A Brief History of Debris Flow Occurrence in the French Broad River Watershed, Western North Carolina

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The Appalachian mountains of North Carolina have a long history of producing destructive debris flows. Steep slopes, a thin soil mantle, and extreme precipitation events all exacerbate the probability of slope instability in the region. For this study, modern accounts of debris flows have been reviewed to construct a history and estimate the frequency of debris flows in the French Broad watershed. Major debris flow forming events occurred in 1876, 1901, 1916, 1940, 1977, and 2004. In western North Carolina, debris flows are activated primarily by either a series of two storms or hurricanes tracking through the area within a 6-20 day period or a prolonged moderate rainfall event lasting several days. In general, precipitation greater than 125 mm (~5 inches) in a 24-hour period can generate debris flows. Although the recurrence interval of individual debris flows may be on the order of thousands of years, when assessed at the level of the French Broad watershed, the average frequency of mass wasting from 1876-2004 is 16 years. Individuals living in the mountainous regions of western North Carolina must be vigilant in monitoring weather conditions and steep hillslopes, especially during intense rainfall events.

Introduction

The Appalachian Mountains have a long history of producing destructive debris flows. Throughout the Pleistocene, temperature and moisture fluctuations associated with the transition from glacial to interglacial ages, destabilized exposed soil and rock. These prehistoric debris flows helped to form prominent modern landforms and a rolling topography (Jacobson et al. 1989b). Written records of flooding in western North Carolina exist back into the 1700s but no descriptive information about debris flows exists before the mid-1800s. Since the early 1900s, several well documented intense storms and hurricanes have tracked through western North Carolina, initiating over 1000 debris flows and causing severe flooding (North Carolina Geological Survey 2006). In the Appalachian Mountains, it has been estimated that several thousand debris flows may have occurred in the 20th Century, killing at least 200 people and destroying thousands of acres of farm and forested land (Scott 1972, Bogucki 1976, Clark 1987, Gryta and Bartholomew 1987, Jacobson et al. 1989a, Wieczorek et al. 2004).

For this investigation, information from historical documents, scientific literature, and first-hand accounts from newspapers have been collected to synthesize a history and estimate the frequency of known debris flow occurrences in the French Broad Watershed. Continued study of the history of debris flows will help identify triggering mechanisms that are particular to western North Carolina and areas that are susceptible to slope movements.

Debris Flows

Of the several types of slope movements that occur in the Appalachians, rapid mass movement, particularly debris flows, are considered the most dangerous and will be the focus of this paper. In the Appalachian Mountains, steep slopes, a thin soil mantle, and extreme precipitation events all increase the risk of slope instability, slope movement and failure (Gryta and Bartholomew 1983, Neary and Swift 1987, Wieczorek 1996).

The term "debris flow" is used herein to describe swift-moving mass-wasting events that occur predominantly in shallow, silty-to-gravelly soil on steep slopes (greater than 30 degrees) during periods of exceptionally heavy precipitation (Cruden and Varnes 1996). Debris flows often begin in concavities or mountain hollows that concentrate subsurface flow and move downslope following preexisting drainage channels (Figure 1). Debris flows can travel for several kilometers before releasing their suspended load and coming to rest upon reaching an area of low gradient (Ritter et al. 2002).

In western North Carolina, debris flows are activated primarily by either localized severe storms that produce intense rainfall for several hours or by more regional moderate storms that may last for several days (Wieczorek 1996). Most debris-flow-producing storms can be linked to the incursion of warm, tropical air masses over the mountains between May and November (Kochel 1990).

The heavily forested slopes of the Appalachians are generally stable under normal rainfall conditions (Kochel 1990). Therefore certain thresholds of rainfall intensity and duration must be reached before slope movements will occur (Figure 2). Precipitation rates that readily induce debris flows in western North Carolina range from 125 mm/day (Neary and Swift 1987) to the upper end of observed precipitation (560 mm/day). Under these conditions, rapid infiltration and a corresponding increase in soil saturation brings the soil mantle to field capacity. This tends to occur in shallow (<1 m thick) mountain soils on slopes averaging 25-40 degrees, overlying an impermeable horizon of bedrock or saprolite (Eschner and Patric 1982). A temporary rise in piezometric pressure within slope sediment causes an increase in shear stress while decreasing shear strength. This, combined with a decrease in soil and root cohesion, reduces the shear strength enough to lessen the stability of the soil and eventually induce failure (Neary and Swift 1987). In North Carolina, the most common movement interface is between the bedrock-soil contact (Clark 1987) but slippage often occurs parallel to the dipslope or along preexisting areas of weakness such as a fracture zone.

Road construction is also a major contributor to slope failure and their mitigation can often incur enormous public cost. Excavation of the toe of a hillslope by emplacing a road, quarry, canal, or other type of cut, removes support and may induce an-

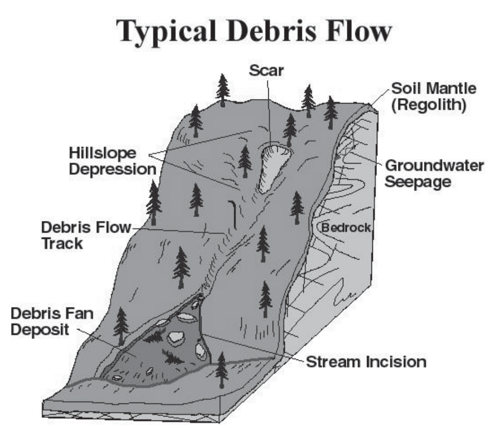

Figure 1: The morphology of a typical debris flow found in the Southern Appalachians (after Gryta and Bartholomew, 1983).

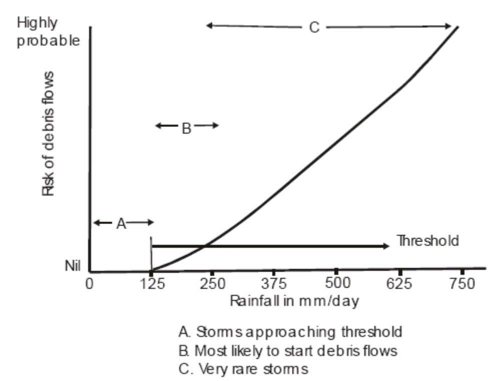

Figure 2: Threshold precipitation values necessary for producing debris flows in the southern Appalachian Mountains. Storms likely to start debris flows occur above the 125 mm/d threshold. Storms with precipitation values higher than 250mm/d are deemed "rare" but do occur in North Carolina (after Eschner and Patric, 1982).

thropogenic slope moment (Cruden and Varnes 1996). Road fill and traffic also increases weight on a hillslope, increasing shear stress on materials. In developed areas, slope saturation may occur, even during moderate recharge events, because of concentrated run-off from rerouting of drainage systems during road construction and from man-made structures such as drainpipes, buildings, and paved impervious surfaces.

The major hazard to human life and property from debris flows is from burial or impact by boulders and other debris. Debris flows can accelerate to speeds between 15-55 kph and often strike without warning (Highland et al. 2004). Because of their relatively high density and viscosity, debris flows can move and even carry away vehicles, bridges and other large objects (Cruden and Varnes 1996). They have been known to remove a home from its foundation and obliterate it completely.

