Chapter 9
Frequency and Magnitude of Selected Historical Landslide Events in the Southern Appalachian Highlands of North Carolina and Virginia: Relationships to Rainfall, Geological and Ecohydrological Controls, and Effects

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Abstract Landsliding is a recurring process in the southern Appalachian Highlands (SAH) region of the Central Hardwood Region. Debris flows, dominant among landslide processes in the SAH, are triggered when rainfall increases pore-water pressures in steep, soil-mantled slopes. Storms that trigger hundreds of debris flows occur about every 9 years and those that generate thousands occur about every 25 years. Rainfall from cyclonic storms triggered hundreds to thousands of debris

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flows in 1916, 1940, 1969, 1977, 1985, and 2004. Debris flows have caused loss of life and property, and severely affected forest lands by altering forest structure and disrupting aquatic ecosystems. Forests on mountain slopes are critical in mitigating the impacts of recurring landslide events. Forest cover is an important stabilizing factor on hillslopes by intercepting precipitation, increasing evapotranspiration, and reinforcing roots. Precipitation and hillslope-scale landforms have a controlling effect on soil moisture, root strength, and debris flow hazards. Anthropogenic influences have increased the frequency of mass wasting for a given storm event above historical natural levels through changes in vegetation and disturbances on mountain slopes. Climate change that results in increased occurrences of high intensity rainfall through more frequent storms, or higher intensity storms, would also be expected to increase the frequency of debris flows and other forms of mass-wasting in the SAH. The interdisciplinary technical and scientific capacity exists to investigate, analyze, identify and delineate landslide prone areas of the landscape with increasing reliability.

Keywords Debris flow • Ecohydrological • Landslide • Blue Ridge Mountains • Southern Appalachian Highlands

9.1 Introduction

Landsliding is a recurring process of mass wasting and sediment transport in the landscape evolution of the southern Appalachian Highlands (SAH) of the USA. The SAH encompasses the Blue Ridge Mountains, and adjoining mountainous and high relief areas of the Central Appalachians, Ridge and Valley, and Piedmont Ecoregions (Greenberg et al. Chap. 1, Fig. 1.1). In comparing the relative frequency of disturbances among ecoregions of the Central Hardwood Region (CHR), White et al. (2011) found that the remnants of hurricanes (tropical cyclones) and, consequently, landslides are more common disturbances in the Blue Ridge Mountains, Ridge and Valley, and Central Appalachians ecoregions. Here we concentrate on the Blue Ridge Mountains and adjacent Piedmont of North Carolina and Virginia where previous and recent landslide mapping and studies have helped quantify the extent and magnitude of major historical landslide events. These events have caused loss of life, damage and destruction of homes, property and transportation networks, and have had major impacts on forest structure and hydrologic systems (Fig. 9.1). Future debris flow events in the SAH are certain and will have similar impacts.

The term landslide refers to a variety of gravity-driven ground movements of soil and/or rock materials. Landslides may be swift and catastrophic (i.e., rockfalls and debris flows) or may travel slowly and incrementally downslope (i.e., some soil slides). Landslide incidence and susceptibility occurs in nearly all of the high-relief areas of the USA including the CHR (Fig. 9.2). Although many types of landslides occur throughout the SAH, debris flow is the dominant landslide process in the Blue Ridge Mountains of North Carolina and Virginia, and the SAH, and will be the

Fig. 9.1 Damaged and destroyed homes, and debris flow erosion and deposition along the run out zone (lower track) of the September 16, 2004 Peeks Creek debris flow in Macon County, North Carolina. The debris flow triggered by rainfall from Hurricane Ivan claimed five lives and destroyed 16 homes (September 19, 2004 NCGS photo). Refer to Fig. 9.17 for location

focus of this chapter. A debris flow is a water-laden (i.e., liquefied) moving mass of rock fragments and soil (debris) in which the majority of soil particles are sand-sized or larger (Cruden and Varnes 1996). Debris flows move rapidly downslope, attaining speeds in excess of 50 km per hour, and are capable of destroying or damaging everything in their paths. A typical debris flow pathway consists of an upper initiation site or source area, a main track or path along a drainage way or stream channel, and a lower depositional area or run out zone on mountain footslopes (Clark 1987; Cruden and Varnes 1996). The present SAH landscape includes many remnants of prehistoric (Pleistocene and older) debris flow deposits (Leigh Chap. 8). These features are typically composite, recording multiple episodes of prehistoric and historic mass wasting in mountain coves and foot slopes. Importantly, these deposits indicate areas that may be affected by future debris flow activity, as modern debris flows generally deposit sediment in areas occupied by past debris flow deposits.

The primary trigger for debris flows is heavy rainfall (generally greater than 125–250 mm in 24 h) that results in excess pore-water pressures in relatively thin soil on steep slopes. From 1916 to 2006 seven major cyclonic storms tracked over the SAH, setting off hundreds to thousands of debris flows in multi-county areas in the North Carolina, Virginia and West Virginia. In addition, rainfall associated with

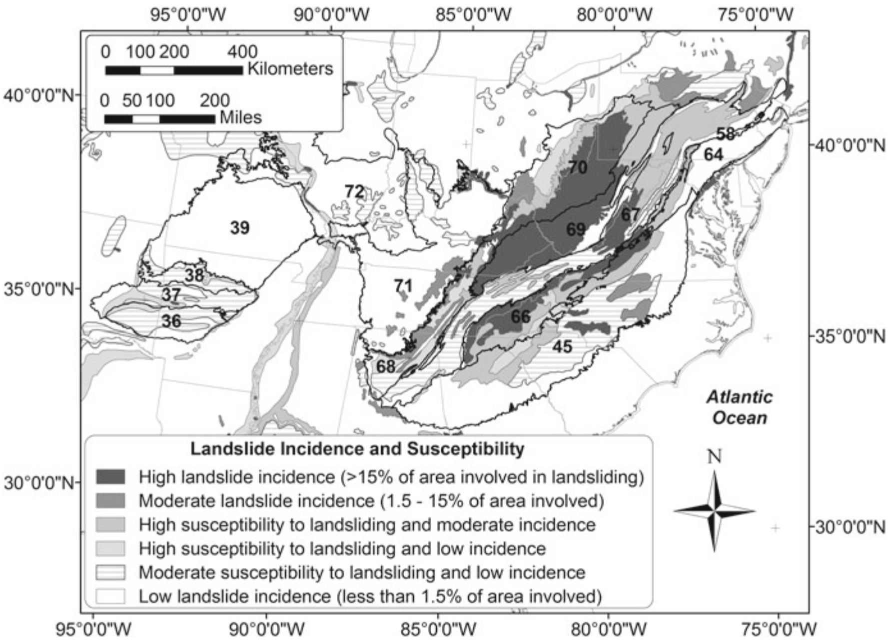

Fig. 9.2 Generalized map of landslide incidence and susceptibility (From Godt (1997) shown for the CHR and ecoregions within it. Within the CHR the Appalachians have the overall highest landslide incidence and susceptibility. Landslide incidence is the percentage of the area involved in landsliding. Susceptibility is defined as the probable degree of the areal response of rocks and soil to natural or artificial cutting or loading of slopes, or to anomalously high precipitation. Ecoregions shown with *bold outlines*: 36 = Ouachita Mountains, 37 = Arkansas Valley, 38 = Boston Mountains, 39 = Ozark Highlands, 45 = Piedmont, 58 = Northeastern Highlands, 64 = Northern Piedmont, 66 = Blue Ridge Mountains, 67 = Ridge and Valley, 68 = Southwestern Appalachians, 69 = Central Appalachians, 70 = Western Allegheny Plateau, 71 = Interior Plateau, 72 = Interior Valleys and Hills

low pressure systems, and localized storms, especially when coincident with periods of above average rainfall can trigger tens to hundreds of debris flows. From 1876 to 2013, at least 16 of these storm events generated tens to hundreds of debris flows.

The majority of landslides in the SAH occur in the Blue Ridge Mountains of North Carolina and Tennessee, the northern Blue Ridge Mountains of Virginia, and the Ridge and Valley of Virginia and West Virginia (Figs. 9.3 and 9.4). The concentration of landslide activity in the North Carolina Blue Ridge Mountains and adjacent portions of the Great Smoky Mountains National Park (GSMNP) in Tennessee is partly the result of the high relief and ruggedness of the terrain, and partly owing to the more frequent impacts of cyclonic storms in this region (9 of 13 storms). Although there are fewer documented landslide events for the Blue Ridge Mountains, and Ridge and Valley of Virginia and West Virginia, rainfall events there have

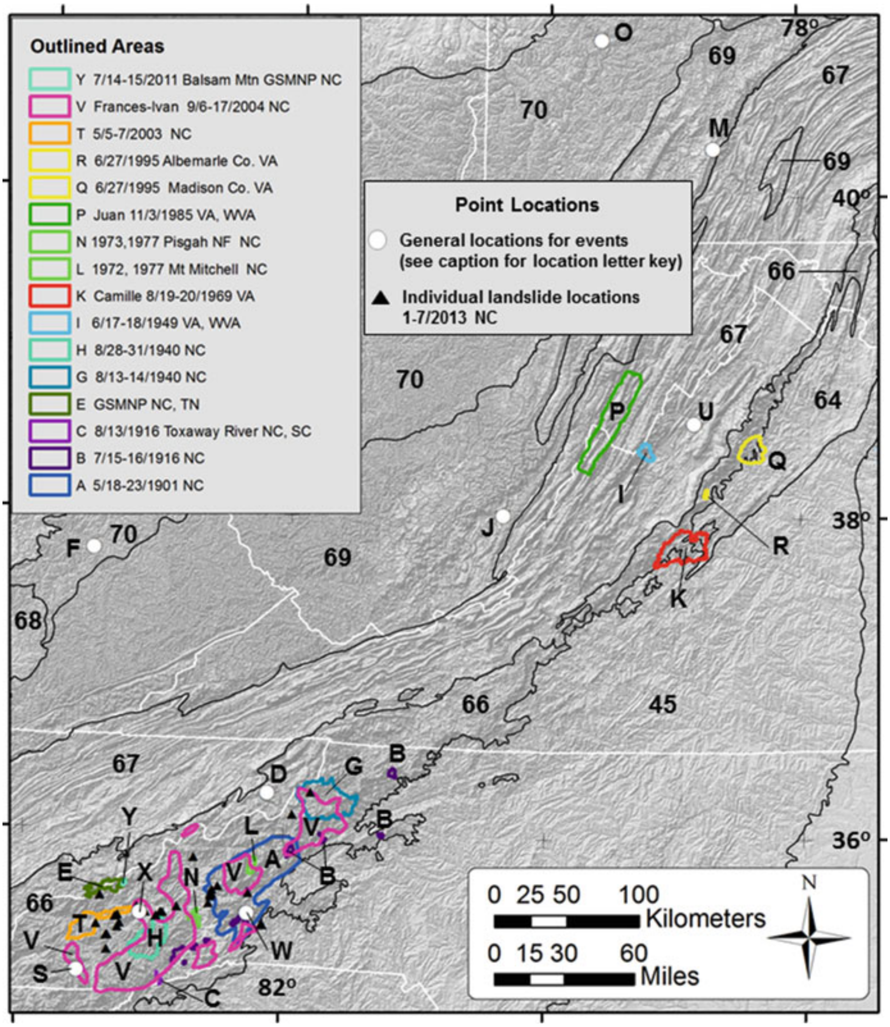

Fig. 9.3 Shaded relief map showing ecoregions and areas of selected past debris flow events in the SAH and other selected locations in the CHR. Lettered locations correspond to events in Table 9.1. General point locations: D = 6/3/1924 Carter Co. TN, F = 7/4-5/1939 KY, J = Camille 8/19-20/1969 Greenbrier C. WV, M = 7/19/1977 PA, O = 8/14/1980 PA, S = Opal 10/3-5/1995 NC, U = Isabel 9/18-19/2003 NC, W = Cindy 7/7/2005 NC, X = Ernesto 8/3/2006 NC. Ecoregion number designation: 45 = Piedmont, 64 = Northern Piedmont, 66 = Blue Ridge Mountains, 67 = Ridge and Valley, 68 = Southwestern Appalachians, 69 = Central Appalachians, 70 = Western Allegheny Plateau, 71 = Interior Plateau

triggered the greatest numbers of documented landslides. The remnants of Hurricane Camille in 1969 generated a total of 5,377 documented landslides (mainly debris flows) in Virginia and West Virginia making it the largest magnitude, well-documented landslide event in the SAH.

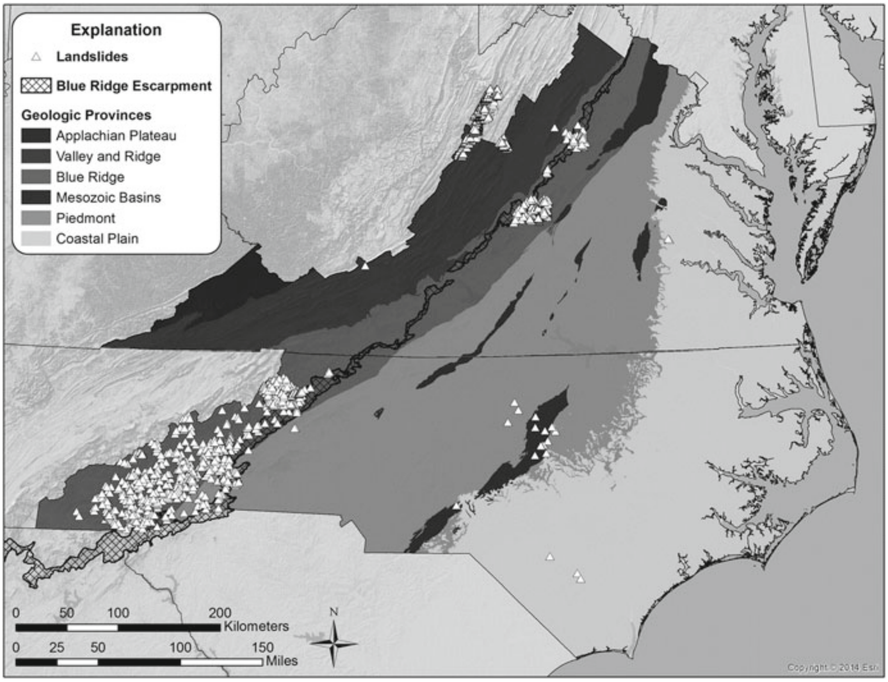

Fig. 9.4 Geologic provinces of North Carolina and Virginia, the Blue Ridge Escarpment, and landslide locations in landslide geodatabases of the North Carolina Geological Survey and Virginia Department of Mines Minerals and Energy. Clustered distribution of landslides results from detailed mapping in some areas of major landslide events, and incomplete mapping in other areas

Geologic, geomorphic, and meteorological conditions influence where debris flows are most likely to initiate on the landscape. Orographic enhancement of rainfall can occur as an air mass or storm moves over a high mountain range from lower elevations. This phenomenon is caused by the lifting and cooling of the air mass as it travels over a high elevation area and often produces excess precipitation. Heavy rainfall, when combined with the high-relief areas of certain landforms (i.e., the multi-basin scale Blue Ridge Escarpment and the watershed-scale Nantahala Mountains Escarpment) and erosional reentrants into them, are more prone to debris flow activity. Geologically, intersecting bedrock structural discontinuities (e.g., fracture, foliation, and bedding planes) and differential weathering control the locations and subsurface morphologies of convergent landforms (i.e., colluvial hollows) where debris flows typically initiate. Less frequently, soil on planar or divergent (i.e., convex) slopes such as ridge noses, also controlled by bedrock discontinuities, serve as debris flow initiation zones. Bedrock geology is dynamically coupled with hillslope geomorphology, hydrology, soil, and vegetation, all of which influence hillslope stability. In addition to these factors, ground disturbance from human activity, such as poorly constructed or maintained cut and fill slopes, and drainage systems, can further destabilize hillsides making them more susceptible to damaging debris flows.

