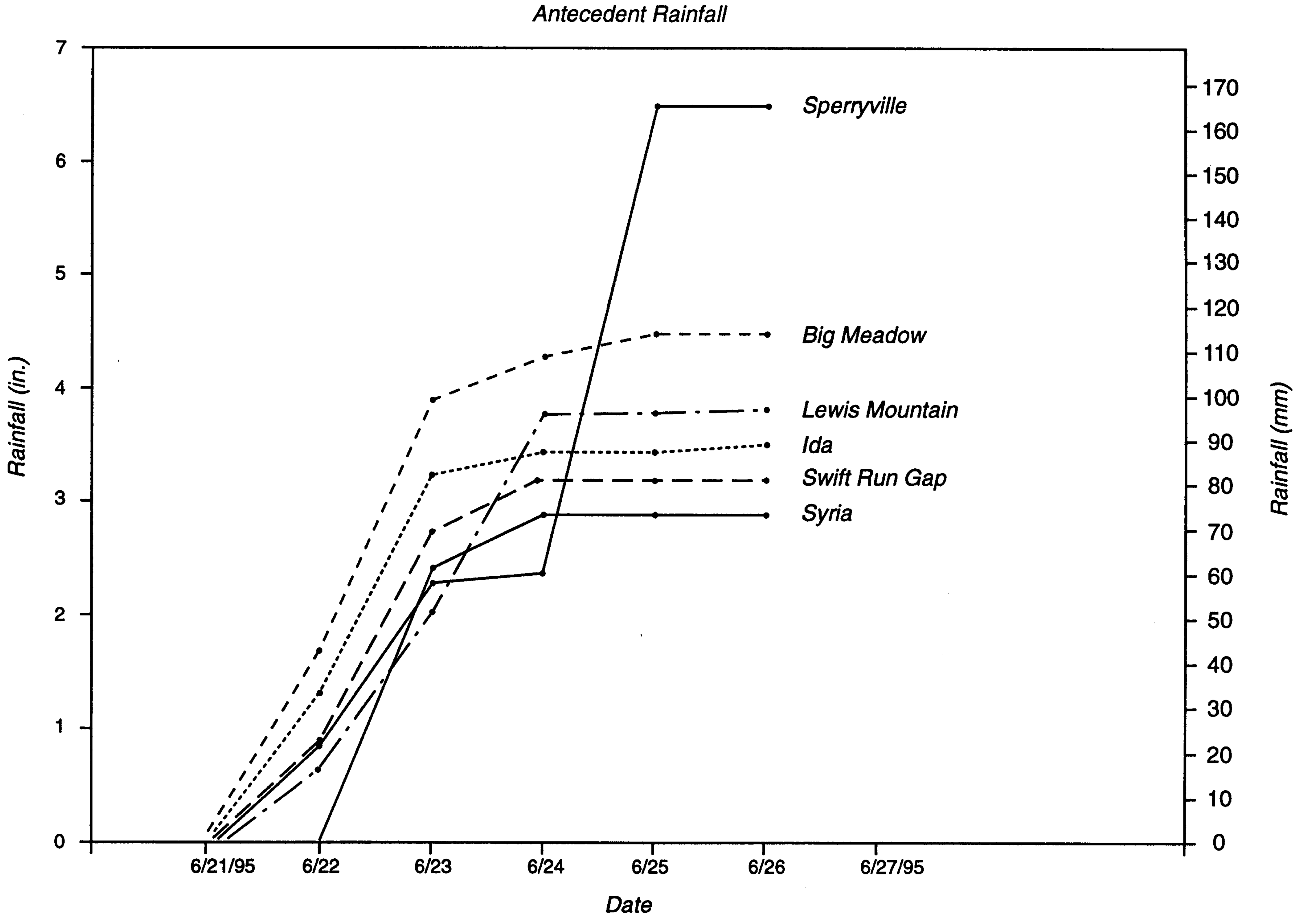
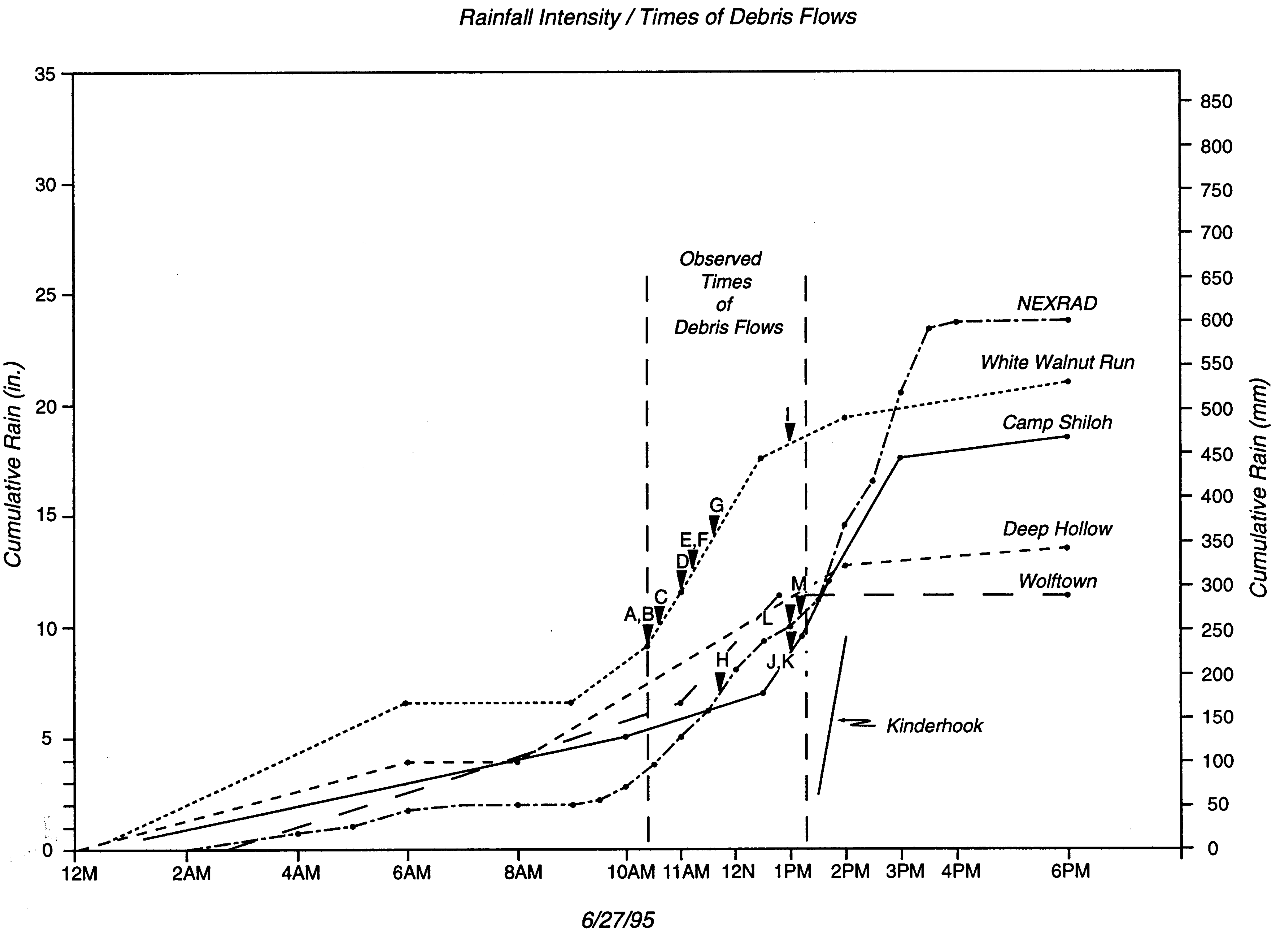


Figure 3. Antecedent rainfall during the five days (6/21–6/26) prior to the June 27, 1995 storm. Locations of rainfall measurement at Sperryville, Ida, and Swift Run Gap are shown on Figure 1; other locations including Big Meadows, Lewis Mountain, and Syria are shown on Figure 2B.