Study Area

This study focuses primarily on the area of the French Broad River watershed within western North Carolina: an area comprising over 7,000 km^2 (Figure 3). The French Broad River itself flows through the City of Asheville, a major commercial and manufacturing center, and a popular mountain resort and tourist destination. According to data collected by the U.S. Census Bureau (2000), approximately 426,000 people live within the French Broad watershed and this population is predicted to increase, particularly in and around the City of Asheville. Two major interstates, Interstate 40 and Interstate 26, cross the basin, as does the Blue Ridge Parkway. Debris flows hazards are a major concern in mountainous areas; debris fans are favored areas of development due to their flat building surface and location above the floodplain (Ritter et al. 2002, Bechtel 2005). With continued development and tourism in the forested areas of the Blue Ridge, the risk to people and property will increase because of debris flows, especially during periods of high precipitation.

Geology and Soils

Given the large size of the French Broad River basin, 40 geologic units and 17 general soil types have been mapped within the watershed by North Carolina agencies. The watershed lies within both the Blue Ridge Belt and, to the east, a small portion of the Inner Piedmont Belt. Bedrock consists of sedimentary, metasedimentary, and intrusive igneous rock of Proterozoic and Paleozoic age (North Carolina Geological Survey 1985). Strike is generally towards the northeast with a dip to the southeast.

Geologic structure and bedrock orientation play a more important role in slope stability than rock type in the Southern Appalachians (Scott 1972). When soils are formed on weathered bedrock surfaces that are nearly coincident with the dip surface, sliding is more likely to occur between the soil-rock interface. Control on groundwater flow by joints and other fractures also can create areas of slope instability. This is particularly true when fracture surfaces are parallel to the dip surface. It was observed in the study area that even during a light precipitation event, groundwater flow through fracture zones was swift. This concentration of groundwater could quickly cause an increase in pore-water pressure in soils on a slope or create ephemeral channels for debris flows to follow. A similar correlation between joint orientation, direction of groundwater flow, and debris-flow initiation was noted in the Coweeta Basin, an experimental forest and research station just south of the watershed (Grant 1988).

The types of soil in the French Broad watershed reflect the regional geology because variation in bedrock mineralogy partly controls soil mineralogy. Steep relief, broad ridges, and humid temperatures allow for a wide range of soil-forming conditions. Soil cover varies in thickness and development depending upon slope and weathering and can range from less than one meter to several meters in depth (Clark 1987). On steep side-slopes, Inceptisols are common whereas Ultisols are found on gently sloping areas (Graham and Buol 1990). Soil textures range from fine clay and silt to sandy- and gravelly-loam (U.S. Department of Agriculture

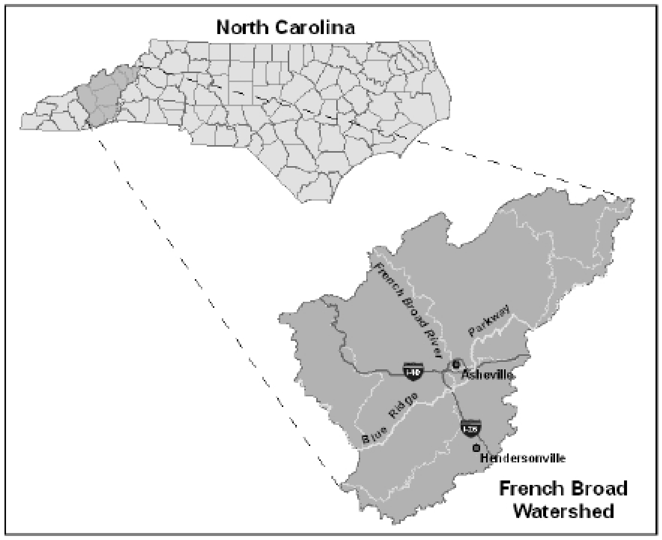

Figure 3: Location map of the French Broad watershed in North Carolina. The watershed includes portions of 8 counties and has an area greater than 7000 km^2.

1998). Generally, soils with a high susceptibility of failure tend to have a large mica content and develop over micaceous schist, slate, and phyllite (Scott 1972).

Climate

Due to the variation of altitude (460-2073 m) within the French Broad watershed, temperature and moisture regimes vary greatly from one place to another. In fact, the mountains have some of the wettest and driest weather in North Carolina (Daniels et al. 1999). The greatest 24-hour rainfall total in the State (565 mm) was measured in the watershed at Altapass in Mitchell County on July 15-16, 1916 when a hurricane passed through the area. In contrast, the station with the driest weather on average is located in downtown Asheville in Buncombe County (State Climate Office of North Carolina 2003).

Mean annual rainfall in the southern Appalachians ranges from 1000 to 2700 mm with snowfall only contributing 5 percent of the total precipitation (Neary and Swift 1987). Rainfall occurs frequently as small, low-intensity rains in all seasons but precipitation is usually greater during the winter and spring, with March being the wettest average month. The highest maximum precipitation amounts have been recorded in the summer months when localized, high-intensity thunderstorms and hurricanes are more common. As a result, a majority of debris-forming rainfall events in the Blue Ridge occur in June, July, and August (Clark 1987). No debris flows have been reported in the months of December, January or February.

Orographic influences generate extremely heavy rainfall in localized mountainous areas, even in storms with weak pressure gradients and gentle air circulation (Scott 1972). Generally, rainfall increases with elevation at a rate of 5 percent per 100 m but altitude is not as important as orographic boundaries (Swift et al. 1988). The Blue Ridge produces an elongate area of high values of mean precipitation (Jacobson et al. 1989b).

Vegetation

Like rainfall, vegetation within the watershed varies with the topography. Slope aspect and shading by adjacent higher mountains also influences the distribution of major tree species (Daniels et al. 1999). At lower elevations (below 1400 m) hardwoods, oak, hemlock and pine forests dominate. Hardwoods such as yellow poplar, ash, and black cherry are found in coves and along steep slopes whereas several varieties of pine and oak thrive in open areas (Scott 1972). Except for the most rugged terrain, the region's forestland has been cut or burned at least once since European settlement (Clark 1987).

In the very high mountainous areas of the watershed (above 1400 m) distinctive ecological systems have been established as a result of the cool year-round temperatures. Areas are often windswept and trees are damaged by ice and winter wind. Red spruce, mountain ash and Fraser fir are common with the latter dominating above 1890 m (Daniels et al. 1999). Grass balds and areas dominated by low shrub like rhododendron and laurel are common on southern-facing exposures (Daniels et al. 1999). These plants create extensive root systems or mats that increase soil and root cohesion, imparting stabilizing influences to the underlying soil.

Quaternary Debris Flows

Quaternary geomorphic features in the Appalachian Mountains are primary the result of Cenozoic uplift and subsequent post-orogenic denudation controlled by climatic variations (Soller and Mills 1991). Much of the terrain is mantled with a thin layer of discontinuous surficial deposits and individual ancient mass movements have recently been identified, dated and studied in the Blue Ridge Province. Studies of these deposits have quantified the rate of soil development and erosion, catastrophic debris-flow frequency and triggering events, and the possible role of periglacial processes in the Appalachians during the late Pleistocene and early Holocene (Table 1).

Pre-historic debris-flow deposits form undulating, hummocky topography and elongated lobes or fans that are expressed as step-like landforms. Debris fans tend to be coarse-grained and poorly sorted, but may be either matrix-or-clast-supported. Typically, fans are composites of several mass-wasting events with a weathered surface on each colluvial unit in the sequence. This indicates that there may be great differences in age between the units and upwards of several thousand years may have elapsed between debris-flow-forming events (Kochel 1990). In the Great Smoky Mountains, characteristic recurrence intervals for debris flows on specific fans are on the order of 400 to 1600 years (Kochel 1990) whereas catastrophic debris flows have been estimated to occur every 3000-6000 years in Nelson County, Virginia (Kochel 1984, Kochel and Johnson 1984). Based on radiocarbon dating, Eaton et al. (2003b) approximate a recurrence interval of debris-flow activity of roughly 2500 years in Madison County, VA.