Forest cover is an important stabilizing factor on steep upland hillslopes through precipitation interception, evapotranspiration, and root biomass (e.g., root reinforcement). Debris flows often initiate where the reinforcing ability of plant roots is at a minimum, either through reduced root biomass and/or tensile strength, and/or less connectivity between roots and the bedrock substrate. The reinforcement provided by the roots of forest plants reflects hillslope-scale differences in below-ground biomass and tensile strength, and is directly affected by precipitation and soil moisture. Systematic differences in forest structure driven by differences in soil moisture and nutrient distributions, combined with the expansion of weakly rooted species such as the shrub Rhododendron (*Rhododendron maximum*), appear to influence the size of individual landslides and possibly regional landsliding events. Studies of SAH woody species show responses of root tensile strength to changes in precipitation and soil moisture. Roots are weaker in convergent compared to divergent geomorphic features, and roots in wetter soils, i.e., after rain events, become weaker compared to when soils are drier. Precipitation, therefore, has a controlling effect on soil moisture, root tensile strength, and debris flow hazards. Although forest cover is beneficial, forested slopes are a common location for debris flows triggered by storm events in the SAH.

9.1.1 Methods

In North Carolina and Virginia, earlier landslide mapping has been integrated into a geographic information system (GIS) environment for ease of data entry and for statistical analyses. Field studies and the development of similar statewide, GIS-based, landslide geodatabases by the North Carolina Geological Survey (NCGS) and the Virginia Department of Mines, Minerals and Energy – Division of Geology and Mineral Resources (DGMR), capture and help to quantify the frequency and severity of debris flow events of various magnitudes in the SAH (Fuemmeler et al. 2008; Bauer et al. 2012; Witt and Heller 2014). The NCGS geodatabase currently has over 3,400 landslide points and over 3,200 landslide deposit (mainly debris) polygons, located primarily in the four counties with completed landslide hazard maps. The DGMR geodatabase currently has over 5,200 landslide points and associated data. Digital elevation models, including those derived from LiDAR, coupled with archival aerial photography and recent orthophotography have advanced the capability to identify, map, and analyze prehistoric and historic landslide features within the context of the current landscapes and land covers. Currently, the NCGS and DGMR do not actively map landslides and landslide deposits, but landslide features are added to the geodatabases on an as-needed basis

A compilation of existing landslide information and new mapping of landslide features in a GIS environment by the NCGS began in 2003 in the western North Carolina Blue Ridge Mountains (Wooten et al. 2005) and was funded in part by the Federal Emergency Management Agency (FEMA). New mapping and data collection in North Carolina included a geologic hazards inventory along the North

Carolina portion of Blue Ridge Parkway (Latham et al. 2009), and completion of landslide hazard maps for Macon, Watauga, Buncombe and Henderson Counties (Wooten et al. 2006, 2008b, 2009b, 2011). The NCGS has also responded to requests for technical assistance in over 85 landslide events in which field data were collected during investigations. In a 1-year FEMA funded pilot project, the Virginia DGMR mapped landslides and prehistoric landslide deposits in Page County, Virginia (Witt and Heller 2012, 2013, 2014; Witt et al. in press).

9.2 General Geologic and Geomorphic Setting

The bedrock geology of the Blue Ridge Mountains in North Carolina and Virginia and the adjacent Piedmont includes metasedimentary slate, phyllite, marble, schist, and gneiss, and metaigneous amphibolite and greenstone (metabasalt), granitic gneiss, and relatively unmetamorphosed granitic rock (Fig. 9.4). Protoliths of these rocks were deposited or crystallized during distinct periods spanning the last 1.8 billion years (Hatcher 2010; Ownby et al. 2004). The oldest rocks, Mesoproterozoic gneisses, are highly metamorphosed igneous and sedimentary rocks formed between 1.8 and 1 billion years ago. These gneisses comprised the edge of the ancient North American craton upon which early Paleozoic sediments were deposited in rift and ocean basins. During the Paleozoic, at least three continental collisional events subjected all of these rocks to high temperatures and differential pressures, creating complex folding, faulting, and widespread metamorphism. Igneous activity associated with the Paleozoic orogenies emplaced numerous granitic plutons into the surrounding country rock. Thrusting along low angle faults folded and transported these rock packages tens to hundreds of km to the northwest, placing them on top of and deforming younger, low-grade to unmetamorphosed, folded and faulted Paleozoic sedimentary rocks of the Valley and Ridge province (Hatcher 1989). The multiple episodes of metamorphism, folding, thrust faulting, and fracturing during the southern Appalachian orogen have resulted in complex ductile (e.g., foliation and shear zones) and brittle (e.g., fractures) bedrock structures that are reflected in the topography at scales from a single outcrop to the region.

Later, Cenozoic uplift and subsequent post-orogenic erosion and denudation, enhanced by climatic variations from repeated glacial and interglacial intervals, have resulted in many of the Quaternary geomorphic features seen in the Appalachian Mountains today (Kochel and Johnson 1984; Kochel 1987,1990; Soller and Mills 1991). The most extensive regional landform in the SAH is the Blue Ridge Escarpment (BRE) (Hack 1982; Clark 1993), which is also referred to the as the eastern Blue Ridge front in Virginia. This high relief, erosional feature extends from northeast Georgia to northwest Virginia, generally corresponds with the Eastern Continental Divide, and marks the boundary between the mountainous Blue Ridge Mountains and the rolling foothills of the Piedmont physiographic province to the east (Fig. 9.4).

Ancient and modern deposits from debris flows and other types of landslides on mountain footslopes and in coves record a long history of mass wasting from early Miocene to the present, reflecting the ongoing landscape evolution of the SAH. These accumulations of unconsolidated, matix- or clast-supported, clay- to boulder-sized sediment (i.e., composite diamictons) are referred to by various names, including debris fans, alluvial fans, and piedmont cove deposits (Kochel and Johnson 1984; Kochel 1987, 1990; Mills 1982, 1998; Mills et al. 1987; Whittecar and Ryter 1992; Mills and Allison 1995a, b). The morphology and composition of these deposits varies greatly depending on their age, topographic setting, and past and present depositional processes. These deposits are typically composites of several generations of debris flows reworked and incised by alluvial action. Individual fan-shaped deposits occur at outlets of first and second order drainages. Coalescing fans can form continuous apron-like deposits, along footslopes, and fill valley floors where topographically constrained (Fig. 9.5). These deposits collectively will be referred to here as debris deposits or debris fans. In North Carolina and Virginia, large debris deposits are often found in the Blue Ridge Mountains, but extend into

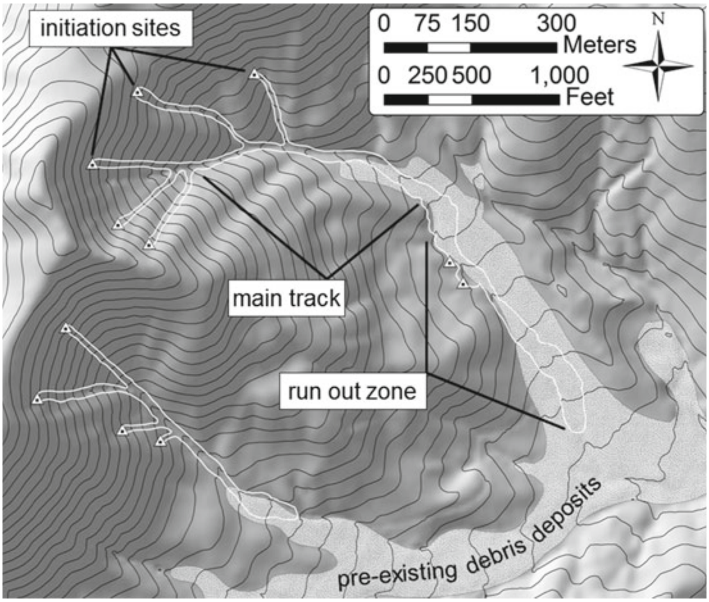

Fig. 9.5 Tracks of 1977 debris flows (*white outlines*) and pre-existing debris deposits (stippled polygons) in the Rocky Branch area, Bent Creek Experimental Forest, Pisgah National Forest, in Buncombe County North Carolina. Initiation sites (*triangles*), main track, and run out zone labels show typical components of a debris flow. The 1977 debris flows deposited material in areas underlain by pre-existing debris flow deposits. Topographic contours (*black lines*) and the shaded relief map are derived from a 6 m-pixel resolution LiDAR digital elevation model (DEM). Contour interval = 6.1 m (20 ft). Elevation ranges from 1,152 to 762 m, with lower elevations in the southeast portion of the map (Derived from Wooten et al. 2009b) (Location N in Fig. 9.3 and Table 9.1)

the adjoining Piedmont along footslopes of the BRE. These deposits also occur along the eastern border of the Ridge and Valley in Virginia.

Recent dating of a large, deeply weathered debris fan in the Big Levels 7.5-min quadrangle in the western Virginia Blue Ridge Mountains was completed using the cosmogenic $^{26}Al/^{10}Be$ burial decay method (Heller et al. 2014). Two samples determined the age of the fan to be early Miocene: sampling at 20 m below the land surface yielded an age of 7.94 ± 2.4 Mega-annum (one million years), while a higher fan layer 15 m below the surface yielded an age of 6.90 ± 1.7 Mega-annum. This age range is much older that those derived using radiocarbon dating on slope deposits exposed by a 1995 storm in Madison County, Virginia (Eaton et al. 2003a) and on debris fans in Nelson County, Virginia (Kochel and Johnson 1984). Eaton et al. (2003a) found that stratified slope deposits in Madison County were formed in the late Pleistocene (15.8–27.4 Kilo-annum, 1,000 years), while maximum ages for debris flow deposits were found to be >50 Kilo-annum. Kochel and Johnson (1984) dated basal units of debris fans in the Davis Creek area of Nelson County to the start of the Holocene (10.7 Kilo-annum).

In the North Carolina Blue Ridge Mountains, large, composite debris deposits are characterized by variation in relative fan-surface ages as reflected by physical differences (e.g., variation in soil matrix color, topographic position, and clast weathering rinds) indicating relative ages that range from Early Pleistocene to Holocene (Mills 1982; Mills and Allison 1995a). Mills and Allison (1995b) used paleomagnetism to determine a minimum relative age of early Pleistocene (78 Kilo-annum) for weathered debris deposits in Watauga County. Subsequently Mills and Grainger (2002) used cosmogenic $^{26}Al/^{10}Be$ to date a debris fan deposit on the slopes of Rich Mountain, also in Watauga County, as early Pleistocene (1.45 ± 0.17 Mega-annum). Late Holocene debris deposits are also present in the region. Radiocarbon dating of charcoal beneath a debris flow deposit at a site near the Nantahala River in Swain County, North Carolina, indicates the debris flow postdates 4,441–4,797 years before present (Leigh 2009; see also Leigh Chap. 8).

Older debris deposits can indicate areas that can be affected by modern debris flows. In the eastern Blue Ridge Mountains of Virginia heavy rainfall in 1969 and 1995 triggered debris flows on older debris fan material in Nelson County (Williams and Guy 1973; Kochel and Johnson 1984) and Madison County (Morgan et al. 1997; Eaton et al. 2003a), respectively. Field studies and mapping in Macon County in the North Carolina Blue Ridge Mountains determined that debris deposits of various ages cover about 4,500 ha or 3.3 % of the land area there (Wooten et al. 2006). These pre-existing debris deposits were identified at all of the 62 relatively recent debris-flow sites in Macon County, evidence that prior debris flow events had occurred at the same locations, in many cases multiple times (Wooten et al. 2008a). The common occurrence of modern debris flow deposition in areas with past debris flow deposits was also identified by landslide mapping in Watauga, Buncombe and Henderson Counties in the North Carolina Blue Ridge Mountains (Wooten et al. 2008b, 2009b, 2011). These studies found that modern debris flows typically affect areas where streams have incised into, or flow around the margins of older deposits. In relatively rare cases modern debris deposition has occurred on fan surfaces outside of stream channels (Fig. 9.5).

On the west slope of the Virginia Blue Ridge Mountains, debris fans tend to be larger, better developed, and more weathered than those along the eastern Blue Ridge front. These west-facing fans appear to be dominated by alluvial and fluvial processes, having more of the characteristics of a braided stream deposit (Kochel 1990; Heller et al. 2014). Debris flow activity tends to be confined to the upper-to-middle reaches of these fans and to active channels (Whittecar and Ryter 1992; Eaton et al. 2003a; Heller et al. 2014). In the western portion of Page County, no modern landslides (post-1950) were found within or along ancient debris fans originating from the western flank of the Blue Ridge Mountains (Witt and Heller 2013, 2014).

9.3 Temporal Frequency and Magnitude of Debris Flow Events Related to Regional and Localized Rainfall Events

9.3.1 Rainfall Scenarios

Building on the work of Scott (1972), Clark (1987), Witt (2005), and Wieczorek et al. (2009), we have compiled existing data and reported new data for a total of 31 landslide events listed in Table 9.1, and shown graphically in Fig. 9.6. Figure 9.3 shows the general locations for the major events. In summary, tropical cyclones and an extratropical cyclone tracked over the SAH, setting off tens to thousands of debris flows in multi-county areas in North Carolina in 1916, 1940, 1977 and 2004, and in Virginia and West Virginia in 1969 and 1985. These cyclonic storms have resulted in the most widespread and numerous flooding and landslide events in the SAH. From 1916 to 2004, 13 cyclonic storms have impacted the SAH, on average, approximately every 7 years. Five of these storms (Agnes, Opal, Isabel, Cindy and Ernesto) generated relatively few landslides in the region. Although no landslides were reported for the July 7, 1916 tropical cyclone, it was significant because it created high antecedent moisture prior to a July 15–16, 1916 tropical cyclone, which was the storm of record for the French Broad watershed of North Carolina.

The short duration between Hurricanes Frances and Ivan in September 2004 was significant in that it established a pattern of back-to-back major storms within 6–20 days of each other causing flooding and triggering debris flows in Blue Ridge Mountains of North Carolina. Three such scenarios have occurred over an 88-year period from 1916 to 2004 (Witt 2005). Work by the US Geological Survey (1949), Tennessee Valley Authority (1964), Scott (1972), and Witt (2005) established that similar weather patterns had triggered regional flooding and debris flows in July of 1916 and August 1940. Following Frances and Ivan, the average frequency of such weather scenarios in western North Carolina is 29 years.