Table 1. *Times and descriptions of debris flows in the Madison County storm of June 27, 1995. Locations identified by letters are shown on Figure 2B and rainfall measurements are plotted on Figure 4.*

Time(s)	Location	Source	Description
10:15 a.m.	A. Sag Top	Khalil Hassan	House struck at 10:15; jumped to ground safely from roof of 2nd floor to avoid flow.
10:00–11:30 a.m.	B. Sag Top	Leighton Brown	Five surges of debris flows travelling at an estimated 20 mi/h.
10:30 a.m.	C. Sag Top	Madison County Eagle (1995)	Struck, crushed, and carried away a house, killing the occupant.
11 a.m.	D. Quaker Hollow	Bob Knightning	Debris flow rumbled by next to house, caused loss of power, and stopped clock.
11:15 a.m.	E. Kinsey Run	Barbara Heyl	Observed debris flow at General Jenkins Farm.
11:00–11:30 a.m.	F. Kinsey Run	G. C. /Rose Dowdy	Lost power at 11:10; heard debris flow pass above roar of rain.
11:30–11:45 a.m.	G. Graves Mill	Randall Lillard	Water with rocks moved house 35–40 ft.
11:30–12 noon	H. Garth Run	James Crossgrove	Flow [in stream] went from 2' deep to a 20' high rolling front in seconds.
1 p.m.	I. Graves Mill	Randall Lillard	Doubled the amount of rock around house but didn't move very much.
1 p.m.	J. Kinderhook	anonymous	Pond filled by a single pulse of a debris flow with logs and mud [with the consistency of] chocolate milk.
1 p.m.	K. Camp Shiloh	Sue Devere	Heard [debris flow] from dining room after lunch.
1 p.m.	L. Allen Mtn	Martin	[Debris flow] rumbled like an earthquake, too loud to talk.
1:15 p.m.	M. Allen Mtn	Martin	[Second debris flow] larger than first [debris flow], 600 ft from house.



Rainfall Intensity / Times of Debris Flows

Figure 4. Cumulative rainfall and observed times of debris flows shown as letters (A–M) with arrows on cumulative rainfall plot for station located closest to observed debris flow. Steepness of cumulative rainfall line indicates intensity of rainfall. The maximum intensity in this storm was measured near Kinderhook by Robert Marshall who measured 178 mm of rain during a 35-minute period between 1 and 2 p.m., equivalent to an intensity of 305 mm/h. Locations of rainfall measurement, including White Walnut Run, Camp Shiloh, Deep Hollow, and Wolftown are shown in Figure 2. NEXRAD rainfall data from Smith and others (1996) for cell with maximum cumulative rainfall. Descriptions of debris flows (A–M) are given in Table 1.

crown of a slide. Initial mobilization was complete, that is, loose material did not remain in the source area. Only rarely did we observe partial mobilization or slide movements that did not produce debris flows. Rapid and complete mobilization of debris flows, as we observed in Madison County, occurs from liquefaction of contractive loose soils (Ellen and Fleming, 1987). Mobilization is complete in contractive soils because the initial strength is greatly reduced with small strain sufficient to collapse the loose structure and liquefy the saturated material; the abundance of water in the pores results in a slurry that rapidly vacates the source area. On hillsides, relatively coarse-grained colluvial soils with low clay content, developed from the granitic rocks, are typical of loose contractive materials. The location of transition from slide to flow was recognized in the field by distinctive features such as an abrupt downslope terminus of slide scar surface, commencement of lateral flow levees, and development of a well-defined channel. Similar features elsewhere illustrating mobilization of debris flows in the source area have been described by Ellen and Fleming (1987).

The sites of initial slope failures occurred preferentially on concave slopes or within "hollows" (Morgan et al., 1997). Field characterization of source areas and analyses of planar curvature using a DEM both determined that about 2/3 of the failures were initiated at concave sites. This finding regarding topographic setting in plan view is similar to many previous studies, e.g. Pierson (1980), Reneau and Dietrich (1987), Ellen (1988), and Sitar and others (1992), that have found debris flows initiating preferentially on concave slopes. The variability of hydrologic convergence of flow lines, soil thickness, infiltration rate and capacity could account for the remainder of failures that initiate on planar and convex slopes near the top of small drainages. In the Santa Cruz Mountains of California, Wieczorek (1987) found that intense rainfall over periods of less than 6 hours triggered debris flows on planar slopes in preference to more concave sites, whereas longer periods of less intense rainfall triggered debris flows more preferentially at concave sites. In light of the above observations in California, the very intense rainfall experienced in Madison County suggests that a combination of geologic and hydrologic

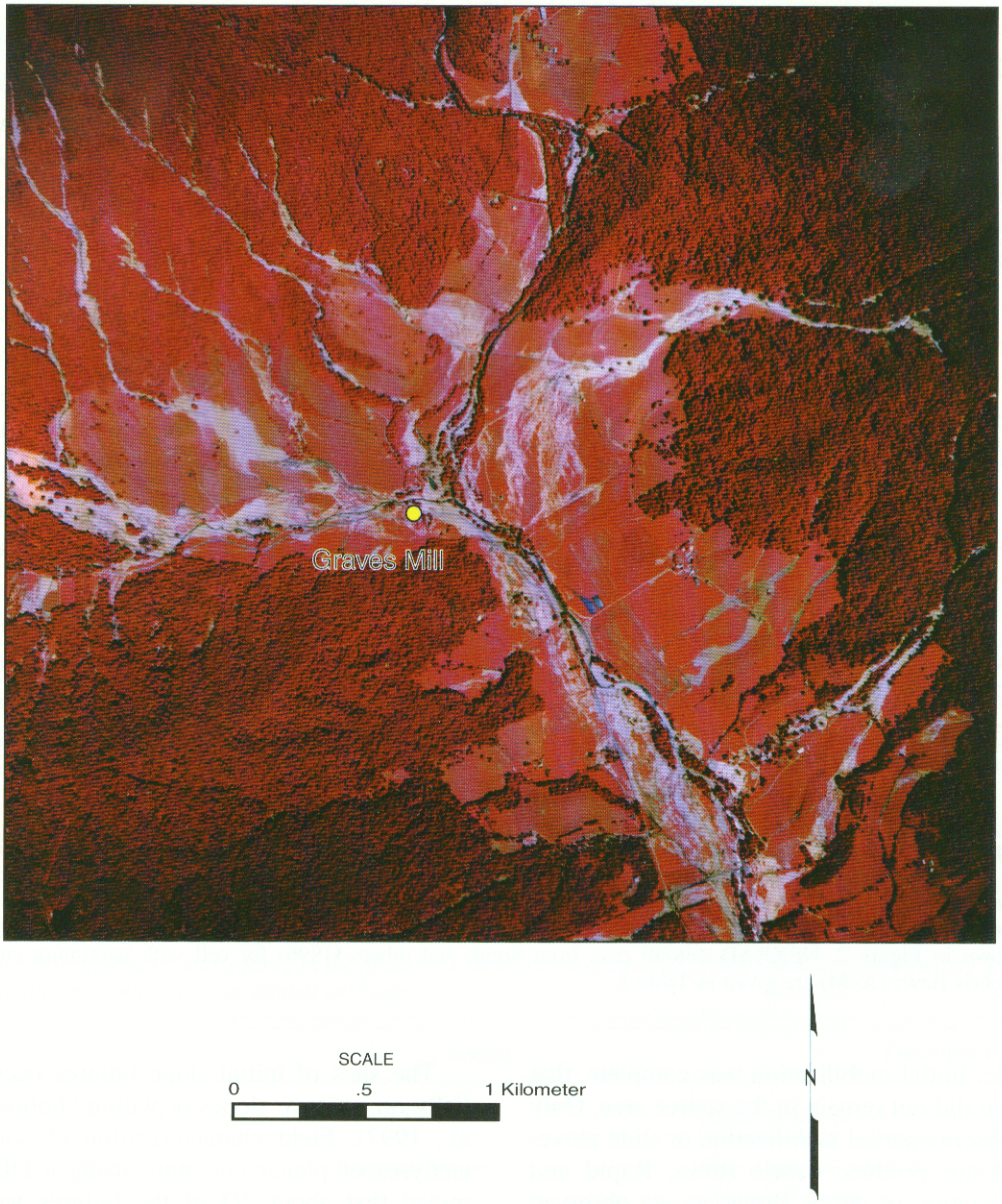


Figure 5. Debris flows, floods, and hazard assessment for a selected area near Graves Mill (yellow dot), junction of Kinsey Run and the Rapidan River. A) False color infrared photo showing debris flow and flood effects (initial landslides, scoured channels and deposition) in bright tones (white) with areas of unaffected forest (dark red) and grassland (pink). Photo taken August, 1995.

factors was responsible for a significant portion (1/3) of source areas on planar and convex hillsides.

Higher proportions of slope failures on concave slopes could be the result of deeper colluvial accumulations than on other slopes, leading to greater instability during intense rainfall. Alternatively, failures on concave slopes could be the result of channeling of rain as surface runoff during the storm with greater efficiency of removal of surficial material, or the result of subsurface concentration of ground water along the axes of hollows and the increase of pore-water pressure leading to reduced strength. We did not find evidence of failures initiated as a result of the removal of surficial debris by surface runoff, but as the result of discrete slides. We measured the volumes of slides and the thickness of material on the crown scarps. The heights of crown scarps ranges from 0.5 to 3.0 m commonly exposing colluvium (Figure 6). The average volume of slides on concave slopes is 620 m^3 and on planar or convex slopes is 150 m^3, indicating a greater efficiency of removal of surficial material on concave slopes.