Numerous studies (Table 1) hypothesize that major Quaternary climate change and periglacial environmental conditions have encouraged the formation of a number of debris flows in the southern Blue Ridge during the Pleistocene. In the last 850 kyr, there have been at least ten major ice advances that have glaciated much of the northern Appalachians and brought periglacial conditions to the southern Appalachians (Braun 1989). It has been suggested that periglacial conditions may have extended as far south as the mountains of Georgia during glacial maxima (Jackson 1997).

During glacial periods, western North Carolina experienced a greater frequency of freeze-thaw cycles and physical weathering. Rock exposed at high elevations decomposed to a thin loose soil mantle (Mills 2000). At the same time, atmospheric circulation would have been unfavorable for the movement of significant tropical air masses into the region (Kochel 1990). In modern polar climates, monthly temperatures average below 10°C year-round, resulting in little to no tree growth providing little inherent root cohesion (Lydolph 1985). These three conditions set the stage for later slope instability during warmer interglacial intervals.

Although a polar climate can create a ready supply of sediment through erosion and physical weathering, the lack of localized high-intensity precipitation inhibits the formation of debris flows. In contrast, slow mass movements, such as solifluction and creep, are common (Ritter et al. 2002). In Virginia, slope wash of material may have proliferated more than debris flows during the Pleistocene (Eaton et al. 1997).

Table 1: Prehistoric debris flow studies in the southern Blue Ridge and the age-dating techniques utilized.

Reference	Year	Dating Technique	Location	Age of Features
Kochel	1987	Radiocarbon	Davis Creek, VA	> 11,000 BP
Jacobson et al.	1989b	Radiocarbon	West Virginia	10,000 - 12,000 BP; 315 BP
Behling et al.	1993	Radiocarbon	West Virginia	17,000 - 22,000 BP
Kochel	1990	Radiocarbon	Appalachian Mountains, NC	16,000 - 25,000 BP
Eaton et al.	1997	Radiocarbon	Upper Rapidan River Basin, VA	2,200 - 50,800 BP
Eaton et al.	2003a	Radiocarbon	Madison Co., VA	15,000 - 27,410 BP
Shafer	1988	Thermoluminescence	Flat Laurel Gap, NC	Late Quaternary
Mills	1982	Relative-age	North Carolina	?
Mills and Allison	1995a	Relative-age /paleomagnetism	Watauga County, NC	780 ka - 1Ma
Mills and Allison	1995b	Relative-age	Haywood County, NC	?
Liebens and Schaetzl	1997	Relative-age	Macon and Swain Co., NC	?
Mills	2000	Relative-age	Appalachians	?

After the late Wisconsin glacial maximum, near the end of the Pleistocene, the northward migration of the polar front would have allowed tropical moisture to reenter the Central and Southern Appalachians during the summer months (Kochel 1987). Previously undisturbed weathered and frost shattered soil and rock then became exposed to heavy precipitation. Slopes that were still sparsely vegetated (due to cold winter temperatures) became saturated and unstable, creating numerous large debris flows. Repeated intervals of glacial and interglacial climate on a periglacial landscape probably created episodic sequences of catastrophic mass wasting during the Pleistocene and early Holocene (Kochel 1990). Several large prehistoric debris flows have been identified in the southern Blue Ridge and the region of the Great Smoky Mountains (Hatcher et al. 1996). These debris flows originated at high elevations (>1100 m), produced large volumes of colluvium (>106 m^3) and may have transported material as far as 8 km in a single event (Hatcher et al. 1996). Hillslopes remained generally unstable during the late Wisconsin glaciation, but transitioned to a period of less-frequent landsliding during the Holocene (Jacobson et al. 1989b).

Modern Flooding and Debris Flows

The first recorded instance of a major flood in the French Broad watershed occurred in April 1791, six years before the city of Asheville was incorporated with its present name (Tennessee Valley Authority 1960). While precipitation records do not exist for this event, anecdotal accounts describe the water level as having been as high or a few meters higher than the well documented flood of 1916 (Tennessee Valley Authority, 1960). Since that time, the French Broad watershed has been plagued by repeated sequences of flooding and slope instability.

June, 1876

The first detailed historical reference of debris flows affecting the North Carolina Blue Ridge occurred on June 15, 1876. At least 40-60 slope movements were reported in a 1554 km2 area of Macon and Jackson counties (Clingman 1877). These debris flows accompanied flooding that is often called the "June Freshet," one of the greatest floods in the upper reaches of the French Broad watershed (Tennessee Valley Authority 1960). Rainfall data is extremely sparse as only two known stations were reporting in the vicinity of the debris flows in 1876 (Franklin, NC and Lenoir, NC). The station at Franklin, only about 8 miles from where the debris flows occurred, reported 165 mm of rainfall on June 15 (NC Agricultural Experiment Station 1892). Anecdotal reports indicate that rainfall was not exceedingly heavy, but had been falling steadily throughout the day (Clingman 1877).

At the time, a debris flow was generally attributed to a "waterspout" (i.e., a sudden funnel-shaped cascade of water falling from the sky during a torrential rain event) (Clingman 1877). It was believed that the force of the falling water ripped away the soil from the side of the mountain, leaving only solid bedrock. Thus, Clingman (1877) used the term waterspout not only to describe a meteorological event but also the geomorphic feature created by this event. Although Clingman (1877) did not provide a reasonable mechanism for the waterspouts, his detailed descriptions of the event, and the geomorphic features produced by the storm are excellent.

Two debris flows occurred in Macon County near the crest of Fishhawk Mountain and the Tessantee River on the afternoon of June 15, 1876. There were no known fatalities, but the Conley family witnessed the debris flow across the river from their home:

> "They saw a large mass of water and timber, heavy trees floating on the top, which appeared ten or fifteen feet high, moving rapidly towards them, as if it might sweep directly across the Tessantee and overwhelm them. Fortunately, however, sixty or seventy yards beyond the creek the ground became comparatively level, and the water expanded itself, became thus shallower, and leaving many of the trees strewn for a hundred yards along the ground, entered the creek with a moderate current." (Clingman 1877, 69)

Another flow also occurred on the opposite side of Fishhawk Mountain. The lengths of both of these debris flows were estimated to be two miles. The location of these slides is noteworthy because Fishhawk Mountain is the same area where four people and an unborn child were killed and several houses destroyed in a debris flow that occurred on September 16, 2004 (see below).

May, 1901

From May 18 to 23, 1901 a series of low-pressure systems passed through western North Carolina and brought heavy rain, with the heaviest precipitation occurring on May 21-22. The storm was centered near the Black Mountains of North Carolina. Total precipitation amounts ranged from 22.8 cm in Marion to 12.8 cm in Asheville (Myers 1902). Extreme flooding affected portions of the Nolichucky, Watauga, Little Tennessee, and Catawba Rivers systems (Myers 1902, Scott 1972). Later flooding in the spring and summer only added to the destruction. Total damage to farms, bridges, highways, and buildings in the French Broad watershed was estimated to be $4M dollars (U. S. Department of Agriculture 1902).