In addition to tropical cyclones, rainfall associated with low pressure systems and localized storms, especially when coincident with periods of above normal rainfall, have triggered from a few to hundreds of landslides in each of the 18 events

Table 9.1 Selected examples of landslide (mainly debris flow) events induced by rainfall in the SAH, and other selected locations in the Central Hardwood Region. Letters in the first column correspond with locations shown in Fig. 9.3. *TC* tropical cyclone, *ETC* extratropical cyclone, *EANR* period of extended of above normal rainfall. Number in parentheses in 'Total Area of Tracks' column represents number of landslides used to determine track area where less than the total number of reported landslides. Other abbreviations used in the table: *NCGS* NC Geological Survey, *TVA* Tennessee Valley Authority, *USDA* US Department of Agriculture, *USGS* US Geological Survey

Lettered location Fig. 9.3	Type of rainfall event	Rainfall total (mm)	Time of most intense rainfall	Landslide dates mm/day/year	Landslides reported	Total track area (ha)	General location ecoregion	Reported landslide locations	Notes – References
–	Storm	165	?	6/15/1876				Macon, Jackson Co., NC	Clingman 1877; Witt 2005
A	Storm	228	?	5/21-22/1901	>17		Blue Ridge Mountains, Piedmont	Buncombe, Henderson, Mitchell, McDowell Co., NC	Holmes 1917; Myers 1902; Scott 1972; USDA 1902; Witt 2005
–	TC (unnamed)		1 day	7/9/1916 (rainfall)	0		Blue Ridge Mountains	Western NC	Henry 1916; Scott 1972
B	TC (unnamed)	564	24 h	7/15-16/1916	Many, >45		Blue Ridge Mountains	Western NC	Bell 1916; Scott 1972; Witt 2005
C	Storm	584	24 h	8/13/1916	1	122.1	Blue Ridge Mountains	Toxaway River, Transylvania Co., NC	Dam failure – debris flow; Wooten et al. 2003a, b
D	Thunderstorm	380	2 days	6/13/1924	~100		Blue Ridge Mountains	Carter Co., TN	Slides from 8/13-14/1940 storm also here (Hack and Goodlett 1960); Scott, 1972
E	Cloudburst	305	4 h	8/4-5/1938	>100		Blue Ridge Mountains	Webb Mountain, TN (GSMNP)	Within concentrated debris flow area in Southworth et al. 2012; Scott 1972
F	Thunderstorm	508	2 days	7/4-5/1939	4		Western Allegheny Plateau	Wolfe, Breathitt Co., KY	Total number of landslides not reported; Schrader, 1945

G	TC (unnamed)	254	6 h	8/13-14/1940	2,120	368	Blue Ridge Mountains	Watauga, Ashe, Allegheny, Avery, Wilkes, Caldwell Co., NC; Unicoi County, TN	USGS 1949; Wieczorek et al. 2004; Witt et al. 2007a; Wooten et al. 2008b
H	Storm	330	2 days	8/28-31/1940	>200			Macon, Jackson (location 6) and Haywood Counties, NC	TVA 1940; USGS 1949; NCGS landslide geodatabase
–	Storm	381	24 h	Winter 1942	Numerous		Blue Ridge Mountains	Watauga Co., NC	Gryta and Bartholomew 1983
I	Cloudburst	400	1 day	6/17-18/1949	466		Ridge and Valley	Augusta and Rockingham Co., VA; Highland County, WV	Hack and Goodlett 1960
E	Cloudburst	100	1 h	9/1/1951			Blue Ridge Mountains	Mt. LeConte, TN (GSMNP)	Within concentrated debris flow area in Southworth et al. 2012; Bogucki 1976; Clark et al. 1987
J	TC Camille	635	8 h	8/19-20/1969 9/5-6/1969	1,584		Central Appalachians	Spring Creek, Greenbrier County, WV	Schneider 1973
K	TC Camille	710–800	8 h	8/19-20/1969	3,793	1,200	Blue Ridge Mountains, Piedmont	Albemarle, Amherst, Nelson Co., VA	Williams and Guy 1971, 1973; Morgan et al 1999a
L	TC Agnes	203	2 days	6/20-21/1972	?		Blue Ridge Mountains	Mt. Mitchell area (location L), Waterrock Knob, Haywood Co., NC.	Bailey et al. 1975; Clark 1987
H, N	Thunderstorms	196	1 h	5/26-28/1973	Many, 8 documented		Blue Ridge Mountains	Tuckasegee watershed, Jackson Co., NC (location H), Pisgah NF, NC (location M)	Young 1973; Zeedyk 1973; NCGS landslide geodatabase

(continued)

Table 9.1 (continued)

Lettered location Fig. 9.3	Type of rainfall event	Rainfall total (mm)	Time of most intense rainfall	Landslide dates mm/day/year	Landslides reported	Total track area (ha)	General location ecoregion	Reported landslide locations	Notes – References
M	Thunderstorm or Cloudburst	300	9 h	7/19-20/1977	Several hundred		Central Appalachians	Johnstown area, western PA	Pomeroy, 1980
L	ETC (unnamed)	300	2 days	11/5-7/1977	13	25.2	Blue Ridge Mountains	Mt. Mitchell, Black Mtns., Yancey Co., NC	Eschner and Patrick 1982; Wooten et al. this chapter
N	ETC (unnamed)	150	2 days	11/5-7/1977	83	32.8	Blue Ridge Mountains	Pisgah NF, Buncombe, Henderson Co., NC.	Neary and Swift 1987; Pomeroy 1991; Otteman 2001; Wooten et al. 2009b, 2011
O	Thunderstorm	115	14 days	8/14/1980	62		Western Allegheny Plateau	East Brady along Allegeny River, PA	Pomeroy 1984
P	TC Juan	350	3 days	11/3-5/1985	3,000		Ridge and Valley	Pendleton Co., WV; Highland Co., VA	Jacobson, 1993
–	Storm	60	1 day	12/23/1990	4	2.57	Blue Rige Mountains	Nantahala NF in Swain, Cherokee, Clay Co., NC	Wooten et al. 2007
Q	Storm	770	14 h	6/27/1995	629	600	Blue Rige Mountains	Madison Co., VA	Eaton et al. 2004; Morgan et al. 1997, 1999b; Wieczorek et al. 1995, 2000
R	Storm	635	1 day	6/27/1995	72	49.8	Blue Ridge Mountains	Albemarle Co., VA	Morgan and Wieczorek 1996
S	TC Opal	274	1 h	10/3-5/1995	2	1.4	Blue Ridge Mountains	Poplar Cove, Macon Co., NC	Wooten et al. 2008a
T	Storm	187	1 day	5/5-7/2003	10	4.5	Blue Ridge Mountains	Swain Co., NC	Wooten and Latham 2004

U	TC Isabel	513	1 day	9/18-19/2003	6		Ridge and Valley	Shennandoah Valley, VA	Wieczorek et al. 2004
V	TC Frances	599	2 days	9/6-8/2004	400+	81.3 (184)	Blue Ridge Mountains	Western NC	Reported landslide total for Frances and Ivan; Collins 2008; Wooten et al. 2008a; Wieczorek et al. 2009; Collins 2014; Roth 2015
	TC Ivan	432	2 days	9/16-17/2004					
W	TC Cindy	110	2 days	7/7/2005	1	0.05	Blue Ridge Mountains	Buncombe Co., NC	Rockslide; Wooten et al. 2007
X	TC Ernesto	168	12 h	8/31/2006	1	1.1	Blue Ridge Mountains	Haywood Co., NC	Wooten and Latham 2006
–	Storm	152	24 h	1/7/2009	2	1.5	Blue Ridge Mountains	Haywood Co., NC	Embankment failures-debris flows; Wooten et al. 2009a
–	Storm	35	4 h	2/5/2010	1	2.6	Blue Ridge Mountains	Maggie Valley, Haywood Co., NC	Witt et al. 2012; Wooten et al. this chapter
Y	Thunderstorm	125	4 h	7/14-15/2011	21	12.9	Blue Ridge Mountains	Balsam Mountain, NC (GSMNP)	Lee et al. 2011; Miller et al. 2012; Wooten et al. this chapter
Point locations	Storm (within EANR period)	388	2 days	1/14-17/2013	Numerous 268 confirmed	5.2 (18)	Blue Ridge Mountains	Western NC	Gibbs 2013; Jennifer Bauer personal comm.; Wooten et al. 2014, and this chapter
Point locations	Storm (within EANR period)	168	2 days	5/4-6/2013	Numerous 50 confirmed	1.3 (8)	Blue Ridge Mountains	Western NC	Gibbs 2013; Wooten et al. this chapter
Point locations	Storm (within EANR period)	250	2 days	7/2-9/2013	Numerous 9 confirmed	5.0 (7)	Blue Ridge Mountains	Western NC	Wooten et al. 2014; and this chapter

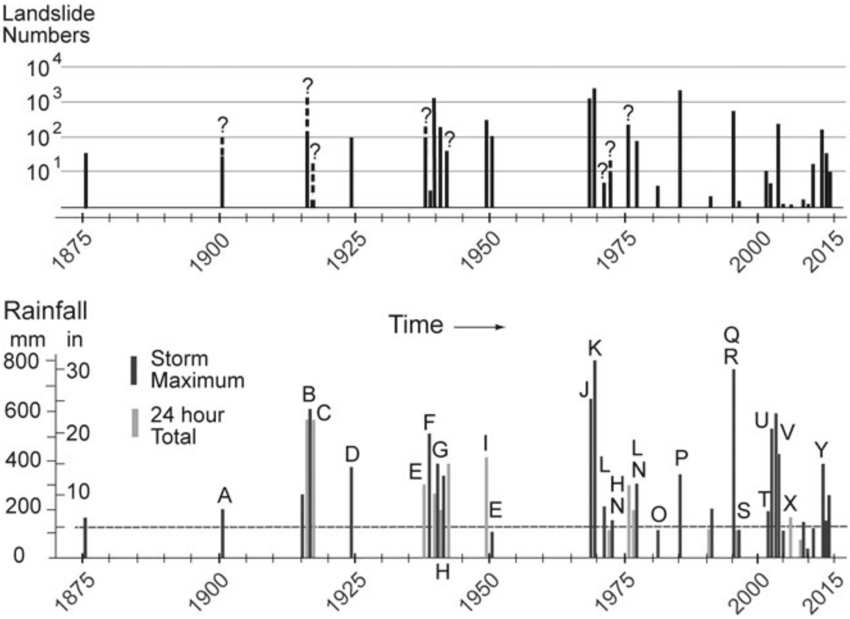

Fig. 9.6 Chart showing the landslide numbers and rainfall associated with tropical cyclones and other storms that triggered landslides in the SAH and other selected locations in the CHR. The 24-h rainfall threshold of 125 mm for triggering debris flows from Eschner and Patrick (1982) shown by a *dashed line*. Single letter in parentheses corresponds with locations in Fig. 9.3, and Table 9.1 (Adapted and expanded from Wooten et al. 2007)

documented for the SAH in Table 9.1. Six events in this category each generated 100 or more reported landslides. The June 27, 1995 storm event in Madison County produced 629 landslides (mainly debris flows) making it the largest event in this category. During a period of above normal rainfall throughout western North Carolina from January to August 2013, four storms collectively triggered more than 300 landslides. Landslides from three of these storms are documented here. Undoubtedly many other landslide events of this nature have occurred throughout the SAH that are not reported here (e.g., Crawford 2014) and not documented in the literature.

9.3.2 *Characterization of Triggering Rainfall*

Total storm rainfall is an important factor in debris flow initiation. As can be seen from Table 9.1 and Fig. 9.6, the majority of events fall within 125–250 mm per day precipitation thresholds presented by Eschner and Patrick (1982) needed to generate debris flows on forested slopes in the SAH. Fuhrmann et al. (2008) found that landslide activity in western North Carolina is strongly related to antecedent precipitation over a 90-day period. Other studies in the SAH of North Carolina and

Virginia have demonstrated that rainfall rate (intensity) and duration is a critical factor in debris flow initiation. Areas of high-intensity rainfall promote the development of debris flows and slides as evident in the 1969 Nelson County storm (Williams and Guy 1973) and the 1995 Madison County storm (Wieczorek et al. 2000). Neary and Swift (1987) concluded that rainfall rates on the order of 90–100 mm per hour (188 mm storm total) initiated debris flows in the Bent Creek area near Asheville, North Carolina, during a November 3–5, 1977 storm, but they do not report specific durations associated with these rates. Wieczorek et al. (2000, 2009) present a rainfall intensity-duration threshold curve for the Central Blue Ridge Mountains of Virginia that ranges from approximately 90 mm per hour for 1 h, to 10 mm per hour for 24 h. Wieczorek et al.(2004) reported that 254 mm of rain within 6 h (42 mm per hour average) triggered over 700 debris flows during the August 13–14, 1940 storm in the Deep Gap area of Watauga County, North Carolina, a value that plots above the Virginia threshold curve. An average rate of 25 mm per hour for the 4.65 h period of peak cumulative rainfall (5.5 mm per hour for the 33.2 h storm total) during Ivan preceded the Peeks Creek and Wayah debris flows in Macon County, North Carolina (Wooten et al. 2008a). This value falls below the Virginia curve threshold; however, the North Carolina debris flows occurred with high antecedent moisture conditions from the passage of the remnants of Hurricane Frances the previous week. An average rainfall rate of 57 mm per hour for 2 h generated the 2011 Balsam Mountain debris flows in the GSMNP (Miller et al. 2012; Tao and Barros 2014), a value that plots below the Virginia threshold curve.

In two North Carolina cases, less rainfall was required to generate debris flows on slopes with evidence of prior instability related to human activity, when compared to debris flows generated on unmodified, forested slopes as described above (Wooten et al. 2009a, 2010b). In 2009, peak rainfall of ~6.4 mm per hour for 1.2 h (3.3 mm per hour for 23.5 h storm total) triggered a debris flow in fill material that destroyed a home. In 2010, peak rainfall of ~3.4 mm per hour for 2 h (4.4 mm per hour for 13.3 h rain total on snow) contributed to a retaining wall failure that mobilized into a debris flow which damaged three homes (Witt et al. 2012). This limited number of cases indicates that the destabilizing effects of human activity likely decreases the requisite rainfall needed to initiate debris flows on some modified slopes in contrast with rainfall amounts needed to generate debris flows on forested slopes not modified by human activity.

9.4 Summary of Selected Major Historical Events

9.4.1 July 1916: North Carolina

The storm of record for the French Broad watershed at Asheville occurred on July 15–16, 1916 when a hurricane made landfall near Charleston, South Carolina and moved northwest over western North Carolina causing extensive flooding and triggering numerous landslides (Bell 1916; Holmes 1917; Scott 1972; Witt 2005).

The storm set the 24-h rainfall record for North Carolina of 564 mm at Altapass on the crest of the BRE in Mitchell County. Preceding the mid-July storm, a tropical cyclone produced 100–250 mm of rain over western North Carolina on July 8 and 9, 1916 (Henry 1916; Scott 1972). Although no landslides were reported for this early July storm, it created high antecedent moisture conditions in advance of the July 15–16, 1916 storm. While only 45 landslides were reported for this storm, they occurred over a widespread extent. Landslides were reported in a 200 km-long corridor of the Blue Ridge Mountains and Piedmont from Brevard in Transylvania County, northeast to Basin Creek in Alleghany and Wilkes Counties (in what is now Doughton Park) and were the direct cause of in 22 fatalities. Devastated by fatalities and destruction from flooding and landslides, the Basin Creek community never recovered.