At the sites of slope failures, we estimated steepness of slopes prior to failure by measuring the steepness of the reconstructed slope using the flanks of the scar. The steepness of source areas ranged between 17 and 41 degrees, with both a median and mean value of 30 degrees

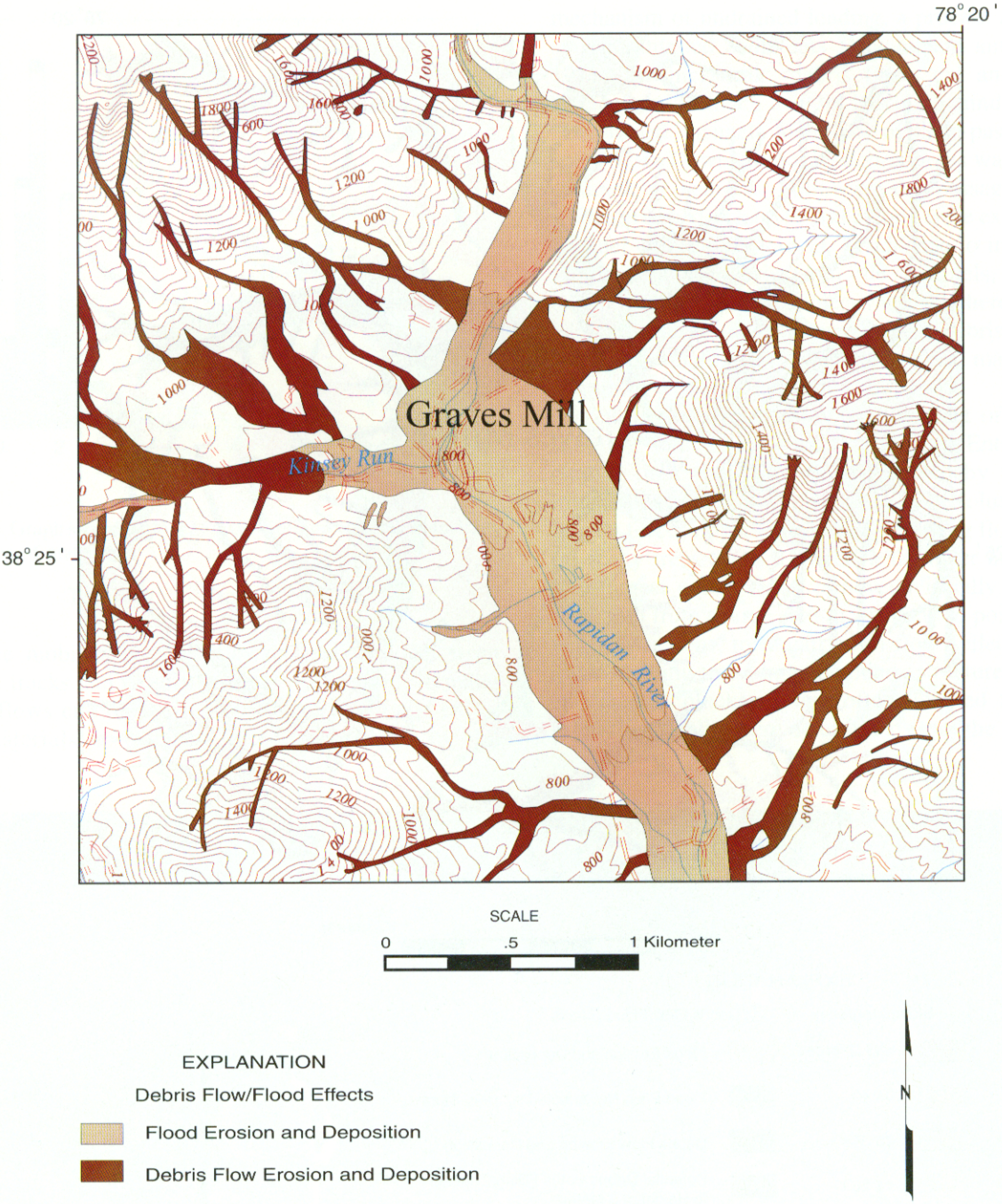


Figure 5. B) Inventory map of debris flows and flood effects (from Morgan et al., 1999a).

(+/– 3.7 degrees). These values are comparable to results from elsewhere (Campbell, 1975; Ellen, 1988). This wide range of slope steepness (17–41 degrees) for sites of failure can probably be attributed to variations in soil strength and pore water pressure during the storm as affected by different soil thickness and permeability at different sites. As slopes became steeper than about 35 degrees, fewer failures occurred perhaps because colluvium became thinner; slopes steeper than 40 degrees usually have outcrops of bedrock.

The slip surface (basal contact between sliding and non-sliding material) of most slides was shallow and planar. The majority (70 percent) of slides initiated in colluvium. Other slides (20 percent) involved a combination of colluvium and weathered rock or saprolite. Partially weathered rock along the base of slides provided

Figure 5. C) Hazard assessment for debris flows and floods (from Morgan et al., 1999b).

a permeability contrast with overlying colluvium and a surface along which sliding was facilitated (Figure 7). A small fraction (10 percent) of slides started entirely in weathered rock. Colluvium exposed in scarps consists predominantly of low plasticity clayey silts or silty sands; grain-size distributions from source areas had a mean clay content of about 16 percent (Figure 8A).

The scars of a few failures revealed a colluvium of semi-horizontal platy rock fragments supported by a fine silty soil. These deposits are probably the result of solifluction processes under periglacial conditions and are termed "stratified slope deposits" (DeWolf, 1988). Periglacial conditions of freeze and thaw during the late Pleistocene periodically mobilized and deposited stratified slope deposits producing a mantle of colluvium on hillslopes in this region. A ^{14}C age from a sample from the basal layer of a stratified slope deposit near Kinsey Run is approximately 25,000 yr BP (Eaton et al., 1997).

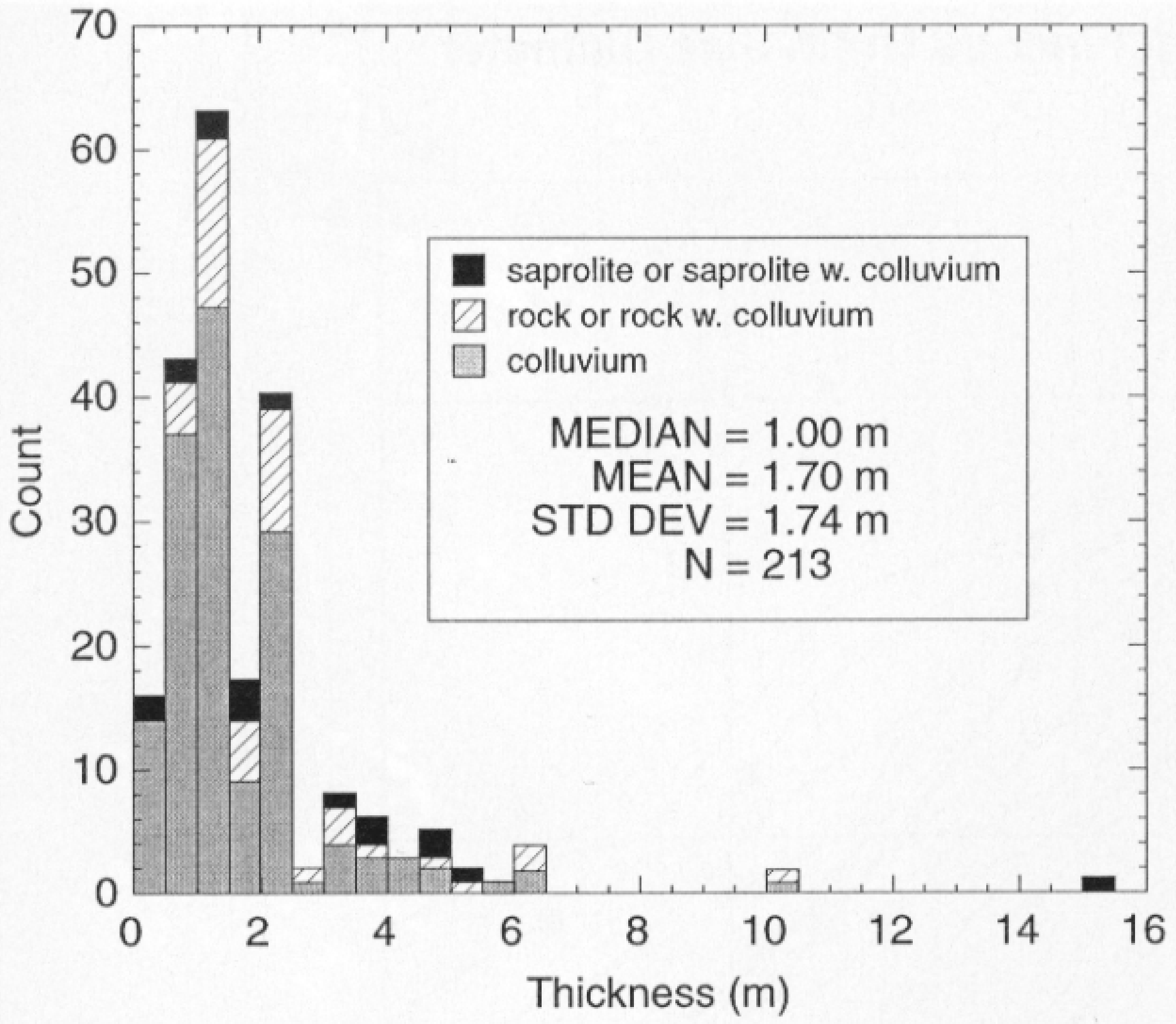


Figure 6. Graph showing thickness distribution of initial landslides and types of material.