Most of the debris flows associated with the 1901 storm occurred in Buncombe, Henderson, Mitchell and McDowell Counties (Scott 1972). The Southern Railroad Company was particularly affected as a number of slides buried tracks for hundreds of meters or washed away portions of track in the associated flooding. A resident of Marion, George Bird, reported that a number of slides occurred in the surrounding hills near his home and generated large piles of timber (Holmes 1917). Landslides and waterspouts seemed to have been particularly prevalent in Mitchell County where as many as 17 slides were observed on one hill by Myers (1902) (Figure 4). Myers (1902, 104) de-

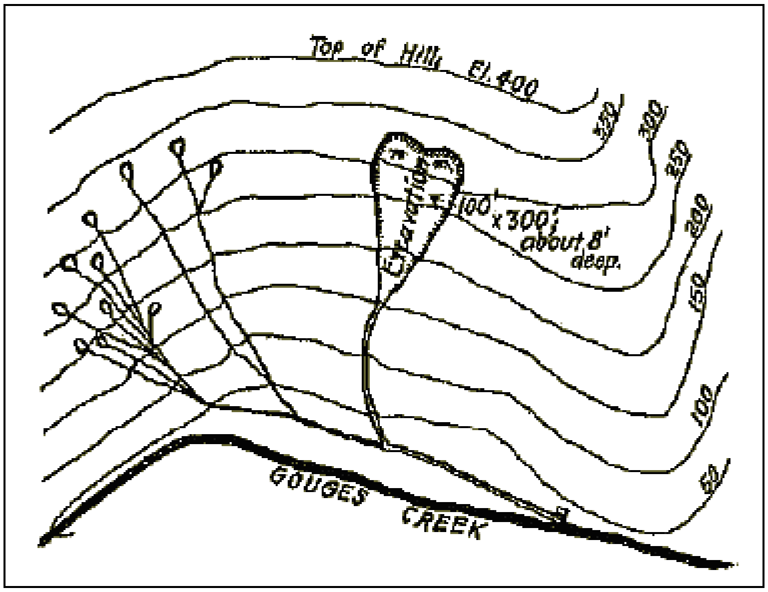

Figure 4: Sketch map of debris flows that occurred along Gouges Creek in Mitchell County, North Carolina in May 1901 (Myers, 1902).

scribes in detail one of the largest slides he encountered:

> "…the excavated area was roughly heartshaped, having an extreme breath of about 100 ft., the distance from head to point being about 300 ft., and it was located on a hillside, sloping from 80° to 45° and having its head about 200 ft. below the crest of the hill, which was as high as any nearby… From the lower end of the cavity a sharp and well-defined channel led down the hill to the stream at the base, this channel being from 5 to 6 ft. wide and from 4 to 5 ft. deep with side walls practically vertical cut down though a gravelly clay… It is estimated that the excavation has a total content of about 2,500 cubic yards of earth which seems to have disappeared utterly."

The particular slide described by Myers (1902) destroyed a log house that was in the flow path. Other accounts by area residents describe cloudbursts of extreme intensity accompanying the waterspouts and that water bubbled and then burst from the ground at the head of many smaller slides (Myers 1902). It can be assumed from these descriptions that the mass movements in Mitchell County were debris flows, given their high water-and-debris content, characteristic flow path, and rupture surface.

July, 1916

In July of 1916, the precipitation from two tropical cyclones moved through the French Broad watershed causing extensive flooding and numerous debris flows. During the night of July 5-6, 1916 a weak hurricane passed over the Mississippi and Alabama coast and followed a slow, sinuous course northeast (Henry 1916) (Figure 5). Eventually the storm deteriorated into a tropical depression by the time heavy rains reached western North Carolina on July 9 (Henry 1916). This storm produced 10 to 25 cm of rain but did not create any known debris flows. Not long afterwards on July 14, another hurricane made landfall near Charleston, South Carolina and traveled rapidly northwest into the mountains of North Carolina (Figure 5). By the morning of July 15, the center of the pow-

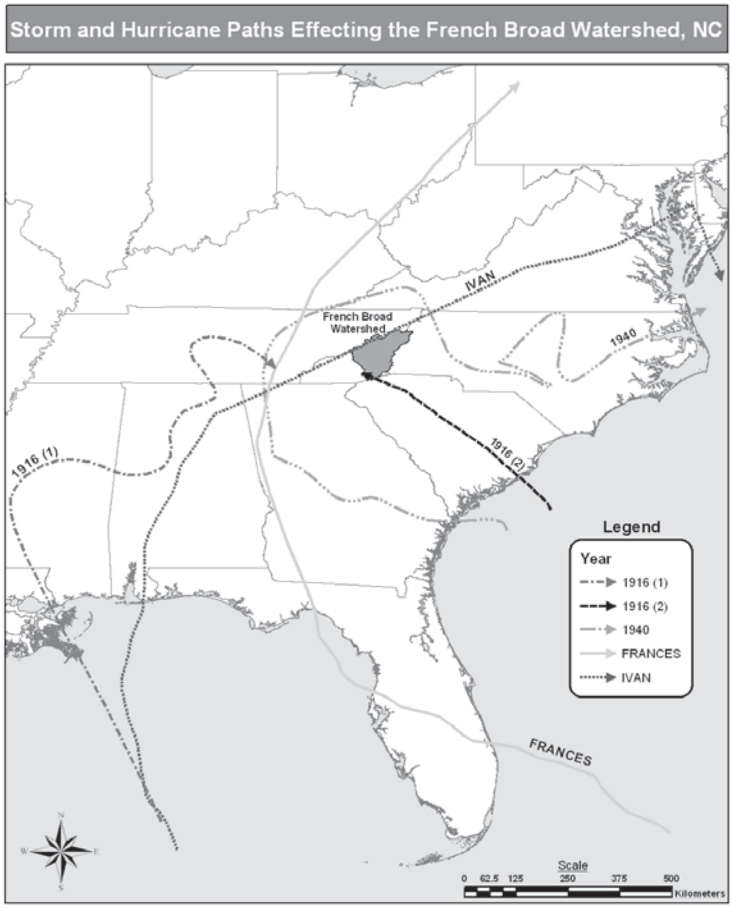

Figure 5: Map showing some of the hurricane paths that have affected western North Carolina as reported by the U.S. National Hurricane Center and the U.S. Geological Survey – Water Resources Branch (1949).

erful storm had already reached western North Carolina. Beginning in the afternoon of that day, unprecedented amounts of rain fell for 24 hours (Henry 1916).

The flood of July 14-16, 1916 was the largest recorded flood on the French Broad River at Asheville. The peak streamflow on July 16 was 3115 m^3/s (110,000 ft^3/s), several times greater than any other recorded streamflow at that station (Figure 6). The storm also triggered numerous debris flows in the mountains. Rainfall totals for the 1916 storm were exceedingly heavy with nearly all of the eastern slopes of the North Carolina Blue Ridge receiving 25 cm of rain or more (Scott 1972). The greatest amount of rain was recorded in the French Broad watershed at Altapass, where 56 cm fell in a 24-hour period (Hudgins 2000). This is also the greatest 24-hour rainfall total ever recorded in North Carolina.