9.4.2 August 13–17, 1940: North Carolina

During August 10–17, 1940, the remnants of a landfalling hurricane caused flooding throughout much of the southeastern USA (US Geological Survey 1949). Rainfall, totaling 340 mm in Watauga and adjacent counties in the North Carolina Blue Ridge Mountains, triggered numerous debris flows during August 13–14, 1940 (Fig. 9.7), during which time as much as 254 mm of rain may have fallen within a 6 h period (Wieczorek et al. 2004). Landslides caused 14 deaths, damaged or destroyed 32 structures in Watauga County, and destroyed transportation networks there and in neighboring counties (Witt et al. 2007a). Over 700 debris flows triggered by this storm were identified in the Deep Gap area of southeastern Watauga County by Wieczorek et al. (2004). Upon completion of the landslide hazard maps for Watauga County, 2,120 landslides, mainly debris flows and debris slides, attributed to this storm were identified and mapped (Wooten et al. 2008b). Of the 2,120 landslides, 2,099 occurred throughout Watauga County, but were generally concentrated in the Deep Gap area (Fig. 9.7) and in a highly dissected, mountainous area in the northwest part of the county. The remaining 21 debris flows occurred in adjacent portions of Wilkes and Ashe Counties mainly along the BRE. Given the magnitude of the debris flow event in Watauga County, and the widespread nature of the heavy rainfall along other nearby areas of the BRE, we speculate that this storm likely triggered many more debris flows in northwestern North Carolina.

Debris flows ranged widely in size from 2 m wide and 12–15 m long, upwards to 60–90 m wide and 400–800 m long. The largest debris flows were in an area of 600 m of relief in the Deep Gap area of the BRE, where the longest track measured from 1940 aerial photography was nearly 2,100 m long (Witt et al. 2008). Within Watauga County, the total area of mapped debris flow tracks was 368 ha in mainly first order and some second order drainages (Witt et al. 2008; Wooten et al 2008b). Although 368 ha is only about 0.5 % of the 819.5 km^2 (81,950 ha) area of Watauga County, it is a significant component of the riparian area. Many of the 1940 debris flows deposited sediment in footslope areas where pre-existing debris deposits were mapped (Wooten et al. 2008b). Examination of the locations of the 1940 debris flow

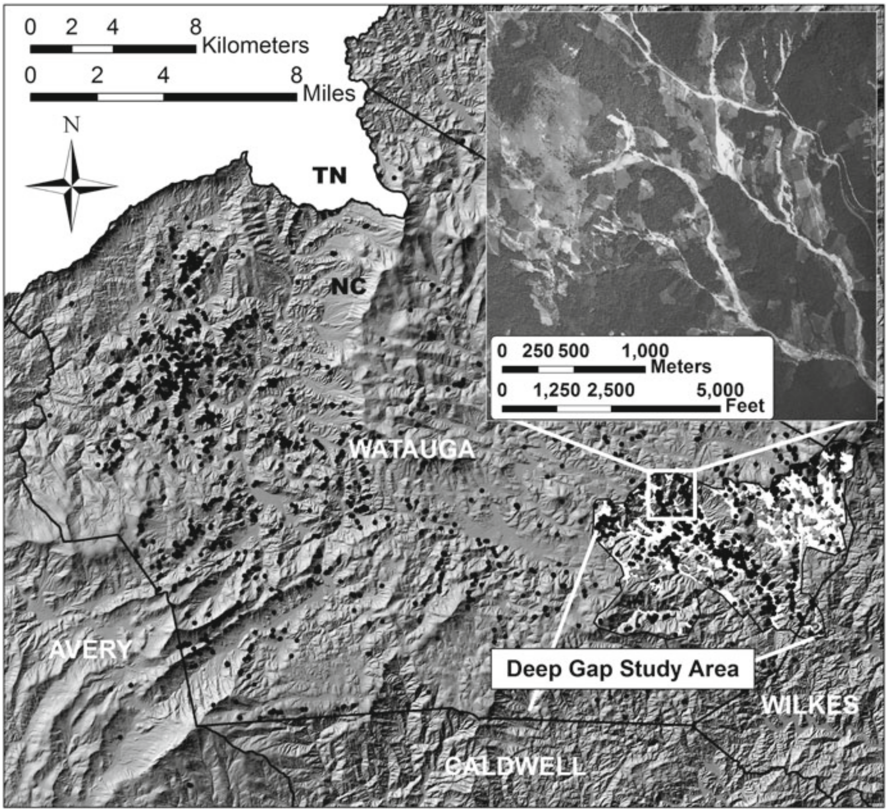

Fig. 9.7 Shaded relief map of Watauga County and the Deep Gap study area (see also Sect. 9.8), *black dots* are point locations for the over 2,100 landslide (mainly debris flow) initiation sites in Watauga and adjacent Wilkes Counties triggered by the August 13–14, 1940 tropical cyclone (from Wooten et al. 2008b). Inset image *upper right* shows debris flow tracks visible as linear high reflectance areas on September 29, 1940 aerial photography. Unforested slopes in the Deep Gap study area are shown in white; remaining slopes within the Deep Gap study area are forested. Shaded relief map derived from a 6 m-pixel resolution LiDAR DEM (Location G in Fig. 9.3 and Table 9.1)

tracks with 2005 orthophotography revealed two findings with respect to current land use patterns and the built environment: (1) since 1940, 136 structures, mainly residences, have been built in the tracks of 1940 debris flows; and (2) 521 tracks of 1940 debris flows cross existing roads (Witt et al. 2007a).

Additional mapping identified another 154 landslides of various types that had occurred in Watauga County since 1940 (Wooten et al. 2008b). Nearly 60 of these landslides were triggered by the remnants of Hurricanes Frances and Ivan in September 2004. Fifteen of the September 2004 debris flow sites were located at, or very near to 1940 initiation sites. Although some of the reactivated sites had been modified by human activity (e.g., fills) since 1940, this finding indicates that the recurrence interval for some landslide prone sites could be on the order of decades, rather than on millennial scales as found in the Virginia Blue Ridge Mountains (Kochel 1987; Eaton et al. 2003a).

9.4.3 August 28–30, 1940: North Carolina

A second major storm struck western North Carolina in August 1940. This storm, a low-pressure system, occurred during August 28–31, and affected mainly the Little Tennessee watershed of Jackson, Macon and Swain Counties, and the French Broad watershed in Haywood County (Tennessee Valley Authority 1940; US Geological Survey 1949; Witt 2005). The Tennessee Valley Authority (Tennessee Valley Authority 1940) reported the heaviest rainfall in the headwaters of the Tuckasegee River in Jackson County where 241–305 mm fell over a 24 h period. The high intensity rainfall over a relatively small area of 388 km^2 triggered more than 200 debris flows which claimed six lives in Jackson and Haywood Counties (Tennessee Valley Authority 1940). High antecedent moisture conditions from the earlier mid-August 1940 likely contributed to the severity of the flooding and debris flows near the center of the late August storm.

9.4.4 August 19–20, 1969 Camille: Virginia, West Virginia

The landslides and flooding associated with the remnants of Hurricane Camille on the night of August 19–20, 1969, was one of the worst natural disasters experienced in Virginia. Approximately 710 mm of rain fell in a span of roughly 8 h, mostly in rural, forested Nelson County in the Blue Ridge Mountains of central Virginia (Williams and Guy 1973). Debris flows and slides permanently altered the landscape and created deep scars in mountainsides that are still visible on aerial photography today. The storm caused the deaths of over 150 people, the majority of whom were killed by blunt force impact related directly to landslides (Simpson and Simpson 1970).

Based on mapping by Morgan et al. (1999a) and Bartholomew (1977), over 3,700 landslides (mostly debris flows and slides) have been identified as occurring during the August 1969 storm. The greatest concentration of debris flows occurred in Nelson County (Figs. 9.8 and 9.9), covering approximately 40 % of the county. Slides were also identified in northern Amherst County and southern Albemarle County. In total, approximately 1,200 ha were damaged by landslide scarring and deposition. Most of this area is comprised of agricultural land and temperate broadleaf and mixed forests with varieties of oak, poplar, and ash (Williams and Guy 1971). The total area stated here is probably a low estimate, as the most recent mapping of these debris flows occurred in 1999 at a scale of 1:24,000 (Morgan et al.

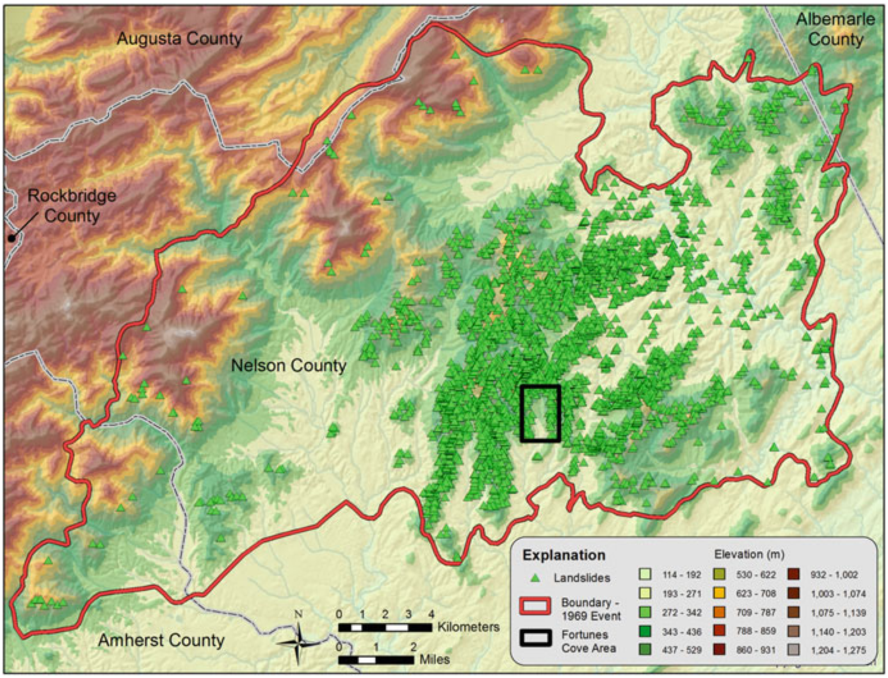

Fig. 9.8 Landslide (mainly debris flow) initiation sites triggered by Hurricane Camille from August 19–20, 1969 in Nelson County Virginia. Camille triggered over 3,700 landslides in this area, impacting 1,200 ha. Map base is a shaded relief map, color-coded by elevation derived from a 30 m digital elevation model. *Black outline* shows the location of the Fortunes Cove area in Fig. 9.9 (Location K in Fig. 9.3 and Table 9.1)

1999a). Re-evaluation of aerial photography, coupled with LiDAR mapping when it becomes available, will likely increase the total amount of land area disturbed.

The greatest number of debris flows occurred along Davis Creek where nearly every first- and second-order stream, and many mountain coves, failed. Along this drainage, over 400 coalescing debris flows and slides destroyed 290 ha. Of the 25 houses along this drainage, 23 were destroyed (Williams and Guy 1971). Along Davis Creek and other heavily damaged drainages, headscarps and scour in the upper portion of the debris flow track frequently left the bedrock exposed. At the headscarps, vegetative cover, including large trees, was completely removed and boulders up to 3 m in length were transported (Williams and Guy 1973). Further downstream, excessive stream discharge scoured even small drainages deeply. The amount of sediment transport and denudation from hillsides and drainages in this area was enormous for a single event. Williams and Guy (1973) studied three watersheds to the south and west of Davis Creek and extrapolated the average denudation for these areas to be approximately 360–500 mm. In comparison, average denudation rates in the Blue Ridge Mountains are estimated to be 150–360 mm per 1,000 years (Judson and Ritter 1964).

Fig. 9.9 Outlines of numerous debris flow tracks that occurred during Camille from August 19 to 20, 1969 and affected nearly every drainage in the Fortunes Cove area of Nelson County Virginia. The outlines are superimposed onto 2009 orthophotography illustrating the progress of vegetative recovery along the debris flow tracks since 1969 (Location K in Fig. 9.3 and Table 9.1)

Forest recovery at the debris flow sites in Nelson County varies depending on the morphology of the headscarp scar (Fig. 9.9). Where bedrock was exposed along debris flow initiation sites, forest recovery has been exceedingly slow and scars are still visible on the landscape today. Until colluvium fills in these areas, vegetation will not return. Where debris flows occurred within colluvium, forest regrowth occurred quickly and may be fully reestablished today (Kochel 1987).

Schneider (1973) reported 1,584 landslides during Camille in the central Appalachians of Greenbrier County, West Virginia. When combined with the 3,793 landslides documented in Virginia, a total of 5,377 landslides resulted from Camille, making it the storm that triggered the greatest number of documented landslides in the SAH.

9.4.5 November 5–7, 1977: North Carolina

During November 2–7, 1977 an extratropical cyclone that originated in the Gulf of Mexico passed over western North Carolina causing extensive flooding and triggering debris flows over a multi-county region (Neary and Swift 1987). Although the total storm rainfall in the area was 150 mm, intense convective downpours on the night of November 5–6, 1977 set off debris flows in the Bent Creek Experimental Forest within the Pisgah National Forest near Asheville in southwestern Buncombe County (Neary and Swift 1987) (Figs. 9.5, 9.10, and 9.11). Pomeroy (1991) mapped 72 debris flows in the Bent Creek area, and Otteman (2001) incorporated his mapping into GIS as part of a study of the area's debris flow susceptibility. Landslide mapping in Buncombe County (Wooten et al. 2009b) and adjacent Henderson County (Wooten et al. 2011) identified 11 additional debris flows attributed to this event bringing the total number of debris flows from the 1977 storm in this area to 83.