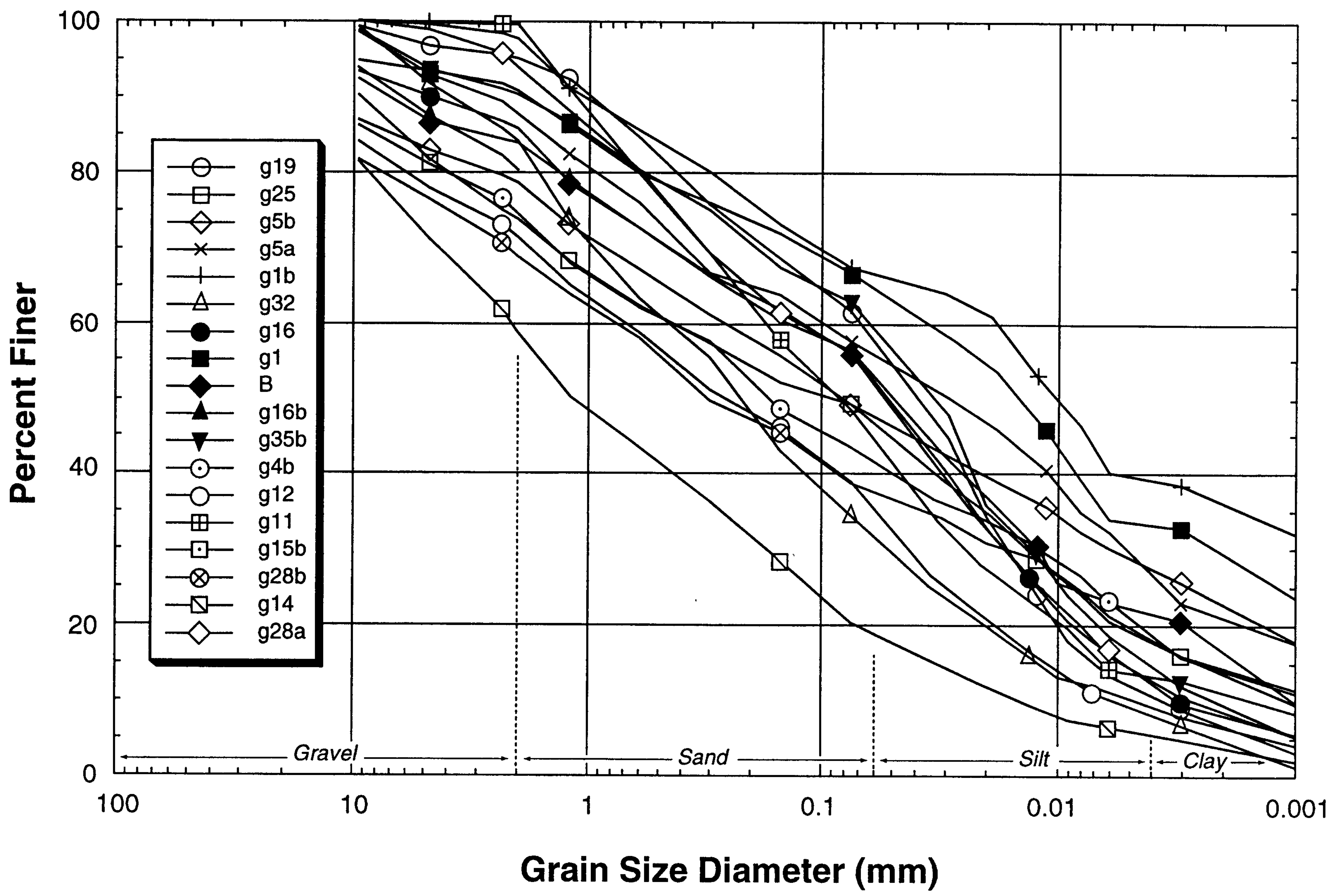
Transport in Steep Channels

Once mobilized, debris flows travelled down steep hillside tracks and rapidly became channelized. In many cases, flows entrained additional channel fill and colluvial materials on adjacent hillsides, perhaps by the mechanism of undrained loading, a process of overpressuring saturated sediments (Hutchinson and Bhandari, 1971). In thick soils, debris flows cut and deepened channels by as much as 9 m, leaving behind steep sided "U"-shaped channels indicative of their passage (Johnson, 1970). Down cutting by debris flows was often constrained by bedrock. Following the passage of flows, stretches of bedrock up to 200 m long were exposed along channel bottoms (Figure 9). In addition to incorporating loose granular debris from the channels, flows also broke off and removed pieces of weathered bedrock. Although the initial volume of many debris flows may have been small, their volumes increased many times by entraining additional channel material.

Debris flows removed a large amount of live timber from the source areas, tracks and fans. Entire trees including their root balls were entrained by flows. Such trees added an unknown, but significant volume to flows. Impact forces imparted by rapidly moving flows snapped off many trees up to a meter in diameter at their base. The largest debris flows removed virtually all trees in their path from source area to termination point. At channel constrictions, trees carried in flows piled up against other standing trees, large boulders, structures or bridges and created blockages that often diverted flow. Maximum flow depths were determined from the elevation of

Figure 7. Shallow planar slide in colluvium over weathered granitic bedrock, scarp about 0.7 m deep and about 9 m wide near Camp Shiloh.

A Debris-Flow Sources Samples Percent Finer vs Grain Size Diameter



B Debris-Flow Deposit Samples Percent Finer vs Grain Size Diameter

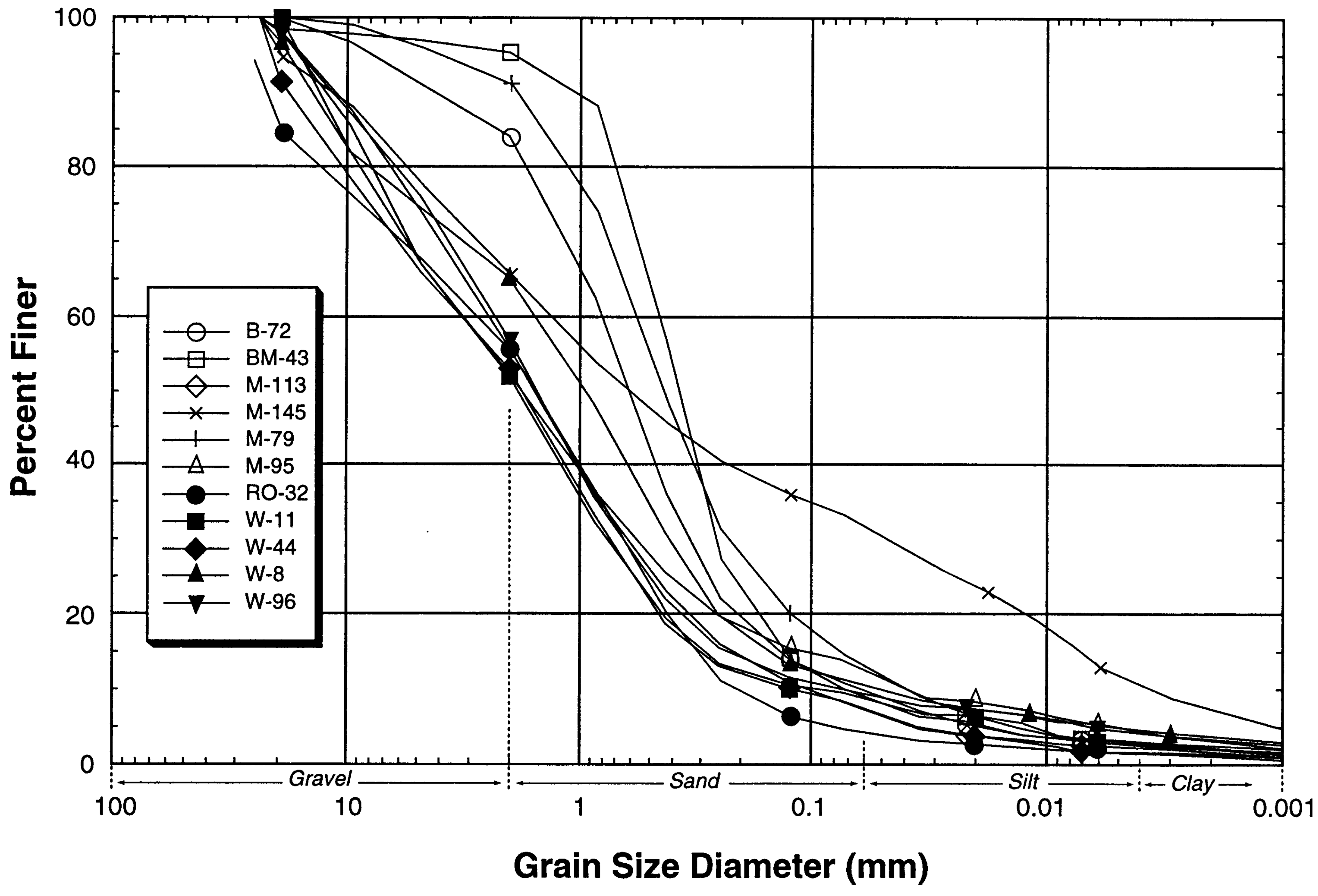


Figure 8. Grain-size distributions for A) samples from scarps of debris flow source areas, and B) samples from matrix of debris flow deposits (not including coarse gravel >20mm; sample numbers from Morgan et al., 1997).