Generally, the storms of 1916 produced two distinct regions of exceptionally heavy precipitation, one in Mitchell, Avery, and Caldwell counties, and the other in Transylvania and Henderson counties (Figure 7). The first storm had already thoroughly soaked the soil, increasing antecedent moisture conditions, and filled most streams nearly to flood stage (Scott 1972). Runoff from the second storm was estimated to be as high as 80-90 percent

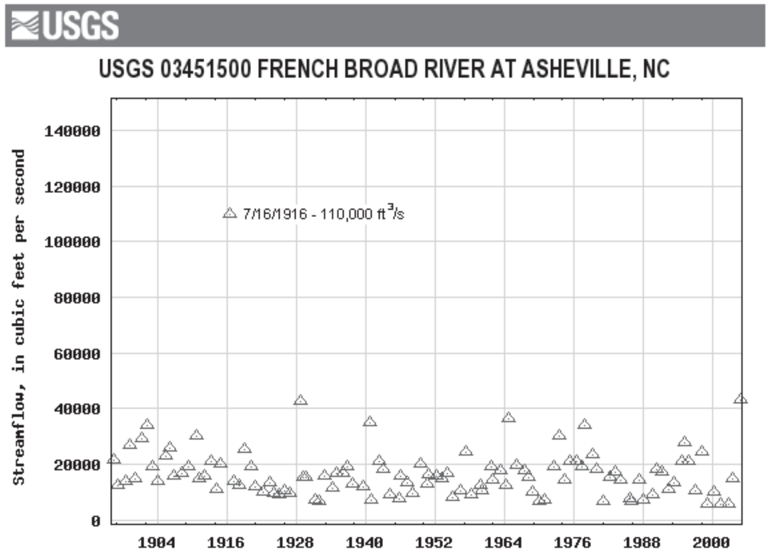

Figure 6: U. S. Geological Survey peak streamflow data for the French Broad River in Asheville from 1896-2004. The maximum peak streamflow recorded at this station (110,000 ft^3/s) was on July 16, 1916; an amount nearly three times greater than any other recorded streamflow.

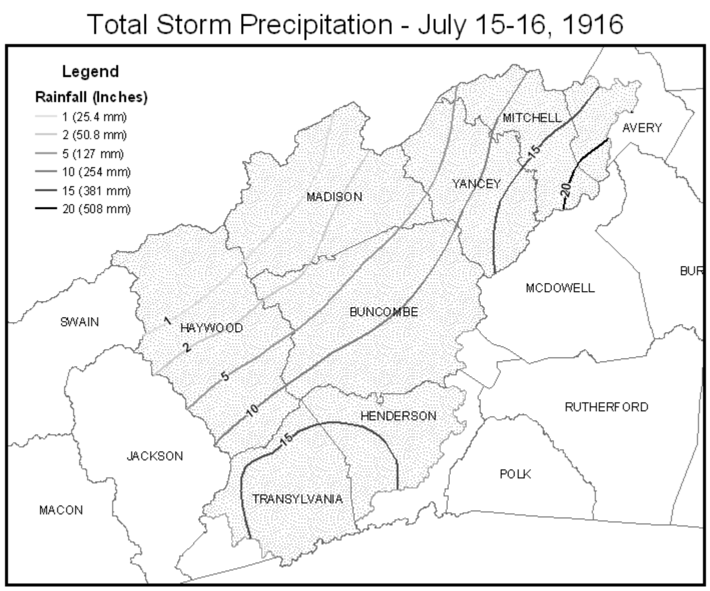

Figure 7: Total storm precipitation for July 14-16, 1916 (adapted from Scott, 1972).

of precipitation and only exacerbated flood conditions (Henry 1916).

The July 1916 storms killed approximately 80 people and caused $22M in damages (Southern Railway Company 1917). In Asheville, flooding destroyed several homes and buildings and four of the main river bridges were washed away (Tennessee Valley Authority 1960). The Southern Railway Company suffered extreme financial losses and transportation within western North Carolina was disrupted for several days. Many railway lines were covered by debris flows, trapping freight and passenger trains between terminals. The Southern Railway Company (1917) reported that almost every mile of track between Asheville and Statesville was covered by debris or washed out. At some places, track was suspended in mid-air after the fill below was washed away (Southern Railway Company 1917).

Generally, debris flows were reported along the Blue Ridge Mountains to the east, southeast, and south of Asheville (Holmes 1917, Scott 1972). Most slides occurred between 5 p.m., July 15 and 7 a.m., July 16. The flows began before dark and could be heard throughout the night during the period of heaviest rainfall. They typically developed in topographic hollows where the soil was thick, near the head of surface streams. Flow thicknesses ranged from 0.6-6.0 m and averaged 1.5-1.8 m. Bedrock was seldom exposed anywhere along any slide (Holmes 1917).

August, 1940

In August of 1940, a pair of storms caused significant flooding and numerous debris flows in the western mountains of North Carolina; the first occurred from August 13-15 and the other from August 28-31. These storms also brought record flooding to portions of Virginia, Tennessee, and South Carolina. Approximately 30 to 40 lives were lost and there were at least $30M in damages (U.S. Geological Survey 1949). The situation was similar to that of 1916, with two large storms occurring in the same month. The 1940 mid-August storm was strikingly similar to the second 1916 storm in terms of rainfall intensity and storm path (Figure 5). However, unlike the 1916 storm, the antecedent moisture conditions in 1940 were relatively dry, allowing for increased infiltration and lower flood discharge levels (U.S. Geological Survey 1949).

The first storm in 1940, an unnamed hurricane, made landfall between Beaufort, South Carolina and Savannah, Georgia on August 11, 1940. Although no wind speeds were recorded, damage reports indicate that trees were uprooted and broken, many buildings were damaged or destroyed, and 20 coastal residents were killed (U.S. Geological Survey 1949). An unusually high tide was reported, reflecting the storm surge. The storm then moved inland and curved northward following the Savannah River Valley, weakening significantly. It followed a semi-circular path through Georgia, Tennessee and Virginia, and then back into North Carolina before it moved offshore on August 16, just south of Norfolk, Virginia (Figure 5).

This mid-August hurricane of 1940 did not affect the French Broad Watershed until August 13-14 (Tennessee Valley Authority 1960). While rainfall intensities were moderate, the slow rate of movement allowed for heavy precipitation for several days over the North Carolina Blue Ridge, resulting in high rainfall totals (Figure 8a). Maximum precipitation totals ranged from 33-41 cm at to as little as 13 cm in Asheville (Tennessee Valley Authority 1960). A series of well-defined storms, centered over the Appalachians Mountains, extended toward the northeast from Blue Ridge, Georgia to Luray, Virginia, apparently due to an orographic influence on the storm precipitation (U.S. Geological Survey 1949).

The second storm in 1940 occurred during the period of August 28-31, but intense rainfall did not begin until the morning of August 29. Rain continued to fall until August 30 when it abruptly ended around noon. By August 31, only passing showers remained (U.S. Geological Survey 1949). This storm was a relatively local meteorological disturbance that only affected the French Broad and Little Tennessee watersheds. Precipitation was shorter in duration and smaller in aerial extent than the mid-August storm, but of higher intensity (Figure 8b).