Rainfall from the 1977 storm also triggered debris flows on the slopes of Mount Mitchell and the Black Mountains in the Pisgah National Forest (Eschner and Patrick 1982). Total rainfall from the storm was 300 mm in the vicinity of Mount Mitchell (Neary and Swift 1987) which at elevation 2,037 m is the highest peak in eastern North America. The upper tracks from these debris flows are still visible on the southeast facing slopes of Mt. Mitchell and the Black Mountains (Fig. 9.12). Silver (2003) relates a personal account of a resident who witnessed one of these debris flows along Shuford Creek that originated on Celo Knob. The upper portion of the track of the Shuford Creek debris flow is visible in 2013 aerial photography. An evaluation of several vintages of aerial photography dating from 1993 to 2013 reveal at least three episodes of debris flows occurring on the southeast-facing

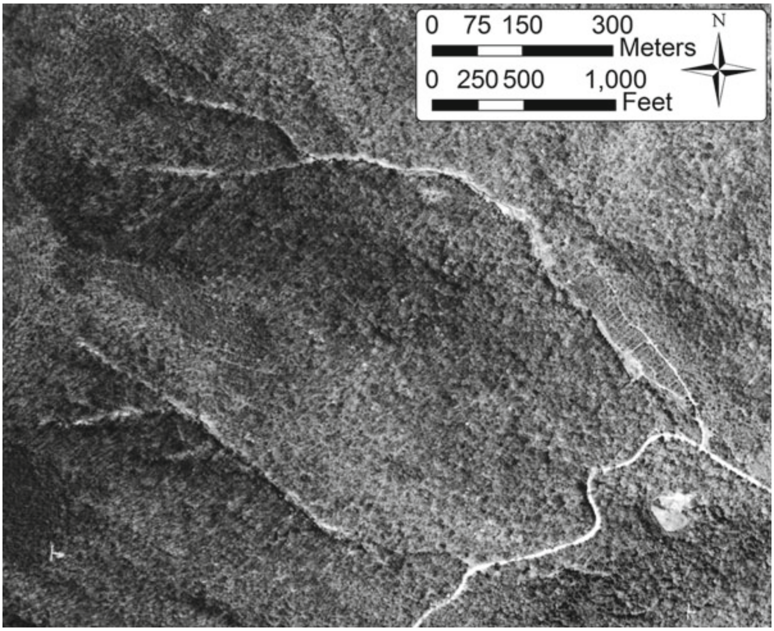

Fig. 9.10 Sparsely vegetated tracks of 1977 debris flows visible in 1983 aerial photography of the Rocky Branch area, Bent Creek Experimental Forest, Pisgah National Forest, in Buncombe County North Carolina. Elevation ranges from 1,152 to 762 m, with lower elevations in the southeast portion of the map. Same view as Fig. 9.5 (Location N in Fig. 9.3 and Table 9.1)

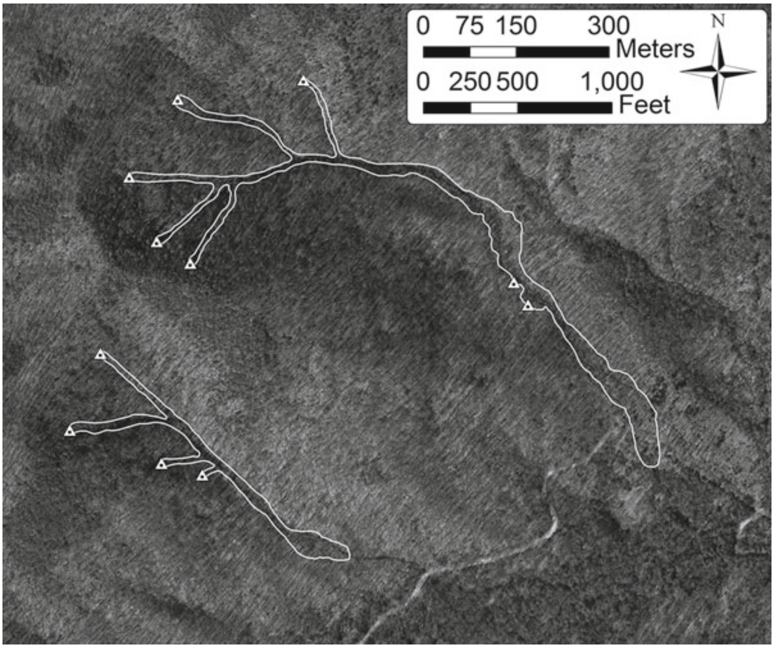

Fig. 9.11 Outlines of tracks of 1977 debris flows visible in 2010 orthophotography of the Rocky Branch area, Bent Creek Experimental Forest, Pisgah National Forest, in Buncombe County North Carolina Debris flow initiation sites shown by triangles (From Wooten et al. 2009b). Vegetative recovery has progressed in the tracks since 1977, and since 1983 as visible in Fig. 9.10. Elevation ranges from 1,152 to 762 m, with lower elevations in the southeast portion of the map. Same view as Figs. 9.5 and 9.10 (Location N in Fig. 9.3 and Table 9.1)

slopes of Mount Mitchell and the Black Mountains. These flows appear to correspond with the occurrence of four separate tropical cyclones in 1972, 1977, 1994 or 1995, and 2004. Clark (1987) reported debris flows during a hurricane in June of 1972 (Agnes) in the area of Mount Mitchell, although the exact location was not specified. As many as 13 of the debris flow tracks are attributable to the 1977 event. Three tracks may correspond with the passage of tropical cyclone Beryl in 1994 or Opal in 1995, and one track probably corresponds with the remnants of Hurricanes Frances and Ivan in September 2004.

The total area of the 83 debris flow tracks for the November 1977 event for the Bent Creek area is 32.8 ha. The 13 tracks on Mount Mitchell and the Black Mountains affected 25.2 ha resulting in a total of 58 ha for the November 1977 event. As in other study areas, the 1977 and 2004 debris flows in the Bent Creek area deposited sediment in areas of pre-existing debris deposits. Neary et al. (1986) point out that although debris avalanching (flows) are destructive events and are major contributors to long term erosion rates, they lead to formation of some of the more productive forest soils. Although the tracks of the 1977 debris flows are still discernable in the Bent Creek area where maximum elevations are on the order of

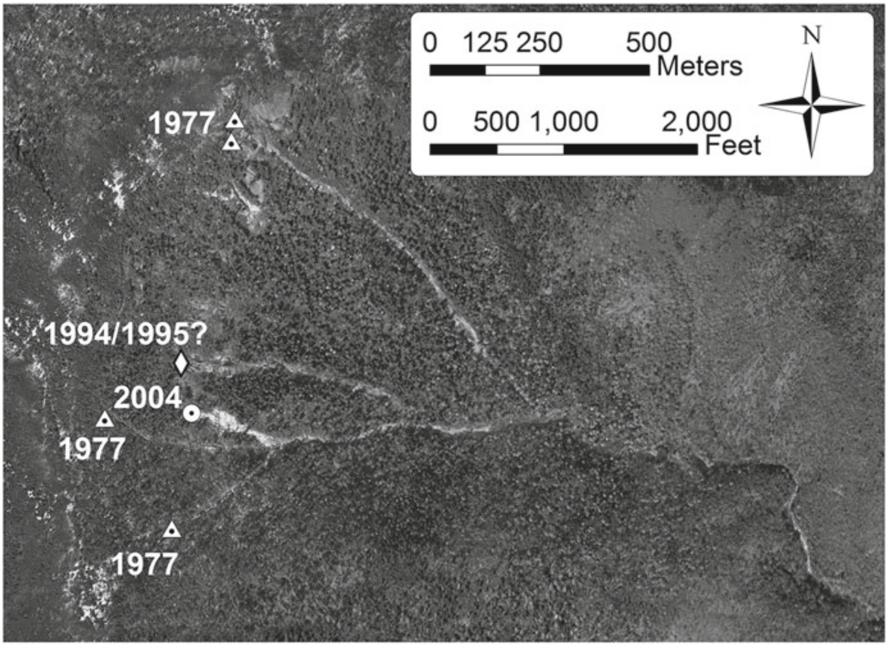

Fig. 9.12 Sparsely vegetated upper portions of tracks from three generations of debris flows in the Black Mountains near Mount Mitchell, North Carolina shown on 2010 orthophotography (initiation sites: *1977 = triangles*, *1994/1995? = diamond*, *2004 = circle*). Debris flow recurrence at steep, high elevation sites can be on decadal time scales; whereas vegetative recovery can be on decadal to centennial time scales. Downslope direction is from west (elev. 2,005 m) to east (elev. 1,260 m) (Location L on Fig. 9.3)

1,150 m; the tracks of 1977 debris flows are more readily visible on the upper slopes of Mount Mitchell and the Black Mountains were elevations range from 2,037 to 1,500 m.

9.4.6 June 27, 1995: Madison County and Albemarle County Virginia

On June 27, 1995, a series of severe rainstorms struck the high relief areas of the Blue Ridge Mountains in central Virginia. Approximately 630–770 mm of rain fell over a period of 16 h causing severe flooding and debris flows and slides in rural Madison County in northwestern Virginia (Fig. 9.13) (Morgan et al. 1997). Flooding and landslides destroyed or damaged 1,700–2,000 residential buildings; property damage was estimated to be $112 million. One fatality was also attributed to a debris flow (Wieczorek et al. 1995).

Landslides related to the June 1995 storm were originally mapped by Morgan et al. (1999b). To improve the inventory of debris flows and tracks for the Madison

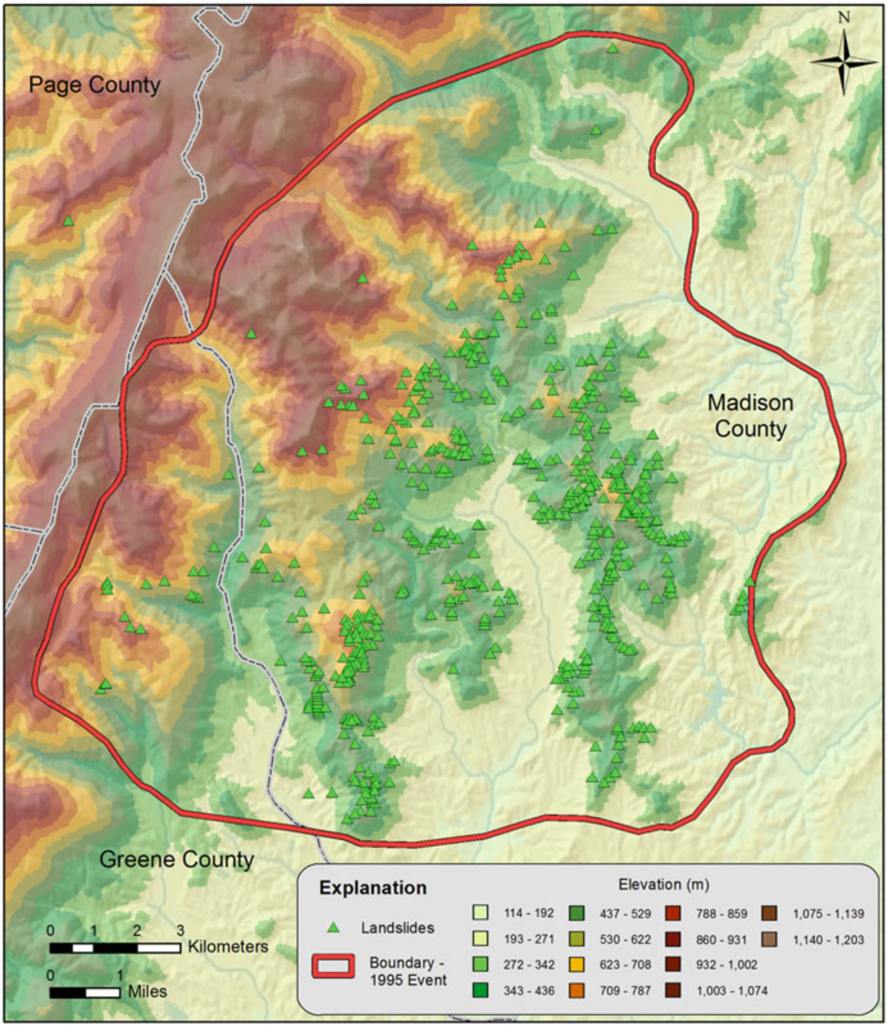

Fig. 9.13 Point locations for 629 landslide (mainly debris flow) sites triggered by the June 27, 1995 storm in Madison County Virginia. Debris flows inundated approximately 600 ha of land here. Map base is a shaded relief map, color-coded by elevation derived from a 30 m digital elevation model (Landslide locations from Morgan and Wieczorek (1996)) (Location Q on Fig. 9.3 and Table 9.1)

County area, we digitized the Morgan et al. (1999b) mapping and identified additional debris flows using 1998 infrared photography and 2002 orthophotography. Based on this work, a total of 629 landslide headscarps or initiation sites were found in both Madison County and northern Greene County occupying an area of about 240 km^2 (24,000 ha) Approximately 600 ha of land were inundated by debris flows and slides.

The largest debris flow occurred along Kinsey Run which damaged a total of 43 ha and contains 29 individual headscarps from multiple coalescing debris flows. The volume of deposited debris attributed to the Kinsey Run debris flow was estimated to be 570,000 m^3 (Mazza and Wieczorek 1997). Much like in the 1969 Nelson County storm, the upper portions of the debris flows exposed bedrock and denuded hillsides of soil, causing significant sediment transport during a single catastrophic event. Eaton et al. (2003a) estimated that the average basin-denudation rates for the upland areas in Madison County were approximately 330 mm during the storm, accounting for 27–65 % of the long-term denudation that would have occurred in 2,500 years.

Numerous debris flows stripped vegetation from the hillsides, sometimes along the entire length of larger debris flows. The rapidly moving flows had sufficient force to snap meter-wide trees at their base (Wieczorek et al. 2000). This vegetative material added significantly to the volume of debris, causing log jams and backups along paths (Wieczorek et al. 2000). The recovery rate of various plant species along the Kinsey Run debris flow was studied and it was found that pioneer species like black locust (*Robinia pseudoacacia)* and (non-native) tree-of-heaven (*Ailanthus altissima*) were the first woody plant types to reestablish and compete with other native species (Eaton and Reynolds 2002).

Landslides were also reported later in the evening on June 27 about 45 km southwest of Madison County along the North Fork of the Moormans River within Shenandoah National Park in western Albemarle County. While no official storm totals exist, eye-witness accounts indicate that rainfall totals varied from 279 to 635 mm (Morgan and Wieczorek 1996; Eaton et al. 2003b). Mapping and field work completed by Morgan and Wieczorek (1996) identified 72 initiation sites of debris flows and slides, many of which were hidden by thick forest cover. Additional interpretation of the area using 1997 infrared photography and 2002 orthophotography allowed for more detailed mapping of individual tracks. Within the 13 km^2 (1,300 ha) watershed, we calculated that a nearly 50 ha area was inundated by debris flows, many of which coalesced into Moormans River. Debris surged downstream into the Sugar Hollow Reservoir, the main water source for Charlottesville, reducing its holding capacity by 15 % (Eaton et al. 2003b).

9.4.7 September 2004 Frances and Ivan: North Carolina

In September 2004, intense rainfall from the remnants of Hurricanes Frances (Sept. 7–8) and Ivan (Sept. 16–17) triggered at least 400 landslides that caused five deaths, destroyed at least 27 residential buildings, and disrupted transportation corridors throughout western North Carolina (Collins 2008, 2014; Witt 2005; Wooten et al. 2005, 2007). Nineteen western North Carolina counties were federally declared disaster areas as a result of flooding and landslide damage from the storms. Known landslide events occurred in a 200 km-long swath in the Blue Ridge Mountains from Macon County northeast to Watauga County North Carolina. Major damage

Fig. 9.14 Large woody debris and boulder deposits along the track the Bear Drive Creek fill failure-debris flow that occurred during Hurricane Frances, September 6–8, 2004. The debris flow initiated as a fill failure on the Blue Ridge Parkway and scoured 8.61 ha along a 2.44 km-long track. Location is in the Pisgah National Forest near Curtis Creek approximately 2 km downslope from the debris flow initiation site. Direction of flow to the right. Geologist at bottom right for scale (November 17, 2004 NCGS photo)

occurred on the Blue Ridge Parkway including three major debris flows that initiated from fill failures that scoured destructive paths downslope into the Pisgah National Forest (Collins 2008; Latham et al. 2009). Figure 9.14 shows imbricated boulder deposits and large woody debris along the track of the Bear Drive Creek fill failure-debris flow near Curtis Creek. Originating at elevations of 1,116, 1,412 (Bear Drive Creek), and 1,349 m along the crest of BRE, these debris flows scoured tracks 2.44, 3.05, and 3.27 km-long, creating canopy gaps of 6.1, 8.0 and 8.61 ha respectively in the headwaters of the Catawba River.