Figure 9. Denuded channel created by rapidly moving debris flow removing colluvium exposing bedrock. Debris-flow trim lines indicate that flow was approximately 3 m high and 12 m wide. Note person along side channel for scale.

deposits, mud lines, and damaged vegetation above the pre-debris-flow channel bed. Trees on the margins of channels commonly were stripped of bark on their upslope sides. Maximum flow depths ranged from 1 to 3 m, but in a few cases depths exceeded 5 m. Bent over and smoothed grasses on steep hillsides indicate that substantial flow of surface water directly entered channels, which probably contributed locally to debris-flow dilution.

Estimated velocities of debris flows in Madison County ranged from about 8 m/s according to eyewitness accounts to as great as 24 m/s from calculations of mean velocity based on superelevation along bends or curves in channels (Johnson, 1984); however, some reservations about the values based on superelevation calculations are given by Iverson and others (1994). Some channels experienced passage of several surges of debris flows, a very likely consequence of multiple slides at different times in the upper parts of drainages. Near Graves Mill, a house was hit and moved by two debris flows about 1.5 hours apart (Figure 10). About fifteen minutes apart an observer east of Graves Mill observed five surges of debris flows in a channel each moving with an estimated velocity of 9 m/s. Table 1 summarizes observations of timing and descriptions of debris flows by eyewitnesses which form the basis for comparison of the timing of debris flows with periods of high rainfall intensity.

We surveyed the channel gradients along debris-flow paths and noted whether debris flows were primarily erosive or depositional. On stream gradients steeper than about 12 degrees erosive processes dominated, whereas deposition was prevalent on gradients less than 10 degrees. This result is similar to observations elsewhere (Campbell, 1975).

Deposition on Fans

A series of prehistoric debris fans are prominent in the Graves Mill area and form coalescing aprons between

Figure 10. Two debris flows separated by 1.5 hours hit and moved the two story farm house (arrow) and destroyed several other farm buildings. Structures were located on a wide fan without a well-entrenched channel.(Photograph copyright by Kevin Lamb, published with permission.)

steeper (>14 degrees) hillslopes and the flood plain of the Rapidan River (Figure 5C). Debris flows from the June 1995 storm crossed these fans eroding them in some areas and depositing material onto the older surfaces in other areas. Extensive scour in several of these fans revealed complex assemblages of prehistoric debris-flow deposits. Carbon-14 ages from these deposits show that debris flows have been periodically active in this area for more than 50,000 yr BP (Eaton and McGeehin, 1997). As the debris flows moved toward the flood plain, the peak flow depth decreased, as indicated by evidence from debris fragments and mudlines left by flow passage across the fans.

Thicknesses of new deposits on fans seldom exceeded 3 m; more commonly, deposits were from 1 to 2 m thick. Many semi-angular to semi-rounded boulders up to 5 m long were transported by flows. The largest boulders were deposited near the heads of the fans where the velocity of the flows decreased. Material ranging from large boulders to small pebbles rested against each other, as well as on other surfaces such as logs, often separated by thin selvages of fine-grained sediments of silty sand. The selvages indicate that the particles were transported as suspended load by the flow rather than being slid or rolled. In most cases (75 percent), the coarsest particles were supported by a finer-grained matrix, rather than by edge to edge contact (Morgan et al., 1997). The samples from Madison County debris flows were poorly sorted, typical of such deposits (Costa, 1984; Johnson, 1984; and Keaton et al., 1988).

Some of the largest boulders on these fans, remnants from older debris flows, did not move in this event. Others, however, were overturned, rolled and moved only short distances. A few boulders that moved could be traced back to their source locations, i.e., holes or pockets where they had been partially buried. The subsurface of boulders which had been partially buried and subsequently exhumed were pitted whereas surfaces previously exposed were stained with oxides and lichen covered.

The finer-grained matrix that supported cobbles and boulders was generally a medium to coarse sand (D50 = 2 mm; Figure 8B). The relatively low percentage of fines (combined fraction of silt and clay) in the matrix ranged from 8 to 14 percent; the clay-sized fraction (percent finer than 0.004 mm) ranged from 2–3 percent. Although similar in their diagnostic characteristics, such as lateral levees and buoyed dense large clasts, Scott and others (1995) distinguished cohesive and noncohesive flows on the basis of clay content of the matrix; specifically noncohesive flows have clay content less than 3–5 percent. Scott and others (1995) also noted that noncohesive flows commonly have a higher rate of attenuation of travel distance than cohesive flows, although the physical reasons are not well understood. Measurements of travel distance of most individual debris flows in Madison County generally were not possible because they either merged with other flows and could not be separately distinguished or because they diluted to hyper-concentrated stream flows (Pierson and Scott, 1985) or floods upon entering higher-order streams and rivers. The paths of most debris flows eventually joined or coalesced and flows travelled about 2 to 3 km from source to terminus; flows that did not coalesce generally travelled no more than about 1 km from source (Figure 5).

Kinsey Run Debris Flow

We illustrate a typical debris flow from the June 27, 1995, storm by describing a series of pulses that flowed down an unnamed drainage and temporarily blocked Kinsey Run about 1 km west of Graves Mill (Figure 11). According to local residents who heard a tremendous noise from this direction, these events took place between 11–11:30 a.m., roughly corresponding in time to the most intense rainfall near Graves Mill during the storm. Two small landslides within colluvium were the dominant sources of material for the two debris-flow pulses; however, as they progressed downslope, they entrained additional channel fill and colluvium from slopes adjacent to the channel amounting to 90 percent of the total volume of deposits. Superposition of deposits indicated that the pulses did not occur simultaneously. The first debris-flow pulse originated from a planar soil slide, 10 m wide by 23 m long by 1 m thick, on a 30-degree slope from an elevation of about 670 m (western landslide source identified in Figure 11). A second (eastern) landslide at an elevation of about 530 m was a slightly larger rotational slide on a 23-degree slope. A third, much smaller, debris-flow pulse probably originated from erosion of debris deposited by the first two pulses. Because it was small, this third remained confined to the channel.

The first debris-flow pulse greatly exceeded the capacity of the narrow (1–2 m) pre-existing channel and with a high velocity exceeding 20 m/s (estimated from super elevation at A and B, Figure 11) in the upper part of the channel cleared a swath from 30 m up to 100-m wide through trees adjacent to the channel. Upon reaching flatter slopes the flow slowed and spread bouldery debris laterally across a wide, debris-flow fan (C, Figure 11). The flow achieved a maximum width of about 200 m on the lower part of the fan. From beginning to end, the first pulse descended about 400 m vertically and travelled about 3 km horizontally. Deposits on the fan included boulders supported by a fine-grained matrix of clay- to sand-sized particles. The maximum thickness of very poorly sorted debris deposits was 1.1 m. The largest boulders, e.g. 7 x 7 x 2 m in size, that were moved may have been rolled, rather than carried in suspension by the flow.