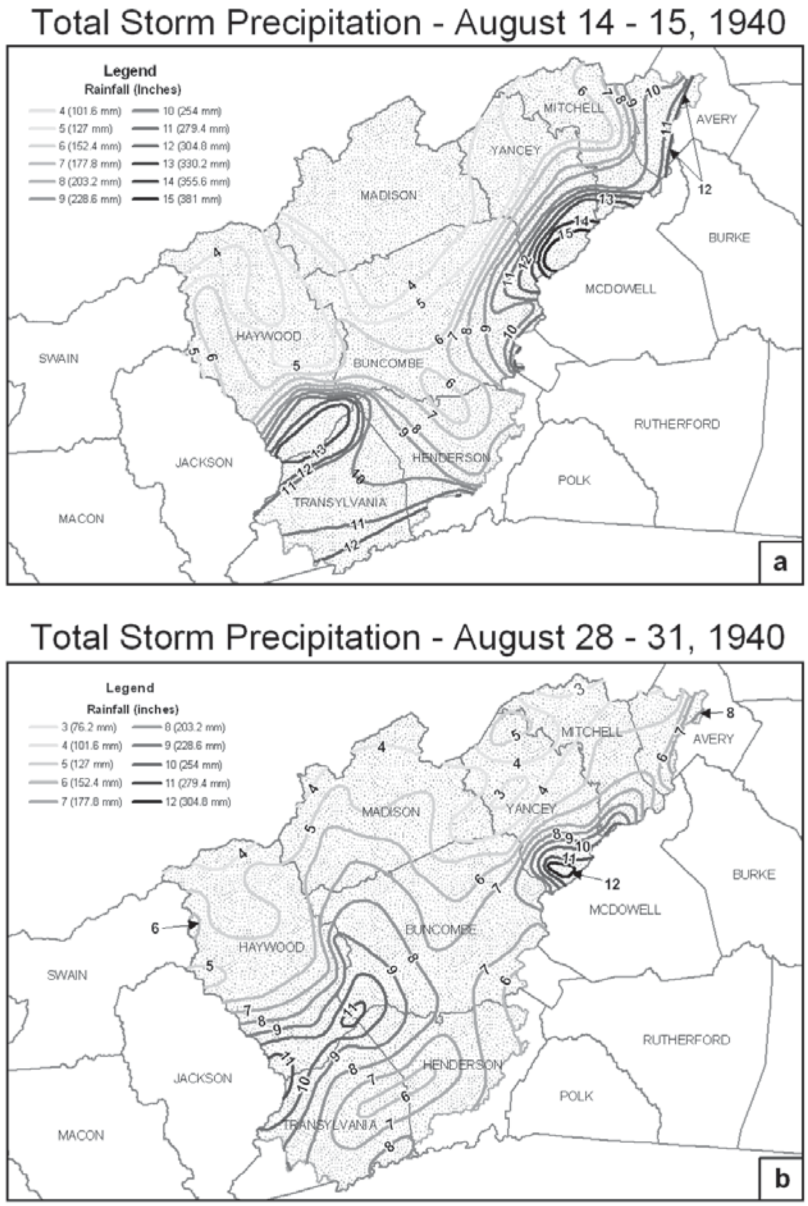

Figure 8: Total storm precipitation for August 14-15, 1940 (a) and August 28-31, 1940 (b) (adapted from U. S. Geological Survey, 1949).

Rainfall amounts ranged from 20-33 cm on the western slopes of the Blue Ridge in 20-30 hours (U.S. Geological Survey 1949). Given the antecedent moisture conditions due to the earlier storm, flooding was more severe near the storm center but overall was not as widespread.

The 200-300 debris flows associated with both 1940 storms, contributed greatly to the devastation wrought by the floods (Scott 1981). These slides occurred near the centers of both storms in shallow saturated soils on steep slopes. Debris flows were up to 91 m wide and 805 m long (U.S. Geological Survey 1949). They originated on shoulder slopes 91-122 m from the tops of mountains and then continued downslope following stream valleys, uprooting trees and destroying structures (Wieczorek et al. 2004).

During the mid-August storm of 1940, debris flows mainly occurred in the Blue Ridge Mountains, from the North Fork of the Catawba River northward into Watauga County near the North Carolina – Virginia border. During the late August storm, debris flows occurred primarily in the Upper Pigeon and Tuskasgee River basins. Because of the concentration of high-intensity rainfall within a small area, more than 200 debris flows occurred in an area of only 388 km^2 (U.S. Geological Survey 1949).

November, 1977

In early November 1977, a storm system that had formed as a low-pressure system in the Gulf of Mexico moved northwestward into the Appalachian Mountains (Neary and Swift 1987). Rainfall began in western North Carolina in the early morning of November 2 and continued at a steady rate (20-50 mm/day) until November 5. This steady rain was followed by intense downpours (102 mm/hr) on the night of November 5-6, during which most of the debris flows were initiated (Nearly and Swift 1987). This heavy precipitation, as in 1916 and 1940, was produced by convection associated with orographic lifting over the southern Appalachians. Four areas of exceptionally heavy precipitation (20-32 cm) were produced along the southeast ridges of the North Carolina Blue Ridge (Neary and Swift 1987). Two of these areas were within the French Broad watershed (Figure 9).

Although the heaviest rainfall in 1977 occurred in the vicinity of Mt. Mitchell, the best information about debris flows and flooding came from the Bent Creek watershed, located about 15 km southwest of Asheville. A survey was conducted here immediately following the storm (Neary and Swift 1987, Otteman 2001). At least seven major flows and other small failures were identified in this area (Neary and Swift 1987). Most of these debris flows occurred on steep slopes (26°-46°) at high elevations (945-1100 m) and flowed downhill following ephemeral creekbeds or along hillslope depressions (Pomeroy 1991). Scarps occurred in shallow residual soils less than 1 m deep over gneissic bedrock (Neary et al. 1986). All of the flows occurred in undisturbed, forested areas (Neary et al. 1986).

Topography in the Bent Creek watershed is at least partially controlled by the underlying concentration of tension joints in the bedrock. Where there is a greater amount of jointing, topographic hollows tend to develop. These joints allow for the infiltration of groundwater, enhancing breakdown of the rock. This accelerates weathering, providing loose material for mass wasting (Pomeroy 1991). Debris flows seem to originate on the bedrock-soil or bedrock-colluvium interface within these hollows.

The November 1977 flood killed at least thirteen people and sixteen counties in western North Carolina were declared disaster areas. The most serious flooding occurred along the French Broad River downstream from Asheville and in Yancey County where nearly every bridge was washed out (Stewart et al. 1978, Eshner and Patric 1982). Flooding destroyed 384 homes, 622 km of highway, and 12 dams. In total there was over $50M in damages associated with this storm (Stewart et al. 1978).

In 1977, precipitation, slope, and topography all contributed to the initiation of debris flows southeast of Asheville (Pomeroy 1991). Compared with other debris flow producing events, the maximum intensities associated with the 1977 storm were in the middle-to-low range but antecedent moisture was exceptionally high (177% above normal) for the two months preceding the storm (Neary and Swift 1987). The combination of very wet antecedent conditions and high-intensity, short-duration rainfall created excellent conditions for debris flows to form.

September, 2004

The 2004 Atlantic hurricane season was exceptionally brutal for western North Carolina. Of the fifteen tropical or subtropical storms that formed in the North Atlantic, nine achieved hurricane intensity (National Weather Service 2004a). In North Carolina, the remnants of three tropical systems (Hurricanes Frances, Ivan and Jeanne) impacted the western part of the state in rapid succession in September. Frances and Ivan caused extreme flooding in Asheville and several debris flows and rockslides in the mountains, causing closures of Interstate 40. Rainfall totals for the month over much of western North Carolina ranged from 25- 64 cm. This was 2-5 times greater than normal (Badgett et al. 2004).

Hurricane Frances struck the east coast of Florida early on September 5, 2004 and quickly weakened into a tropical storm (National Weather Service 2004a). The storm then rapidly moved across the state, through the panhandle of Florida, and northeastward across the eastern United States (Figure 5). The effects of hurricane Frances could first be felt in North Carolina on September 6 around 6:00 p.m. (Boyle 2004) but most of the flooding and mass wasting occurred on September 8.