The deadliest of the September 2004 debris flows occurred along Peeks Creek which resulted in 5 deaths (including an unborn child), 2 serious injuries requiring amputation, and 16 destroyed residences (Latham et al. 2006, Witt 2005, Wooten et al. 2006, 2008a). Residents reported that the debris flow occurred at about 2110 EST on September 16, 2014, corresponding to the time of heaviest rainfall from a spiral rain band as it passed over Macon County. The debris flow began on the steep (33–55°) forested slopes of Fishhawk Mountain and traveled 1.5 km through the Nantahala National Forest before entering private land where the fatalities and destroyed homes occurred in the run out zone (Fig. 9.1). The 3.6 km-long track of the debris flow covered an area of 13.8 ha from the upper, northeast-facing slopes of Fishhawk Mountain (Fig. 9.17) downstream to the Cullasaja River. Calculated estimates of a peak velocity of 14.8 m per second, and discharge values ranging from 1,275 m^3 per second to 1,980 m^3 per second for the debris flow attest to its destructive power. Pre-existing debris deposits exposed along the path of the Peeks Creek debris flow indicate that at least two debris flows had occurred before the September 2004 event. Clingman (1877) reported 'water spouts' on the southwest and northeast sides of Fishhawk Mountain in 1876 that, from his description, were likely debris flows (Witt 2005).

Of the 48 landslides attributed to Frances and Ivan in Macon County, 33 were debris flows that initiated on relatively undisturbed forested slopes, mainly on the Nantahala National Forest. The total area of the 27 mapped debris flow tracks throughout Macon County is 26.9 ha, with over half of that being the 13.8 ha of the Peeks Creek debris flow. The tracks of the 184 mapped debris flows in western North Carolina attributed to Frances and Ivan constitute a total disturbed area of 83.1 ha. Of this total, 45.6 ha (54.8 %) resulted from debris flows that originated on slopes modified by human activity, whereas 37.1 ha (44.6 %) resulted from those that originated on forested slopes not modified by human activity.

9.4.8 July 14–15, 2011 Balsam Mountain Debris Flows: North Carolina

On the night of July 14–15, 2011, a stationary thunderstorm storm over the GSMNP caused flash flooding in Straight Fork and triggered debris flows on Balsam Mountain (Miller et al. 2012). The flash flooding resulted in major damage to the Eastern Band of Cherokee Indians fish hatchery on Straight Fork where damage estimates ranged from \$30,000 to \$50,000 (Lee et al. 2011). Rainfall measurements made from the high elevation Duke University GSMNP rain gage network (Tao et al., 2012) indicate that the storm produced intense rainfall of 125 mm in a 4-h period (Miller et al. 2012) and set off 21 debris flows on the slopes of Balsam Mountain (elevation 1827 m), upstream of Straight Fork (Fig. 9.15). Here the high elevation peaks and watershed divides of GSMNP likely contributed to orographic forcing of rainfall (Tao and Barros 2014) which in combination with steep slopes predisposes these locations to debris flow activity.

In September 2011, NCGS geologists made field investigations of three debris flows in the Gunter Fork watershed on the northeast slopes of the Balsam Mountain (Tao and Barros 2014). An additional 18 debris flows were also identified on the southwest slopes of Balsam Mountain through the analysis of 2013 aerial photography. Scoured tracks, downed trees in initiation sites, and accumulations of large woody debris along the tracks are visible in the 2013 imagery. The 18 debris flows on the southwest side of Balsam Mountain all fed in into the upper reaches of Balsam Corner Creek or its tributaries which then flow into Straight Fork. National Park Service staff confirmed that the damage from debris flows in Balsam Corner Creek occurred in the July 14–15, 2011 event. Southworth et al. (2012) previously

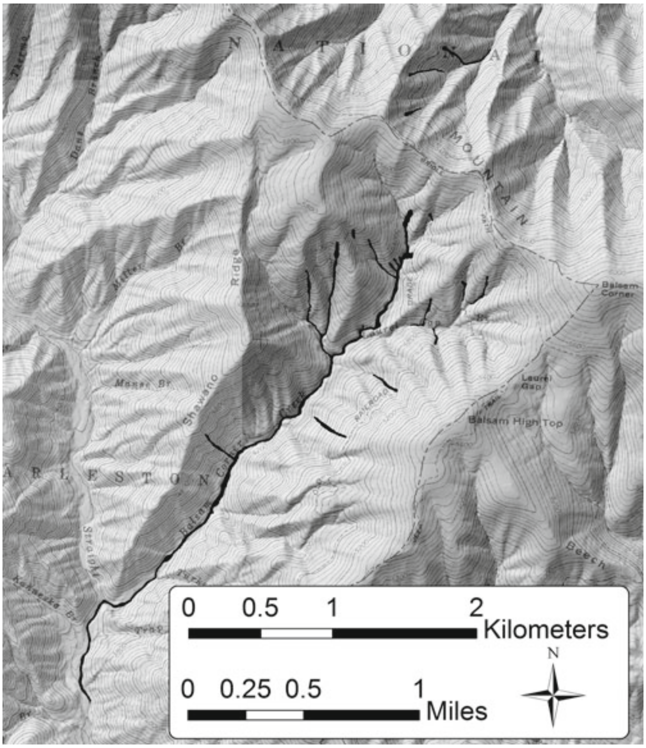

Fig. 9.15 Tracks of 21 debris flows (*black*) triggered by the July 14–15, 2011 storm near Balsam Mountain, GSMNP, North Carolina. Coalescing debris flows scoured a 4.6 km reach of Balsam Corner Creek. Map base is an excerpt of the USGS 7.5-min Luftee Knob quadrangle superimposed onto a 6 m-pixel resolution LiDAR Hillshade map (Location Y on Fig. 9.3 and Table 9.1)

mapped numerous pre-existing debris flows in the headwaters of Straight Fork immediately west of the headwaters of Balsam Corner Creek indicating that the area is prone to debris flow activity.

The track area for the Balsam Mountain debris flows measured from aerial photography is 13 ha, with 12 ha of that total contributed by the Balsam Corner debris flows. The damage to the riparian area from the main debris flow visible in the aerial imagery extends 4.6 km along Balsam Corner Creek. The debris flows in Balsam Corner Creek are significant not only because of the riparian damage along 12.9 ha of tracks, but because they likely contributed to the flooding at the Cherokee Fish hatchery 13.3 km downstream, and 760 m lower in elevation from the initiation sites. This event demonstrates that summer thunderstorms with the potential to trigger debris flows and flash flooding, can develop with little, if any, warning and cause significant damage to resources and communities located several km downstream.

9.4.9 2013 Extended Period of Above Normal Rainfall: North Carolina

Record amounts of rain fell in western North Carolina in between January and August of 2013. By the end of August, the National Weather Service had recorded 1,730 mm of cumulative rainfall for the year at the Asheville airport, 585 mm above a 30-year normal (Fig. 9.16). From July through August 2013, 335 reported landslides of various types occurred throughout western North Carolina (Gibbs 2013; Wooten et al. 2014). Six storms within this period triggered landslides, and the storm events of January 14–18, July 2–7 and July 27, 2013 were federally declared disasters for landslides and flooding. During this timeframe the NCGS, in response to requests for technical assistance, investigated 33 of the reported landslides that resulted in 5 destroyed or condemned homes, and damage to 4 other homes and 24 roads.

Information to date indicates that the vast majority of the 335 reported slope failures involved slopes modified by human activity, mainly embankment slope failures that mobilized into damaging debris flows. Only two landslides that occurred during this period are known to have originated on natural (i.e., unmodified by human activity) slopes. This finding indicates that although record rainfall amounts occurred throughout the region, rainfall was mostly below thresholds necessary to trigger slope failures on forested slopes not modified by human activity.

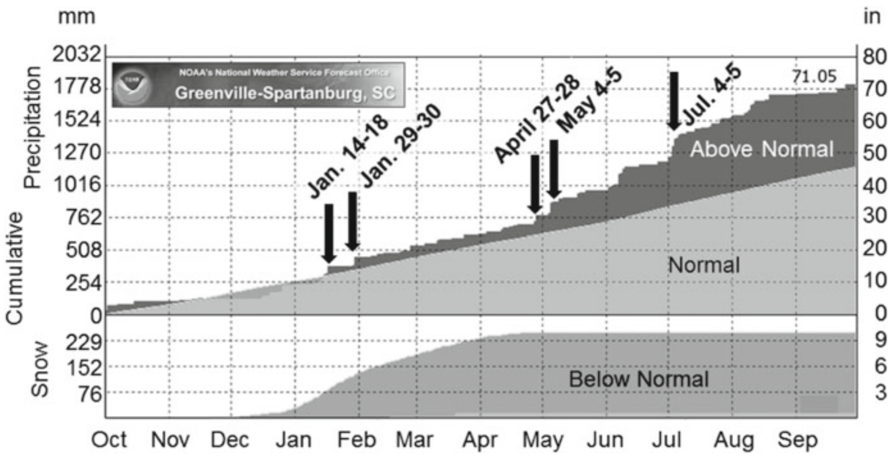

Fig. 9.16 Precipitation chart for the period October 2012 through September 2013 showing rainfall departure from the 30-year normal at the Asheville Regional Airport (KAVL) determined by the National Weather Service. The January 14–18, 2013 event began an extended period of above normal rainfall. *Black arrows* denote rainfall events that triggered landslides throughout western North Carolina (Note: Snow season typically ends in April. The graph shows below normal snow accumulation remained constant after April)

Two debris flows that occurred during this period are noteworthy with respect to impacts of forest structure and riparian areas. On December 16, 2013 a major debris flow occurred on US 441 in the GSMNP, cutting off the main transportation route through the Park from Cherokee, North Carolina to Gatlinburg Tennessee. Accounts by National Park Service staff and field investigations by the NCGS indicate that a debris slide began in road fill and mobilized into a rapidly moving debris flow. About 68,000 m^3 of road fill and the underlying colluvial deposits were involved in the debris flow that removed vegetation and scoured 1.4 ha of slopes that drain into the Beech Flats Prong of the Oconaluftee River. One of the two landslides that initiated on naturally forested slopes not modified by human activity was the July 4, 2013 debris flow on the Nantahala National Forest along Herron Branch, a tributary to the Tuckasegee River in western Jackson County. The scoured riparian area of the 2.1 km-long track was about 3.4 ha as mapped from field investigations. The debris flow did not damage any structures, but large dams of woody debris remained in the track near private homes built along Herron Branch.

A similar, but lesser period of above normal rainfall occurred between September 2009 and February 2010 (Bauer et al. 2010). Western North Carolina received about 1,060 mm of rain, approximately 400 mm above normal. Rain events during this period triggered over 40 landslides; 15 of those investigated by the NCGS were on slopes modified by human activity.

9.5 Landform-Geologic Controls on Debris Flows Initiation

Bedrock structure and to a lesser degree lithology influence the development of geomorphic features prone to debris flows at a variety of scales. At a regional, multi-basin scale the BRE extending from northeast Georgia to northeast Virginia (Fig. 9.4) makes it prone to debris flow activity. Although the geologic origins of the BRE have long been debated (Soller and Mills 1991) the overall southwest to northeast trend of major geologic features in the southern Appalachian orogen (Hatcher 2010; Hibbard et al. 2006) strongly influence the parallel trend in the BRE. The distribution of the generalized locations of areas affected by debris flows for the July 15–16, 1916 event, and the locations of mapped debris flows for the August 13–14, 1940 event in North Carolina, and the August 19–20, 1969 (Camille), the June 27, 1995 events in Virginia generally correspond with the BRE (Figs. 9.3 and 9.4). Geologically, the high relief, steep slopes, and highly dissected nature (a possible reflection of the spatial frequency of bedrock discontinuities) of the BRE make it susceptible to debris flows. Orographic forcing of rainfall along the BRE is shown by the greater rainfall totals along the BRE as compared to the surrounding regions for the storms of July 15–6, 1916 (Scott 1972, Witt 2005), August 10–17, 1940 (US Geological Survey 1949; Wieczorek et al. 2000, 2004; Witt 2005) and June 27, 1995 (Wieczorek et al. 2000, 2004). Steep topography in Madison County, Virginia along the Blue Ridge Mountains likely favored the development of heavy rainfall during the 1995 storm due to orographic lifting (Pontrelli et al. 1999), although the relation between orographic lifting and the heavy rainfall in Nelson County during Hurricane Camille remains unclear (Williams and Guy 1973).

Similar geologic controls on the configuration of landforms prone to debris flows occur in the mountain headwaters of river basins and individual watersheds. For example, the majority (25 of 33) of the debris flows related to the September 2004 rainfall from Frances and Ivan in Macon County, North Carolina occurred on the steep eastern flanks of the Nantahala Mountains Escarpment (NME) (Wooten et al. 2008a). Here, the 100 km^2, 25 km-long NME forms an abrupt topographic rise that contains the headwaters of east-flowing tributaries of the Little Tennessee River (Fig. 9.17). The main northwest and north trends, and secondary northeast trends of its different segments parallel numerous topographic lineaments with orientations similar to measured bedrock discontinuities in the area, reflecting the influence of bedrock structures on the NME. Wooten et al. (2008a) used the term 'structural-geomorphic domain' for such features. Orographic forcing of rainfall by the NME occurred during Hurricanes Frances and Ivan. The Mooney Gap rain gage (elevation

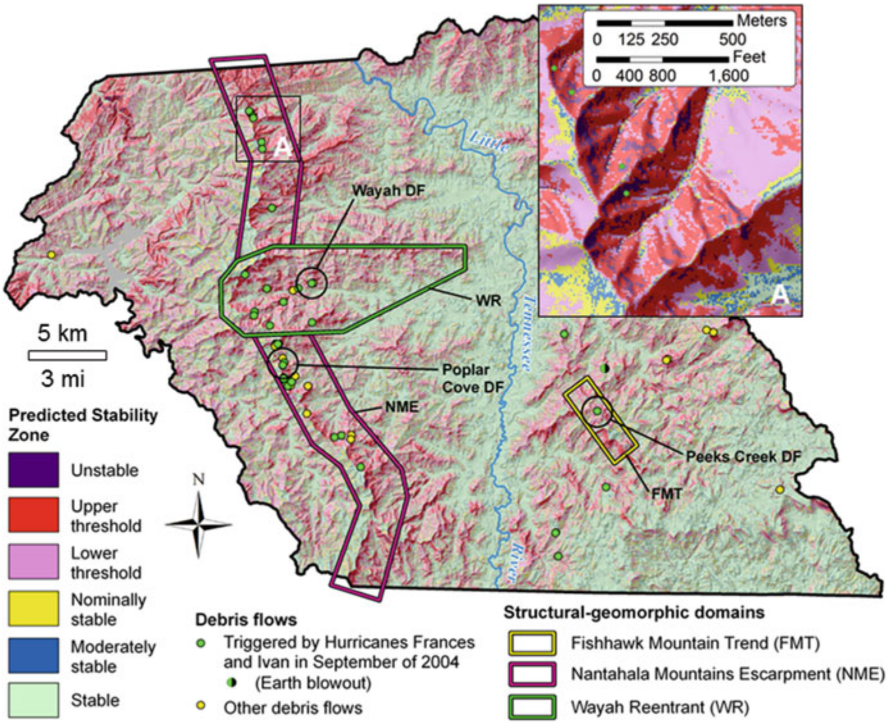

Fig. 9.17 Structural-geomorphic domains in relationship to debris flow locations for Macon County. Map base is a shaded relief 6 m LiDAR DEM overlain by a stability index map (Modified from Sheet 2 of Wooten et al. 2006). Unstable (*purple*) and upper threshold (*red*) stability zones portrayed on the map highlight the topographic features of the structural-geomorphic domains discussed in the text. Inset *A* shows enlarged area for color resolution (Reproduced from Wooten et al. (2008a)). DF = named debris flow location. Poplar Cove debris flow is location S on Fig. 9.3 and Table 9.1

1,364 m) on the crest of NME at the USDA Forest Service Coweeta Hydrologic Laboratory received 100 mm more rainfall in each storm than did several lower elevation gages in the area (Wooten et al. 2008a). At the watershed scale, the September 2004 debris flows were concentrated within the Wayah Creek and Poplar Cove erosional reentrants on the NME, which are likely controlled by bedrock structures that intersect the NME. The Fishhawk Mountain trend, where the 2004 Peeks Creek debris flow originated, has a similar orientation and configuration of geologic structures as the NME, but is a smaller-scale structural geomorphic domain. Perhaps the best example of where bedrock structure can be related to a concentrated debris flow activity is the Deep Gap area of Watauga County (Fig. 9.7, and Sect. 9.8), where 700 debris flows occurred during the August 13–14, 1940 storm (Wieczorek et al. 2004; Wooten et al. 2008b). Here, Elk Creek and its tributaries form a highly dissected erosional reentrant within the BRE that corresponds with WNW-trending ductile faults (Bryant and Reed 1970) and other WNW-trending topographic lineaments that intersect the BRE (Wooten et al. 2008a, b; Gillon et al. 2009).