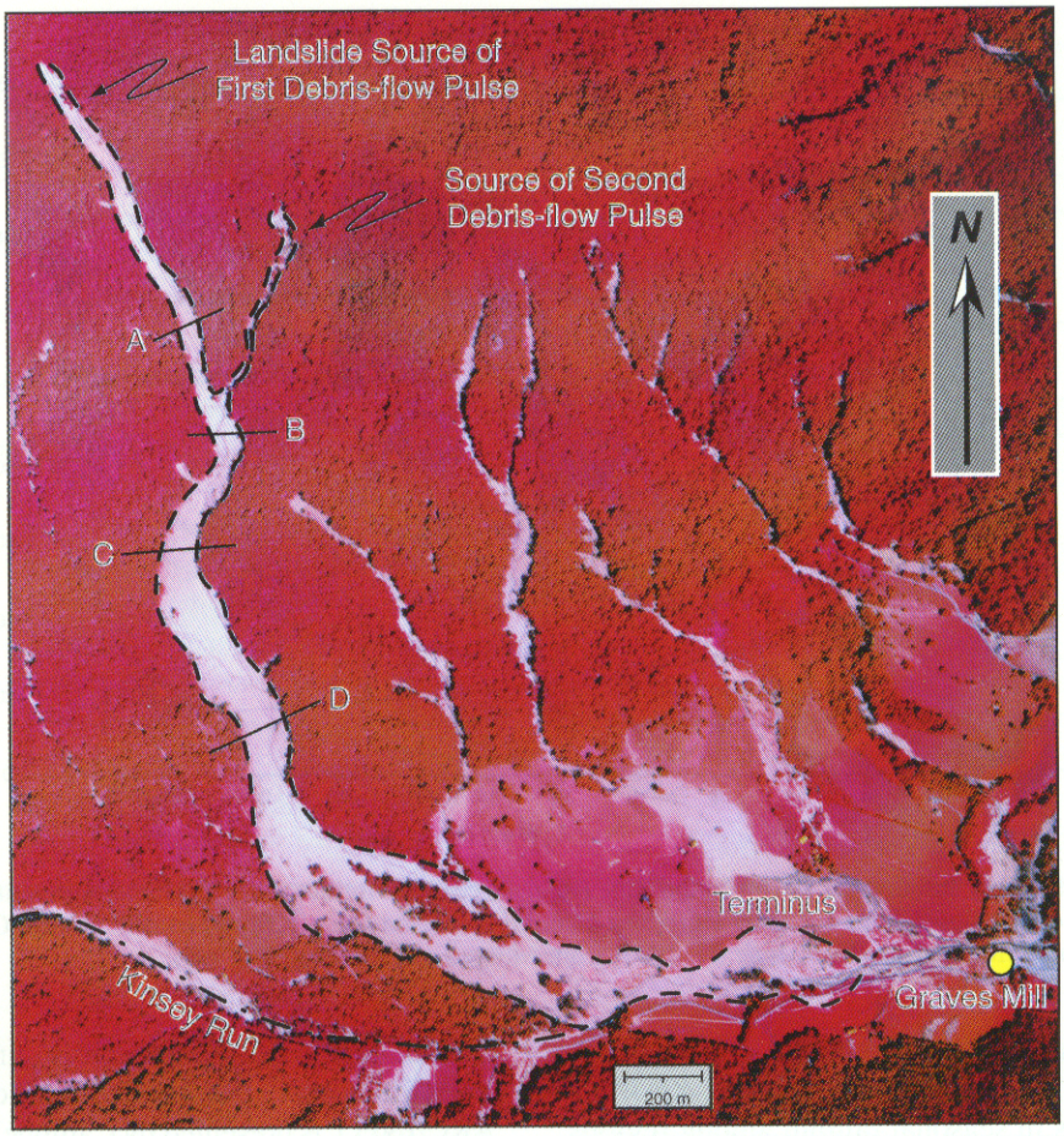


Figure 11. Infrared photograph of debris-flow path and deposit (taken August 22, 1995) near Graves Mill. Velocity estimates at A, B, C, and D were 24, 20 16, and 8 m/s, respectively. Margins of debris-flow path and deposits are shown by dashed line.

Volumetric calculations made using stereo photos to map the deposits and field measurements to determine depth, indicate that the series of debris flows deposited approximately 5.7 x 10^4 m^3 of debris on the fan (Mazza and Wieczorek, 1997). By accounting for the original volume of the two landslide sources, we determined that about 90 percent of the deposit volume originated from material derived from the channel fill and colluvium-covered slopes adjacent to the channel. This large proportion of contributions from channel fill and slopes adjacent to the channel is similar to that reported for debris flows elsewhere (Santi and Mathewson, 1988; Jibson, 1989; and Wieczorek et al., 1989).

RAINFALL THRESHOLDS

We compared rainfall intensity and duration from the Madison County storm with storms elsewhere in the Blue Ridge of central Virginia. Based on locations where debris flows were and were not triggered in areas of similar granitic rocks, we identified a minimum continuous rainfall intensity-duration for storms capable of triggering debris flows (Figure 12). Caine (1980) first introduced this type of intensity-duration plot for identifying a threshold for the triggering of landslides. This threshold indicates that sustained intensities of 70 mm/hr for 2 hours, 50 mm/hr for 4 hours, 40 mm/hr for 6 hours, and 25 mm/hr for 12 hours, are sufficient to trigger debris flows for the Blue Ridge of central Virginia. This range of intensities and durations of rainfall may be met by a variety of storms, including short, but intense convective storms and hurricanes.

Rainfall thresholds for triggering debris flows have been similarly identified in other regions, e.g. Puerto Rico (Jibson, 1989; Larsen and Simon, 1993), Hawaii (Wilson et. al., 1992), and the San Francisco Bay Region (Cannon and Ellen, 1985). However, compared with these other areas, the threshold in this temperate forest of mixed hardwoods of the Blue Ridge of central Virginia is the highest recognized (Figure 13), exceeding those of tropical, humid environments of Puerto Rico and Hawaii. The threshold for the Blue Ridge greatly exceeds that of the San Francisco Bay region (Cannon and Ellen, 1985), an area with a strongly seasonal Mediterranean climate.

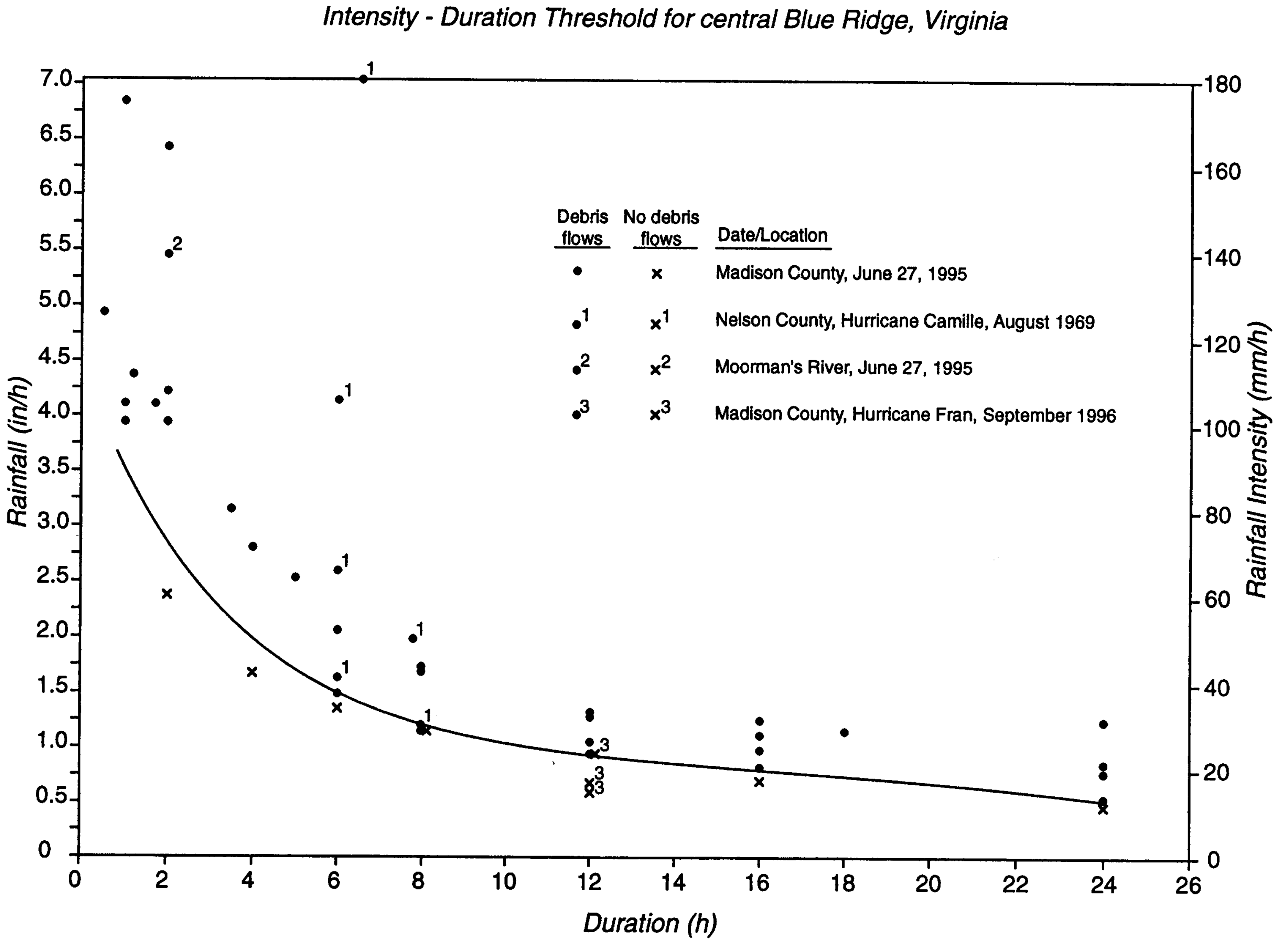


Figure 12. Rainfall intensity and duration for storms in the Blue Ridge of central Virginia and a threshold representing the minimum values necessary for triggering debris flows. Data for 1969 Hurricane Camille in Nelson County from Peatross (1986), Camp and Miller (1970), and Kochel (1987). Data for Moormans River, June 27, 1995, from Morgan and Wieczorek (1996).