The heaviest precipitation occurred slightly east of the French Broad watershed in Transylvania, Yancy and McDowell Counties (Figure 10a). The highest precipitation total was recorded in Edgemont 130 km northeast of Asheville, which received 42 cm of rain. One hundred kilometers southwest of Asheville, Lake Toxaway received 36 cm of rain (Nowell 2004). In total, 17 western counties were affected by flooding, hundreds of people were evacuated from their homes and several had to be rescued from the rising water (Nowell 2004). Areas of Asheville located near the

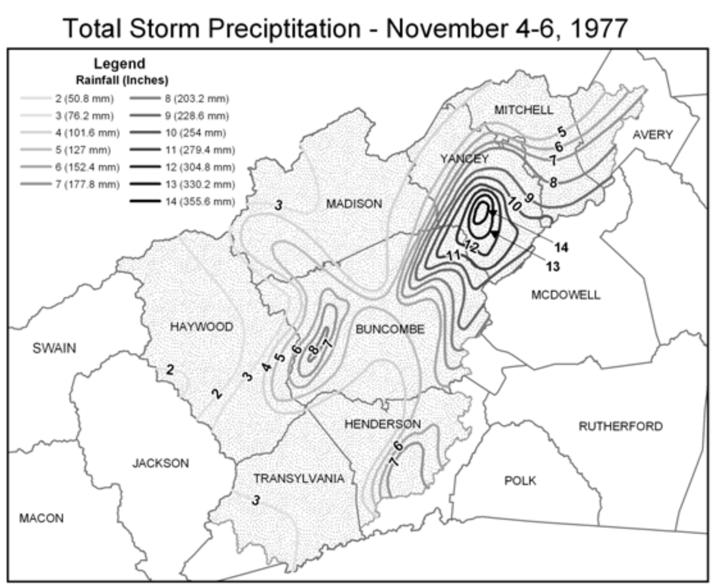

Figure 9: Total storm precipitation for November 2-5, 1977 (adapted from Neary and Swift, 1987).

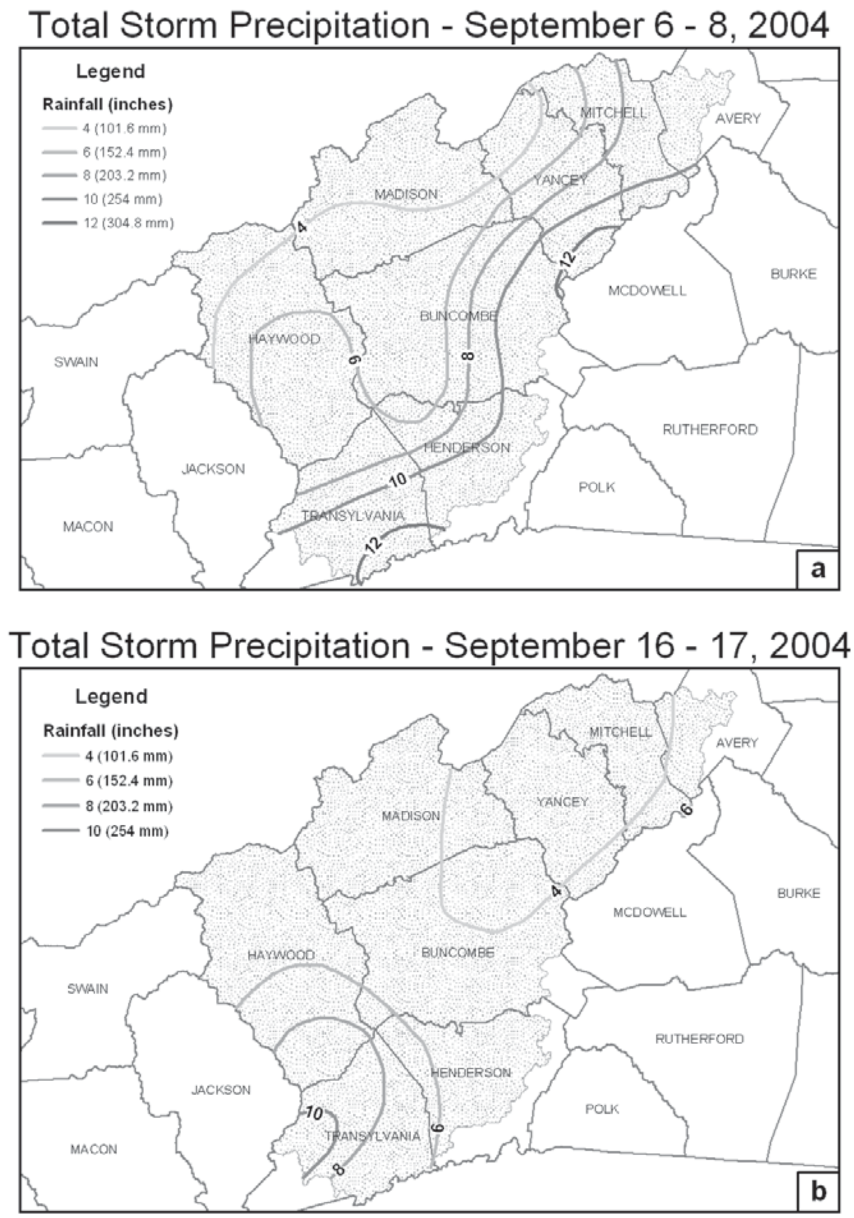

Figure 10: Total storm precipitation for the remnants of (a) Hurricane Frances (September 6-8, 2004) and the remnants of (b) Hurricane Ivan (September 16-17, 2004) (adapted from National Weather Service, 2004b and 2004c).

Swannanoa River were flooded, particularly the shopping center near the entrance to the Biltmore Estate, where water stood as much as 1.5 m deep (Nowell 2004). In Haywood County, flooding along the Pigeon River also inundated downtown Canton and Clyde.

The remnants of hurricane Frances caused at least 21 reported incidents of mass wasting along several major roadways in seven western North Carolina counties. However, only three counties within the boundaries of the French Broad Watershed experienced debris flows (Avery, Henderson, and Transylvania). One of the largest reported debris flows occurred east of Asheville on Interstate 40, near Old Fort Mountain in McDowell County. This flow crossed the westbound lane and the median to block four of the six lanes of an eight-kilometer stretch of Interstate 40 (Nowell 2004). In Watauga County, one house was destroyed and eight others condemned when a debris flow tore through a subdivision (North Carolina Geological Survey 2004a). Portions of the Blue Ridge Parkway were closed when at least six debris flows destroyed the roadway in four areas between Linville Falls and Waynesville (Ball 2004). About 250 roads became impassable or were closed due to flooding and mass wasting (Barrett 2004). Most of the road damage was in Buncombe County (Ball 2004).

Ivan was an unusually long-lived hurricane that made landfall along the United States coast twice. Ivan struck the Alabama coast early on September 16 as a Category 3 hurricane and gradually weakened as it moved northeastward into the southeastern United States (Figure 5). After emerging off of the Delmarva Peninsula on September 19, remnants of the storm moved southwestward, crossed over Florida and then into the Gulf of Mexico. By September 23, the remnants of Ivan had restrengthened into a tropical storm that made landfall for the second time on September 24 over southwestern Louisiana (National Weather Service 2004a).

The remnants of Ivan moved into western North Carolina early on September 16. Although Ivan had weakened to a tropical storm by the time it reached North Carolina, it still packed powerful winds and heavy rain. Rainfall was not as heavy as rainfall from Frances, mainly because the storm moved rapidly northeastward, but the western portion of the state still received 10-20 cm of rain. The heaviest precipitation fell in Transylvania, Jackson and McDowell Counties at high elevations. Black Mountain (near Asheville) received 29 cm of precipitation and Sapphire (in Transylvania County) reported 38 cm (Figure 10b).