At the hillslope scale, individual debris flows typically originate in convergent colluvial accumulation zones or catchments called hollows (Hack and Goodlett 1960) that occur on steep hillslopes above the highest extent of channelized streams in mountainous terrain (Fig. 9.18). Colluvial hollows are widely recognized geomorphic features known to be initiation sites for debris flows triggered by heavy rainfall in mountainous terrain (Kochel 1987; Reneau and Dietrich 1987). Residence time of colluvium within individual hollows between successive debris flow events can be more than 20,000 years. The two oldest radiocarbon ages for colluvium in hollows determined by Hales et al. (2011) were 23,989 ± 238 (S.D.) and 23,546 ± 265 radiocarbon years before present in one trench. Samples collected at higher levels in

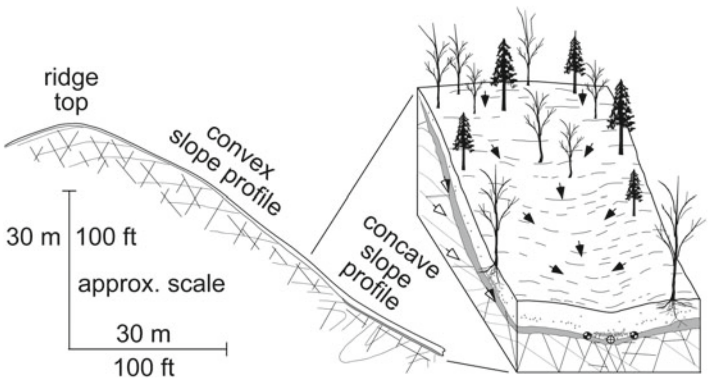

Fig. 9.18 Generalized conceptual model of a hillslope profile (*left*) and hollow (*right*) with colluvial soil layers overlying bedrock (shown with lines depicting curved and planar discontinuities). *Black arrows* depict directions of surface water flow; *black and white arrows* depict shallow groundwater seepage along the colluvium-bedrock contact; *white arrows* depict bedrock fracture flow. *Circles* depict out-of-plane seepage

the same trench had ages that ranged from 4,278 ± 129 to 569 ± 61 radiocarbon years before present. In another pit ages ranged from 8,065 ± 95 to 2,964 ± 112 radiocarbon years before present.

Workers have long recognized the influence of bedrock structure (e.g., planar discontinuities such as fractures, bedding and foliation planes) on the formation hollows in the SAH (Grant 1988; Wooten et al 2008a; Sas and Eaton 2008). Differential weathering of bedrock and enhanced weathering along intersecting discontinuities influences the formation of trough- or wedge-shaped depressions in bedrock surfaces that underlie hollows (Fig. 9.18). In some locations underlain by moderately dipping (less than 45°) layered metasedimentary rocks, the opposing slope (or scarp slope) of the landform is steeper, and contains more colluvial hollows than the slope that coincides with the dip direction (Wooten et al. 2003a). The convergent surface and subsurface geometries of hollows contribute to the accumulation of colluvial soil, which along with the build-up of excess pore-water pressures from infiltrating rainfall and fracture flow along bedrock discontinuities (Sas and Eaton 2008), combine to initiate debris flows. The relationships between topographic convergence in hollows, soil moisture content, and root cohesion are discussed in detail in Sect. 9.7.

Of the 880 debris flows and slides in the NCGS landslide geodatabase where the geomorphic shape of the initiation sites was categorized, 68 % (601) occur on concave slopes or hollows; 18 % (157) are on convex slopes; and 14 % (122) are on planar slopes. Although the majority of debris flows originate in colluvial soil, a lesser number initiate in residual soil derived from the in situ weathering of bedrock. Where detailed studies were done at 21 debris flow initiation sites in western North Carolina Wooten et al. (2012) found that soil at 65 % (15) of the debris flow detachment surfaces to be colluvial soil, and soil at 35 % (6) sites to be residual soil. Steep slopes and relatively thin soil characterize debris flow initiation zones. Slopes at the detailed study sites range from 22° to 40°; inferred detachment depths range from 0.6 to 3 m, which generally correspond with soil depth. Ground slopes (28–44°) and soil depths (0.5–2.4 m) were within similar ranges at 28 debris flow sites investigated in Macon County (Wooten et al. 2008a).

Relationships between bedrock type and debris flow occurrence are less clear. In the Virginia Blue Ridge Mountains, bedrock resistance to weathering contributes to the ruggedness of the topography and thus to the overall steepness of the area. Gryta and Bartholomew (1989) conclude that bedrock lithology is related to preferred debris flow initiation by contributing to topographic relief as a function of resistance to weathering in areas that experience heavy rainfall. In the Nelson County area, a majority of 1969 debris flows initiated in foliated biotite gneisses with steep topography. In contrast, low-relief areas with similar bedrock lithologies did not experience debris flows, even if heavy rainfall was recorded (Gryta and Bartholomew 1989). Morgan et al. (1997) concluded that bedrock type had a negligible effect on debris flow initiation during the 1995 Madison County storm, except in relation to soil and colluvial development. As in Nelson County, the bedrock underlying the areas of debris flows is primarily highly resistant bedrock, commonly granitoids and granitic gneisses, interspersed with high-strain mylonitic zones (Eaton et al. 2004).

There was, however, a minor correlation between the phyllitic metasedimentary units within the Catoctin Formation (metabasalts) and debris flow initiation in western Nelson County, although only a few debris flows failed in this area due to lesser rainfall totals (Gryta and Bartholomew 1989). A similar correlation was noted by Witt and Heller (2014) in Page County in the phyllitic units of the Catoctin Formation; two debris flows and one potential debris flow occurred in phyllites with a foliation dipping to the SE, parallel to slope. Clusters of August 1940 debris flows in western North Carolina correspond with highly dissected areas underlain by Proterozoic granitic gneisses in northwest Watauga County, and in the Deep Gap area of the BRE (Wooten et al. 2008b; Gillon et al. 2009). Further analysis is needed to determine if this apparent correlation results from bedrock lithologies, bedrock structure, meteorological affects, or some combination of factors.

Several investigators have documented slope instability associated with sulfidic rocks in the southern Appalachians. Clark et al. (1987) reported an increased severity of [debris] slides and flows in pyrite-rich rocks of the Anakeesta Formation in the GSMNP. During the May 5–7, 2003 storm in western North Carolina (location T, Fig. 9.3 and Table 9.1) six debris flows originated in embankments constructed with pyrite-bearing rock derived from the underlying sulfidic and graphitic metasedimentary rocks (Wooten and Latham 2004). Latham et al. (2009) reported on rock slides that involved sulfidic and graphitic rocks on the North Carolina portion of the Blue Ridge Parkway.

The weathering of sulfidic rocks can decrease the stability of slopes in several ways (Bryant et al. 2003). Sulfuric acid produced by the breakdown of the iron-sulfide minerals pyrite and pyrrhotite reduces the shear strength of rock and soil. The acid accelerates the rate of rock weathering, and over time the rock fragments in a fill will behave mechanically more like soil, and less like rock. The acid also attacks the clay mineral structure in soil and decreases the cohesion, thereby possibly reducing the shear strength of the soil component of the fill. Sulfidic materials are also susceptible to heaving due to mineral expansion as sulfide minerals oxidize when exposed to moisture. Heaving can increase the porosity and decrease the relative density of the material allowing for more infiltration and the destabilizing build-up of pore-water pressure. Graphite, typically present in sulfidic rocks in western North Carolina, may reduce the shear strength of rock and soil materials.

9.6 Anthropogenic Influences

Anthropogenic influences on hillslopes can have destabilizing effects (causes) which predispose them to slope failures in precipitation events (triggers). Inadequately constructed and maintained fill slopes are a well-documented source of debrisflows in mountainous terrain (Collins 2008; Wooten et al. 2009a, 2014) (Fig. 9.14). Excavations (i.e., cut slopes) into hillsides can also destabilize slopes (Collins 2008; Gillon et al. 2009; Latham et al. 2009); however, debris flows that originate from fill failures typically travel greater distances and impact larger areas. Of 3,267 landslides analyzed in the NCGS landslide geodatabase, 380 (11.6 %) are categorized as cut slope failures, and 421 (12.9 %) are embankment (fill) failures. The remaining 2,466 landslides are categorized as initiating on slopes not modified by ground-disturbing human activity; however 1,752 of those occurred on unforested slopes during the August 1940 storm in Watauga County. Forest cover is an important stabilizing factor, particularly on mountain slopes. This factor and consequences of forest removal are addressed in Sect. 8.8. Given that the vast majority of those unforested slopes likely resulted from human activity, as many as 78 % of the total of 3,267 landslides analyzed may have been influenced in one way or another by humans. Examples of landslides related to ground-disturbing activity follow to help illustrate their spatial impacts on the landscape.

The largest known single debris flow event related to human activity in western North Carolina occurred on August 13, 1916 when the original earthen dam at Lake Toxaway failed when a low pressure system dropped 584 mm of rain over Transylvania County (Wooten et al. 2003a, b). The catastrophic dam failure triggered a debris flow covering a minimum area of 122 ha along an 11.4 km reach of the Toxaway River where it flowed down the BRE and into the adjacent Piedmont of South Carolina (location C Figs. 9.3 and 9.6). The enormous outflow of the breached dam, calculated to be on the order of 8,665 m^3 per second (Wooten et al. 2010a) scoured the steep valley walls and transported boulders as large as 18 m long. Deposits from this event are preserved in Gorges State Park and beneath the upper portion of Lake Jocassee. The debris flow scoured to bedrock a 3.7 km length of the upper reach of the river from Lake Toxaway downstream to Wintergreen Falls, a condition that persists today. Boulder levees and other deposits left by the debris flow below Wintergreen Falls now support vegetation. Initial revegetation of the deposit areas probably began soon after the debris flow. Tree ring studies in Gorges State Park (Wooten et al. 2003a, b; 2004) show 1917 to be the beginning growth year for a pitch pine (*Pinus rigida*) now growing on the 1916 boulder deposits near the confluence of Bearwallow Creek and the Toxaway River.

Three major debris flows that damaged the Blue Ridge Parkway and slopes below on the Pisgah National Forest during Frances and Ivan in September 2004 originated as fill slope failures (Collins 2008, Latham et al. 2009). Collins (2014) assessed 105 of the hundreds of landslides on the Pisgah and Nantahala National Forests triggered by rainfall from the remnants of Frances and Ivan and found that 78 (74 %) were road-related failures, mainly fill slope failures. In 2010 a retaining wall failure that mobilized into a 0.82 km-long debris flow damaged three houses and 2.6 ha of mountain side riparian area in Haywood County, North Carolina (Witt et al. 2012). More recently, during the period of extended above average rainfall throughout western North Carolina in 2013 (Sect. 8.4.9) only two of the reported 335 landslides occurred on slopes not modified by human activity. Although the assessment of the 2013 landslides in western North Carolina is incomplete, this high proportion of landslides related to human activity points to the destabilizing influence that some slope modifications and vegetation removal can have.

9.7 Ecohydrological Controls on Debris Flows Initiation

The historical range of variation in landslides is important to consider in the context that the past may be an adequate predictor of the future. However when novel conditions occur, as are expected with changes in precipitation amount and distribution (Ford et al. 2011) and changes in species' ranges (Hansen et al. 2001; Burrows et al. 2014), it is important to consider the ecological and hydrological controls on landslide initiation. The large majority of landslides that initiate in the SAH are 'shallow' landslides that initiate in the soil column and often form debris flows. The spatial distribution of these shallow landslides and their frequency is strongly controlled by the cohesion of the soils (Crozier et al. 1990; D'Odorico and Fagherazzi 2003). Where soils have no cohesion, landslides are smaller and more frequent than in cohesive soils. Cohesive soils are thicker (i.e., can support a greater volume of soil), require larger precipitation events (usually tropical cyclones) to initiate slides that are of a greater volume (magnitude) (Gabet and Dunne 2003). In the southern Appalachians the steep, colluvial soils that initiate landslides typically have a low soil cohesion, so the cohesive strength provided by the roots (this is technically an apparent cohesion, see Schmidt et al. (2001) for a full derivation) of plants acts as a primary driver of the spatial and temporal distribution of shallow landslides. In addition to the provision of cohesive strength, there are a number of additional ways that vegetation affects landslide initiation including adding weight from the stem and aboveground biomass, altering shallow surface hydrology, and affecting soil structure particularly by adding macropores (Hales et al. 2009).

Because of the important role that vegetation plays in influencing the distribution and thickness of soils, landslides initiate where additional cohesion provided by roots is at a minimum (Roering et al. 2003; Hwang et al. 2015). The role that vegetation plays in controlling the initiation of southern Appalachian debris flows, can be challenging to generalize due to the interactions that occur among forest ecology and physiology, and hydrology (henceforth ecohydrology). Differences among species and forest structures are found not only in transpiration and interception rates (Ford et al. 2012), but also in root system architecture, root density, root strength, and how these change with local soil moisture conditions driven in-part by topography.