All these regions have steep slopes with soils susceptible to debris flows during intense rainfall. Even if we account for variations in seasonal rainfall among regions by normalizing rainfall intensity with respect to seasonal (yearly) rainfall (Figure 13), the threshold for the Blue Ridge still exceeds the others.

Possible reasons for the high threshold in the Blue Ridge may be high permeability of the coarse, granitic soils and the high moisture-storage capacity of the colluvium. Under these conditions, critical pore-water pressures are unlikely to develop except during the most intense storms. Prolonged weathering and denudation that the region has experienced since at least the late Cretaceous Period under climate conditions that ranged from tropical to periglacial has produced soils and shallow bedrock with high permeability and storage capacity.

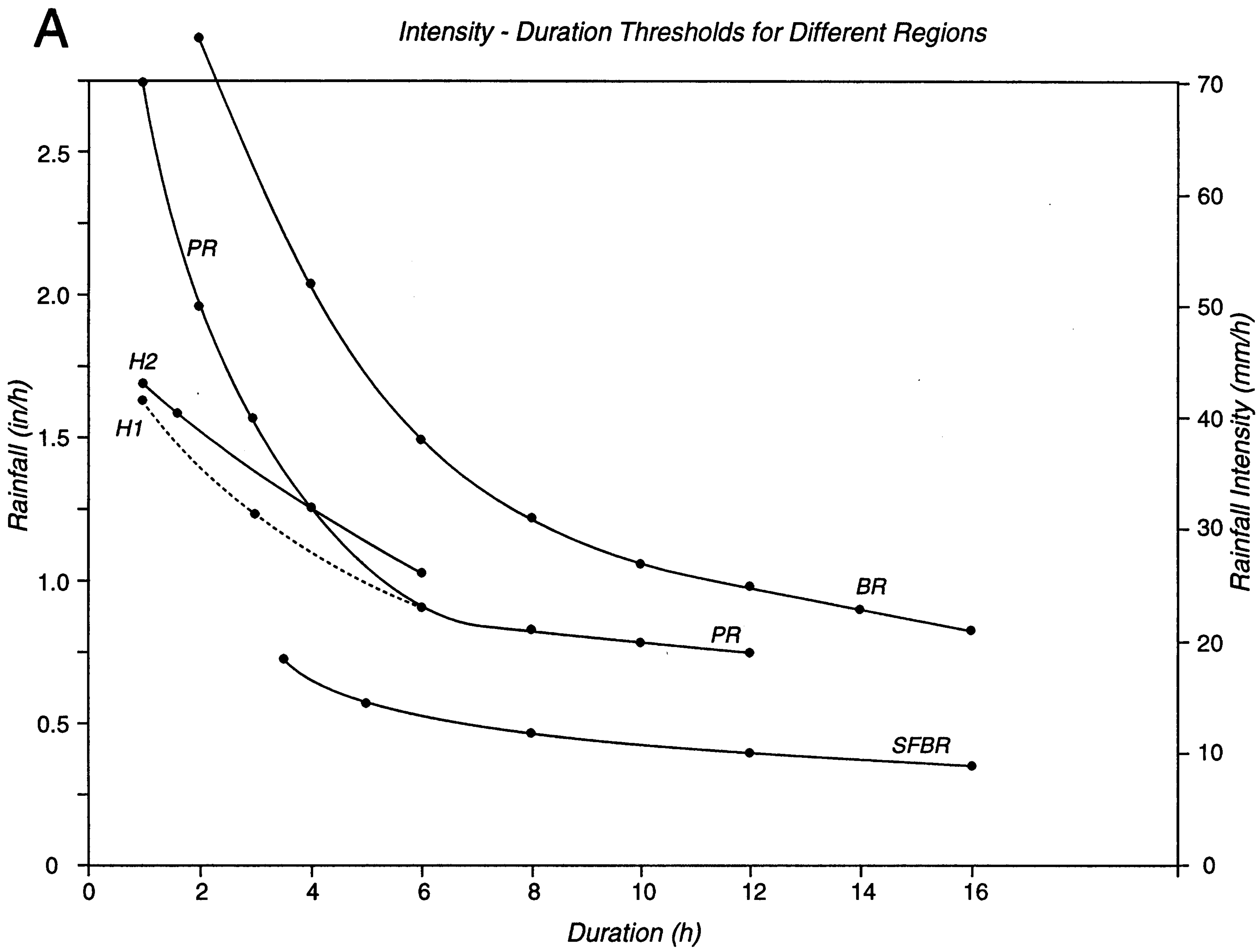
HAZARD ASSESSMENT

We developed a simple method to identify areas in Madison County subject to hazards from debris flows based on field observations of the bedrock and surficial geology, on topography and geomorphology. Factors that influenced initial landslides and consequent debris flows are the amount and intensity of precipitation falling within a given area, the slope steepness, the presence of a stream channel network draining steep slopes, and the hillslope, fan and valley topography. A geographic information system (GIS) was used to delineate areas of debris-flow hazard. The general approach is summarized below; but a detailed description, including a computer program in ARC/INFO, is presented by Campbell and Chirico (1999).

A small part of the Madison County hazards map (Morgan et al, 1999b) for an area near Graves Mill is shown in Figure 5C to illustrate the result of the GIS approach. Hazard identification is based on the following criteria:

1. Areas traversed by debris in June, 1995.
2. Areas flooded in June, 1995.
3. Areas identified by the distribution of alluvial sediments deposited by earlier floods.
4. Areas underlain by older debris-flow deposits.
5. Areas having slopes equal to or greater than 26 degrees.
6. Drainage channels having an origin on slopes equal to or greater than 26 degrees, with a lateral extent defined by a buffer formulated by Campbell and Chirico (1999).

Areas traversed by debris flows and floods in June, 1995 (Figure 5B) are taken from an inventory prepared from aerial photos and field observations (Morgan et al., 1999b). The extent of alluvial sediments defining the existing flood plain, and areas underlain by prehistoric debris-flow deposits were determined by inspection of aerial photos and 1:24,000-scale topographic maps, and by field mapping of deposits. Large areas of prehistoric debris-flow deposits display a characteristic topographic