Although Ivan produced less rain than Frances, high antecedent-moisture conditions and saturated soils allowed for more slope movements to be produced. A total of 53 reported slope movements have been attributed to hurricane Ivan (Cabe 2004). But several other slope movements may also have occurred in undisturbed or rural areas and were not reported by either the North Carolina Department of Transportation (NCDOT) or major news agencies. Further work will have to be conducted to obtain a complete record of these slope movements.

Slope movements, downed trees, and flooding obstructed several roads throughout western North Carolina, stranding residents in several communities in Avery, Jackson and Haywood Counties. A major slope movement occurred in the westbound lane of Interstate 40 in Haywood County. Farther to the west, near the North Carolina-Tennessee border, a large portion of the eastbound lane of Interstate 40 collapsed due to undercutting by the swollen Pigeon River. A major debris flow also destroyed a home in Candler in Buncombe County (Cantley-Falk 2004).

The worst damage occurred in the community of Peeks Creek in Macon County. At around 10:10 p.m. on September 16, a debris flow originating near the peak of Fishhawk Mountain destroyed at least fifteen houses, injured several people, and resulted in the deaths of four people (and an unborn baby). The debris flow traveled approximately 3.6 km dropping nearly 670 m in elevation as it progressed down a mountain cove and into the north fork of Peeks Creek (Cabe 2004). The velocity of the flow was estimated to be 33 kph near the scarp and 53.5 kph just upstream of the area of major damage (Cabe 2004). The force of the flow scoured the streambed, ripped trees down and left others striped of bark; houses were removed from their foundations (North Carolina Geological Survey 2004b). The flow probably originated as a debris slide; a slab of cohesive rock, debris and earth the size of a football field detached from the side of the mountain and quickly disintegrated into a debris flow as more water mixed with the slide material (Cabe 2004) (Figure 11).

What is remarkable about the Peeks Creek disaster is that this location is the same area where two large debris flows occurred in 1876 (Clingman 1877). Observations of residents living in the area were strikingly similar in both incidents. Clingman (1877) describes trees stripped of bark and limbs, a "clean, broad furrow more than two miles" long carved into the side of the mountain, and boulders weighing several tons moved by the flow, similar to what was found after the Peeks Creek flow (Figure 12). Residents during both the 1876 and 2004 incidents reported seeing or hearing a tornado or "waterspout" just before or during the debris flow. In 1876, residents described seeing funnel-shaped spinning masses of water near the crest of the mountain (Clingman 1877). In the light of an exploding electrical transformer, one resident described seeing debris spinning and flying around in the air in a circular motion above their house (Biesecker and Shaffer 2004). The National Weather Service (2004c) reported that a storm cell that spawned a tornado in Georgia moved over the Peeks Creek area around the time that the debris flow occurred. Tornadoes are fairly rare in mountainous areas, but do occasionally develop. While there was wind damage throughout the Peeks Creek area after the passage of Ivan, this damage was more consistent with wind shear. So far, the National Weather Service has not been able to conclude if a tornado actually did touch down on Fishhawk Mountain, but they do not discount the eyewitness accounts of local residents (Cabe 2004).

The question remains as to why mass movements occurred in these Macon County areas as opposed to elsewhere. In the Peeks Creek flow, fracture planes in the rock, sloping 35-55 degrees, provided a smooth slip surface near the headscarp. Soil layers over this bedrock were thin, generally less than 1 m deep (Cabe 2004). Meteorologically, the rainfall rates from the remnants of hurricanes Frances and Ivan were not unusually intense for

Figure 11: The head scarp of the Peeks Creek flow near the crest of Fishhawk Mountain. The overlying soil was ripped away, exposing the underlying bedrock for several hundred meters down the channel of the flow (courtesy of the North Carolina Geological Survey).

Figure 12: Large imbricated boulders and woody debris in the main channel of the Peeks Creek debris flow (note geologist for scale). Features such as these indicate the velocity of the material moving in the channel during the failure (courtesy of the North Carolina Geological Survey).

either event. However, the combined rainfall totals were exceptionally heavy. The rainfall produced by Frances initially saturated mountain soils and slopes. Before the soil had a chance to drain sufficiently, Ivan moved through the area, bringing even more rain to already waterlogged soils. The rainfall from Ivan may have caused even higher soil-water pressure on slopes, explaining why there was more mass wasting during the second storm. Ultimately, the exact reasons why debris flows occur in one area and not another, under similar meteorological and physical conditions, are not fully understood.

Precipitation Thresholds and Debris Flow Frequency: Lessons Learned

Most of the rainfall totals associated with the 1876, 1901, 1916, 1940, 1977 and 2004 events are well within the 125-250 mm/d precipitation thresholds suggested by Eschner and Patric (1982) as necessary for debris-flow generation in the Southern Appalachians (Figure 2). Average 24-hour rainfall totals were greater than 125 mm/d (the minimum precipitation necessary to saturate soil and set the stage for debris flows) in 7 out of 9 cases (Table 2). Extreme precipitation does not necessarily guarantee that debris flows will occur, as during the July 5-6, 1916 storm, but extreme precipitation certainly increases the risk of slope instability. In many cases, such as with the Peeks Creek debris flow and the 1977 storm, rainfall intensity is an extremely important triggering agent.

Few studies have attempted to delineate a recurrence interval for debris flow activity in small mountain watersheds in the Appalachians based purely on historical documentation. Studies have instead relied on dating techniques to determine the age of sequences of preserved ancient debris flow deposits. Recurrence intervals for individual first-order drainages may be on the order of thousands of years (Eaton et al. 2003b). As the area of interest increases in size, the probability of debris-flow activity also increases. Based on the occurrence of major debris-flow triggering storms from the historical record (those that have extensive amounts of precipitation and debris-flow location data), a frequency of slope instability can be estimated for the French Broad watershed. The average frequency of mass wasting from 1876-2004 (for eight events) is 16 years. This calculation excludes

Table 2: Major debris flow producing storms within the French Broad Watershed: minimum, average, and maximum precipitation amounts and the approximate duration of the storm.

STORM DATE	Min. (mm)	Avg. (mm)	Max. (mm)	Duration (hr)
1876*	110	138	165	24(?)
1901	128	178	228	48(?)
1916 (1)**	102	178	254	48
1916 (2)	25	254	564	24
1940 (1)	102	330	406	48
1940 (2)	76	203	330	24
1977***	51	203	356	72
2004 (Frances)	102	262	422	48
2004 (Ivan)	102	241	381	24

* rain gauge data limited to two stations
** no debris flows produced
*** most intense rain occurred in the 24-hr period when debris flows occurred

the first 1916 storm, as no debris flows were triggered during this event. The return interval for such storms has varied from as few as 15 years to as many as 37 years. On human timescales, this is still enough time for people to forget that mass wasting can occur in their area.

Nearly all of the major events that caused debris flows in western North Carolina occurred when two storm systems, producing heavy precipitation, traveled over the area within 6-20 days of each other. Antecedent moisture and rainfall intensity seems to play a crucial role in predisposing slopes to debris-flow generation. The locations of prehistoric and modern debris flows, and their associated geomorphic features, are also a good indicator of areas that may be prone to slope instability. Geoscientists, emergency management, and citizens must be cautious when modifying slopes and building homes and critical structures in these mountainous areas. It will also be necessary to be vigilant in monitoring weather conditions, particularly with repeated sequences of heavy rain events.

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