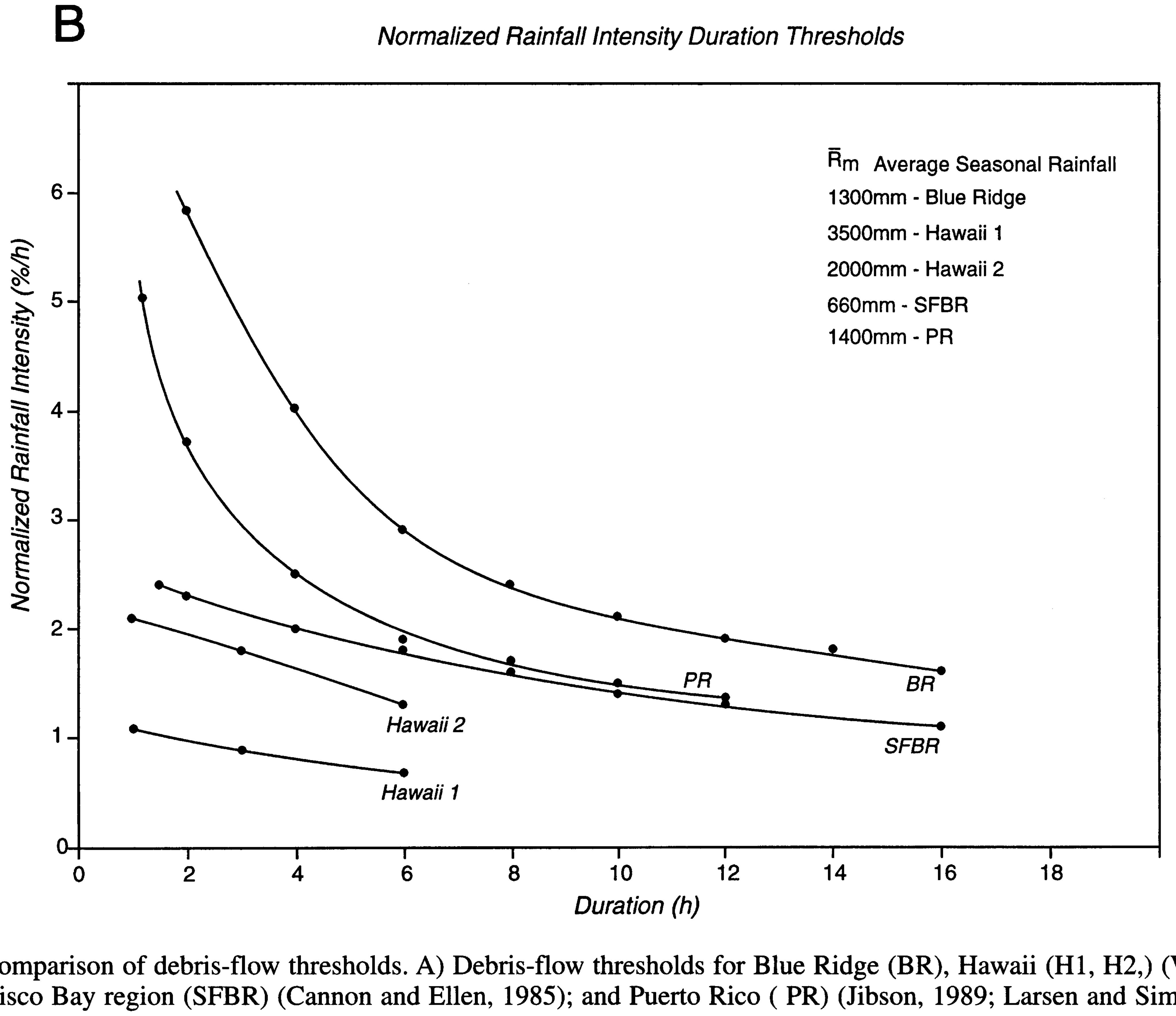


Figure 13. Comparison of debris-flow thresholds. A) Debris-flow thresholds for Blue Ridge (BR), Hawaii (H1, H2,) (Wilson et al., 1992), in San Francisco Bay region (SFBR) (Cannon and Ellen, 1985); and Puerto Rico (PR) (Jibson, 1989; Larsen and Simon, 1993). B) Same data as A but normalized by mean seasonal rainfall.

signature of irregular elevation contours that can be correlated with objects, such as large, oxidized and lichen-covered, semi-angular to semi-rounded, boulders atop or partially buried within a fine-grained soil matrix. These older deposits, having widely varying ages, indicate that flows in this area have a long recurrence interval. Existing channels do not accurately portray travel paths of potential flows. On gentle slopes with irregular topography, debris flows can fill and block channels, and randomly divert flows into other areas.

Slope, aspect, and elevation were derived for 10-m grid cells from a digital terrain model created from USGS digital line graph (DLG) data. Slope angles of slope segments 10 m in length or shorter cannot be resolved by these terrain data. Moreover, slope angles derived from these data are less accurate where slopes are generally low (particularly for slopes less than about 10 degrees). For ease of map display (Figure 5C), cells of similar slope have been grouped together in five intervals (less than 14 degrees, 14–26 degrees, 26–34 degrees, 34–45 degrees, and greater than 45 degrees) depicted by different colors. These slope intervals and their relations to debris flows in other regions have been described and discussed by Campbell and others (1989).

Several site specific factors, including slope curvature in plan and profile, drainage area, soil thickness, permeability, and strength, influence landslide initiation (Wieczorek et al., 1997). For simplicity, we selected potential source areas of debris-flow initiation based solely on slope steepness. Hillsides having slopes between 26–34 degrees identify approximately (within one standard deviation) areas most susceptible to landslides in Madison County (Morgan et al., 1997). Although many steeper slopes are likely to contain relatively stable bedrock outcrops, we conservatively categorize all slopes of equal or greater than 26 degrees as capable of initiating debris flows. The color codes (Figure 5C) showing these steep slopes identify areas with a high susceptibility of failing under storm conditions similar to that of June 27, 1995.

Potential debris-flow paths were derived using ARC/INFO Grid functions designed for hydrologic modeling (Campbell and Chirico, 1999). The elevation grid provided the principal basis for deriving grids representing flow direction, flow accumulation, stream lines and stream order, which were utilized to delineate the areas of debris-flow hazard. Stream channels draining slopes of 26 degrees and steeper constitute the principal source areas for debris flows and therefore provide a guide for predicting locations of future debris flows. Stream lines are defined by making the flow-accumulation grid display only those cells that receive flow from a number of cells greater than a selected threshold. We first tried a 100-cell threshold and, when superimposed on the topographic map, it failed to capture many of the short, steep drainages where debris flows had originated. Next, we tried a 50-cell threshold, which successfully captured all of the short, steep drainages where debris flows originated. Potential pathways (Figure 5C) show results of modeling the lateral extent that would be occupied if a debris-flow front three meters high moved through existing drainage channels. We modeled debris flows based on a 3-m flow depth, which represents an average of flow depths observed in the field (see Morgan et al., 1997).

In the algorithm (Campbell and Chirico, 1999) debris flows that emerge from steep channels spread laterally onto fans, maintaining a constant flow height (3 m) along the centerline of flow. However, in the field we generally observed that as flows travelled down a fan, their deposit thickness gradually decreased with distance; the mean (and median) slope where deposits terminated was about 6 degrees. In the algorithm, we chose the simple approach of continuing the path to the terminus of the debris-flow fan or its intersection with flood waters because of the difficulty of accurately determining such low slopes from a DEM and of modeling debris-flow thickness. These assumptions, which simplified the algorithm, resulted in a conservative hazard map; that is, the area shown as vulnerable to inundation by debris flows is larger than would be expected if the algorithm included a provision for thinning across the fans. Another approach for debris-flow routing by Ellen and others (1993) assumes an initial flow volume and models increase and decrease in volume during travel as a function of channel steepness based on empirical measurements of erosion and deposition. Other approaches that predict debris-flow travel distance and depositional area have been suggested by Nakagawa and Takahashi (1997), Iverson and others (1998), and Hirano and others (1997).

The resulting hazard map prepared at 1:24,000-scale is not sufficiently detailed for specific evaluations of individual building sites. The map should serve, however, to identify larger areas, such as tracts, or subdivisions, where county officials may wish to adopt and implement grading code measures, such as those outlined in Scullin (1983) or in the Uniform Building Code (International Conference of Building Officials, 1997). Areas identified as hazardous could also alert county officials to sites that might require site specific studies by engineering geologists prior to granting building permits. The map could also alert emergency response officials to areas likely to have the greatest need for services when National Weather Service (NWS) forecasts warn that extreme rainfalls are imminent.

Rainfall intensity-duration threshold curves in conjunction with a real-time network of rainfall monitoring can serve as a basis for a regional landslide warning system in the Blue Ridge, as in the San Francisco Bay region (Keefer et al., 1987) or in Hong Kong (Hansen et al., 1995). In conjunction with maps indicating where debris-flow hazards are likely in the Blue Ridge, emergency warning response measures can be considered if forecasts of heavy rainfall likely to exceed intensity-duration thresholds can be made with sufficient advance notice.

APPLICABILITY TO OTHER PARTS OF THE BLUE RIDGE

The methods used to make the Madison County hazard map are probably valid for parts of the Blue Ridge, and possibly for other parts of the central and southern Appalachian Mountains from Pennsylvania to Alabama, where digital line graph data are available. The occurrence of many debris flows concentrated in a small area is not uncommon, as demonstrated by similar events in 1949 in the Little River Basin of northwestern Virginia (Hack and Goodlett, 1960; Williams and Guy, 1973), in 1969 in Nelson County, Virginia (Kochel, 1987; Gryta and Bartholomew, 1989), and in 1985 in the Potomac and Cheat River basins in West Virginia and Virginia (Jacobson, 1993). Evidence of prehistoric debris fans below steep terrain in the Blue Ridge and adjacent Appalachian region indicates that debris flows have been widespread and active since the Late Pleistocene.

Recurrence times of debris flows in any small local area (~100 km^2) of the Blue Ridge, such as the affected area in Madison County, may approach two thousand years (Eaton and McGeehin, 1997). If the triggering storms are spatially random, then the recurrence interval for debris flows grows shorter as the area of consideration increases; catastrophic storms are likely to occur more frequently somewhere within a progressively larger area. The Virginia State government and its Office of Emergency Services are responsible for areas of elevated and steep terrain that may be affected by debris flows every ten to twenty years; at least four events in Virginia have occurred during the last 50 years. The Federal Emergency Management Agency is responsible for an even larger area. The central and southern Appalachian Mountains may experience debris flows every three to five years (Clark, 1987).

Over a broad area such as the central and southern Appalachian Mountains (some 416,000 km^2) the following general principles should be applicable in considering the potential for debris flows:

1. Debris flows are triggered by rainstorms having a continuous high intensity lasting for at least several hours. In the Appalachians, such storms are most likely to be generated in the Atlantic or Gulf of Mexico. The Appalachians act as an orographic barrier to weather systems forcing storms to concentrate their energy and lose their moist air close to the land's surface.
2. Storms must sweep over areas with steep slopes. In Madison County, slopes that failed averaged 30 degrees. These observations probably apply to the wider area of the central Blue Ridge and southern Appalachians, but field examination should be completed to confirm this.
3. Debris flows may be triggered in many different geologic and topographic settings. Depositional fans with evidence of previous debris-flow history can often be identified by reconnaissance methods and provide important indications of areas where future debris flows are likely.

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