The additional soil shear strength provided by roots is a large proportion of total shear strength of the thin (average soil depth is 0.9 m), low (soil) cohesion, colluvial soil in the southern Appalachians (Band et al. 2011; Hales et al. 2009). For example, the apparent cohesion provided by roots can represent up to 100 % of the cohesive strength of hillslope soils (Abernethy and Rutherfurd 2001). Roots add shear strength through a frictional coupling with the surrounding soil particles (Schwarz et al. 2010). The shear strength provided by roots is an 'apparent' cohesion, or an additive force (of a magnitude between 0 and 50 kilopascals) when calculating the overall stability of a slope (Waldron 1977). Before a landslide can initiate, the total tensile strength of all roots crossing the slide plane must be exceeded (Schmidt et al. 2001). This is typically envisioned in terms of a dynamic bundle of roots with different elasticities and tensile strengths that break progressively (Pollen and Simon 2005; Schwarz et al. 2010). Thus higher below-ground biomass imparts higher soil cohesion. However, both the elasticity (Schwarz et al. 2010) and tensile strength (Hales et al. 2009) of roots vary with their diameter. The distribution of biomass by soil depth and root diameter is also is also important (Hales and Miniat 2015). While forest ecologists have long recognized the relationship between below-ground biomass, root diameter distribution and soil resources (Albaugh et al. 1998; Joslin et al. 2000; Keyes and Grier 1981), these relationships have been largely absent in the theoretical considerations of predicting whether slopes will fail.

Debris flows typically initiate on the steep upper slopes (Wooten et al. 2008a), above the highest extent of stream channels (0 order basins), where the topography is dissected into minor ridges called noses, and convergent colluvial accumulation zones (Fig. 9.18) called hollows (Hack and Goodlett 1960). Hollows are wetter and have roots that are weaker, with more even vertical root distributions when compared with noses (Figs. 9.19 and 9.20) (Hales et al. 2009). Although roots are exponentially distributed with depth in hollows and noses (Fig. 9.19), soils in hollows tend to have a higher number of roots at depths greater than 50 cm compared to noses. This greater number is important for slope stability, as the total strength of the soil is dependent upon the total tensile strength of roots crossing the failure plane. Hollows, in this case, would have a greater frequency of roots relative to other parts of the landscape. Tree root tensile strength is controlled by the amount of cellulose within the root structure; hence, larger diameter roots that have a greater number of cellulose microfibrils are stronger (Genet et al. 2005; Hales et al. 2009). This effect is modified by soil moisture content and wood structure (Fig. 9.20) (Hales et al. 2013). In the same way that wet wood is weaker than dry wood, root tensile strength decreases in wetter roots through the breakdown of electrostatic bonds between cellulose fibrils at the microscopic level (Winandy and Rowell 2005). The relationships among geology, topographic convergence, soil moisture content, and hollow stability provides a framework for estimating regional apparent root cohesion and how it might change with changing land cover and land use.

Plants also alter soil moisture primarily through transpiration and interception losses and the development of macropores that increase the transmissivity of the soil and reduce the magnitude of the pore pressures produced by any given storm (Selby 1993). During transpiration, plants remove water from the soil column as it is lost from leaf surfaces in the process of CO_2 uptake. In the soil, there is a concurrent increase in apparent cohesion through the addition of a matric suction force. Matric suction is the capillary stress formed in partially saturated soils and is dependent on the soil moisture content and soil matrix properties (Selby 1993). The total amount of apparent cohesion added to the soil by suction is reduced during large storms, as plants cease to transpire when leaves are wet and atmospheric humidity is near saturation. Interception losses are the amount of precipitation that is intercepted by plant and litter surfaces and subsequently evaporates. These losses reduce the total volume of water added to the soil during precipitation events. During a rain event, these losses introduce a lag in the time taken to reach maximum soil pore water pressure (Keim and Skaugset 2003). Landslide initiation tends to occur during large storms

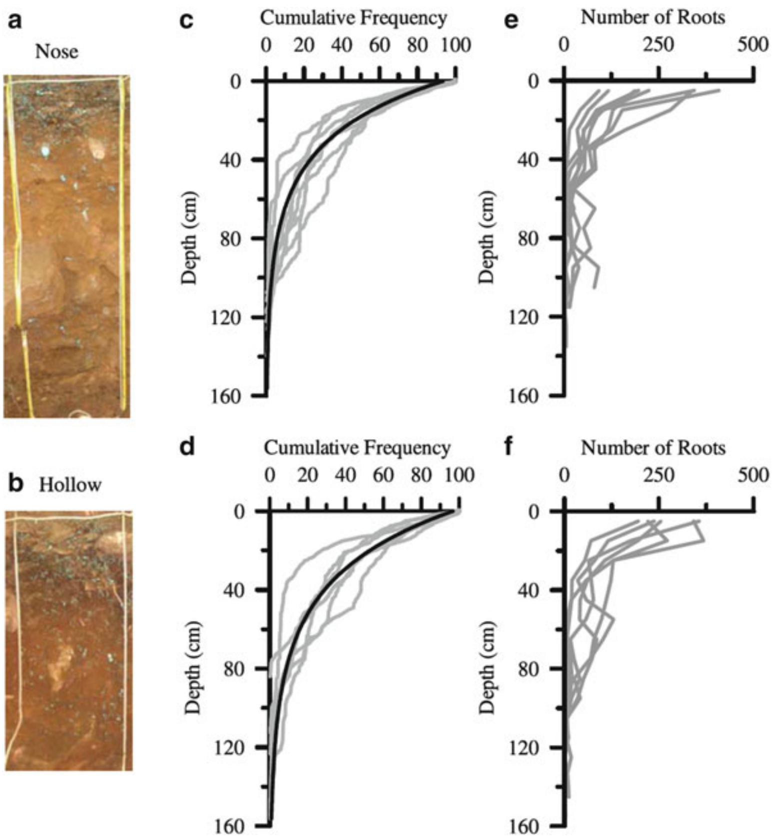

Fig. 9.19 The distribution of roots as a function of soil depth for 16 pits—9 were located on noses and 7 in hollows. (**a** and **b**) Photographs are vertical sections of two northern red oak (*Quercus rubra*) pits dug within 20 m of each other. The diameters of the blue painted roots (high reflectance areas) were measured in an image analysis program to calculate the depth distributions. (**c** and **d**) The cumulative frequency of the number of roots as a function of depth, with gray lines representing individual pits, while black lines are the modeled mean of all pits. (**e** and **f**) The absolute number of roots binned at every 10 cm depth interval, which provides an approximate measure of root area ratio. *Gray lines* are individual pits (From (Hales et al. 2009)

when transpiration is minimal and soils are at or near saturation and suction forces are low (Godt et al. 2009; Montgomery and Dietrich 1994). As a result, plants primarily affect soil shear strength through the added shear strength of roots distributed throughout the soil column rather than through transpiration and interception (Pollen and Simon 2005; Schwarz et al. 2010).

In summary, vegetation is a strong control on size, spatial distribution, and frequency of landsliding in the southern Appalachians. Vegetation serves to both mitigate and promote landslide initiation, with the primary driver of this being the support provided by the roots. Densely rooted forests are more resistant to the effects of large storms, despite having a larger stems that add more weight to the soil, because of the mitigating effects of a large, strong root mass, and more efficient

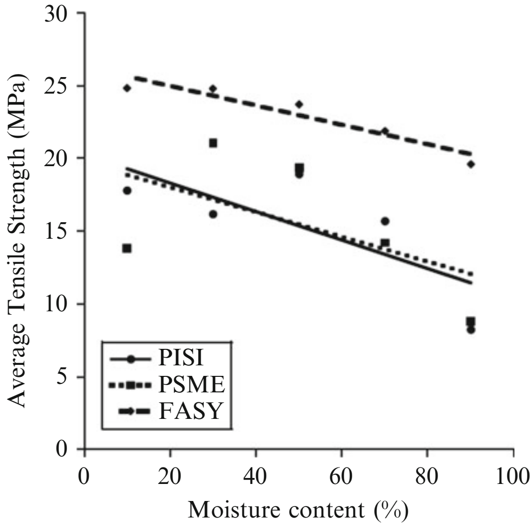

Fig. 9.20 Average root tensile strength as a function of laboratory-controlled root moisture content for species representing two main root xylem architecture types. European beech (FASY; *Fagus sylvatica*), a hardwood with more evolutionary advanced, stronger xylem; and Sitka spruce (PISI; *Picea sitchensis*) and Douglas fir (PSME; *Psuedotsuga menziesii*), coniferous trees with evolutionarily older, weaker xylem. Within each wood type, the wetter the root, the less force required to make the root fail (Modified from Hales et al. 2013)

transpiration. The large roots of trees also increase the porosity and permeability of soils through the development of macropores, reducing the likelihood of high pore pressures required to initiate landslides.

9.7.1 Southern Appalachian Land Use and Slope Stability

Humans have made extensive changes to land cover and land use in the southern Appalachians. Forest types have been affected by land-use change to varying degrees, with high-elevation, northern hardwood forests remaining less affected by development than lower elevation, cove hardwood forests. For example, up to 70 % of the lower elevation cove hardwood forests have been altered by various disturbance processes (Turner et al. 2003). Land-use changes have affected landslide distributions through changes in vegetative land cover. Forests, with deeply rooted trees on cohesive soils have been replaced with agricultural and pasture lands that have shallowly rooted grasses, crops, and shrubs on less cohesive, weak soils. Replacement of trees with grasses, crops and shrubs reduces the apparent root cohesion to values <10 kPa (Schmidt et al. 2001), meaning that shear strength of soils is dependent primarily on the cohesive and frictional properties of the soil particles. Reduction of apparent root cohesion can increase both the number and frequency of shallow landslide events (Gabet and Dunne 2003).

The species and age structure of forests has also changed, with invasive insects and pathogens causing mortality to specific tree species and with forest harvesting (Sakals and Sidle 2004). Recent introductions of two invasive species, the chestnut blight (*Cryphonectria parasitica*), and the hemlock woolly adelgid (*Adelges tsugae*), have functionally removed American chestnut (*Castanea dentata*) and eastern hemlock (*Tsuga canadensis*) trees from southern Appalachian forests. The species that is increasing more than any other in response to eastern hemlock loss is the rhododendron shrub (Ford et al. 2012). As shrubs generally have weaker roots than trees (Hales et al. 2009), soils likely will become weaker over time in these impacted forests. Observational records show that southern Appalachian landslide initiations appear to be strongly concentrated in areas containing this shrub. Additionally, harvesting changes the age structure of the forest and thus affects landslide -susceptibility (Fig. 9.21) (O'Loughlin and Watson 1979; Sidle et al. 2006). After harvest, tree root strength decays exponentially (Schmidt et al. 2001). Young trees with sparse, shallow root systems do not provide as much root reinforcement as mature trees. Therefore, after forest harvest a minima in root reinforcement exists, usually at around 10 years after forest harvest when harvested tree roots have decayed and the young forest is not old enough to provide significant root reinforcement (Fig. 9.21) (Sidle et al. 2006).

Considering all of the interacting factors affecting landslide susceptibility—including vegetation, hydrology, geology—requires an integrated modeling approach. Differences in below-ground biomass and the root strengths of different forest tree and shrub species affect the stability of steeper slopes. A transition from forests to shrub thickets or grasslands means the landscape will support thinner soils and require lower soil pore water pressures to trigger landslides (Gabet and Dunne 2003) (Fig. 9.22). Ecohydrology controls the spatial distribution of root strengths

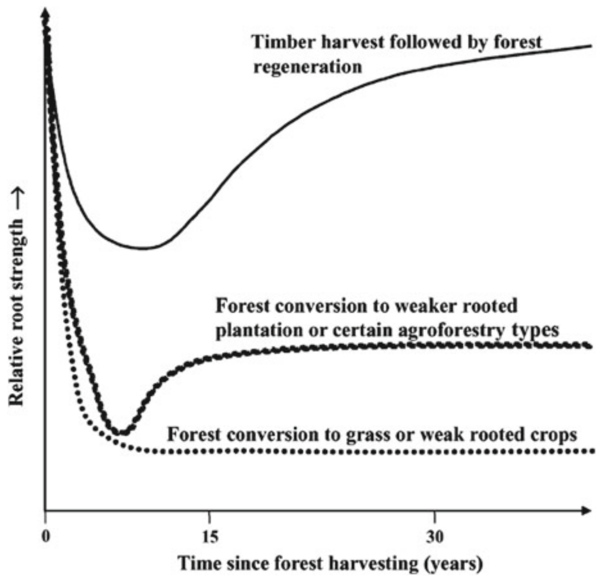

Fig. 9.21 Conceptual diagram showing the temporal response of root cohesion to forest harvest and land use change (From Sidle et al. 2006)

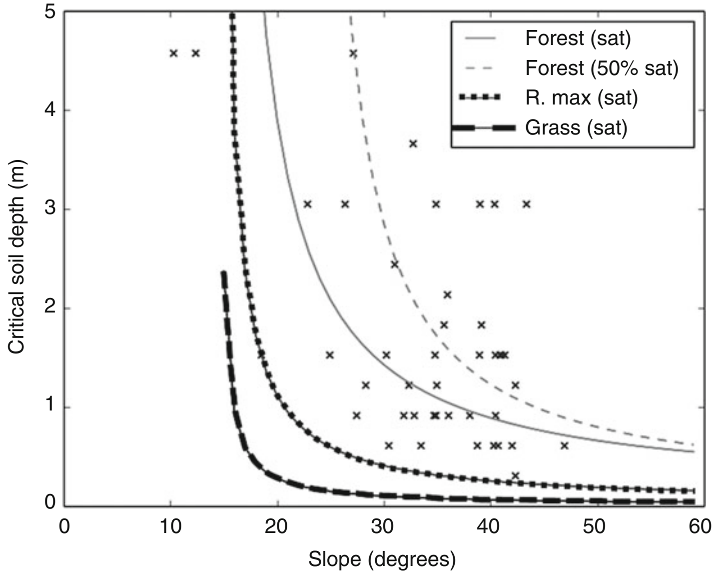

Fig. 9.22 Plot of the relationship between slope and soil depth (measured as the thickness of the landslide scarp) for landslides recorded in the North Carolina landslide database in Macon County, North Carolina. Blue crosses represent each individual landslide event. The four lines represent theoretical failure criteria for different vegetation and hydrologic conditions calculated using the infinite slope model, points that fall above the line should theoretically fail under these conditions. In this model we have maintained constant values of soil cohesion (0 kilopascals) and friction angle (30°) measured using triaxial tests. The *lines* represent failure criteria for average Appalachian hardwood forest (*solid line*, cohesion 6 kilopascals), *Rhododendron maximum*, a common shrub species associated with landslide initiation zones (*dotted line*, 2 kilopascals), and grass (*heavy dashed line*, 0.5 kilopascals) under fully saturated conditions. The *light gray dashed line* is for average Appalachian hardwood forest but with a soil that is 50 % saturated

within forested landscapes, with hollows having the lowest root cohesions. This results in increased landslide potential in these areas (Fig. 9.23). This is an area of significant future research. It is anticipated that more accurate maps of land surfaces and forest structures made using high resolution LiDAR data will lead to more accurate models of root cohesions.

9.8 Vegetation- Debris Flow Relationships: Deep Gap North Carolina

We empirically assessed the spatial relationship between vegetation type and debris flow occurrence in the Deep Gap area of Watauga County and adjoining Wilkes County. The Deep Gap study area was chosen because of the high concentration of debris flows triggered by rainfall from the remnants of a hurricane that passed over

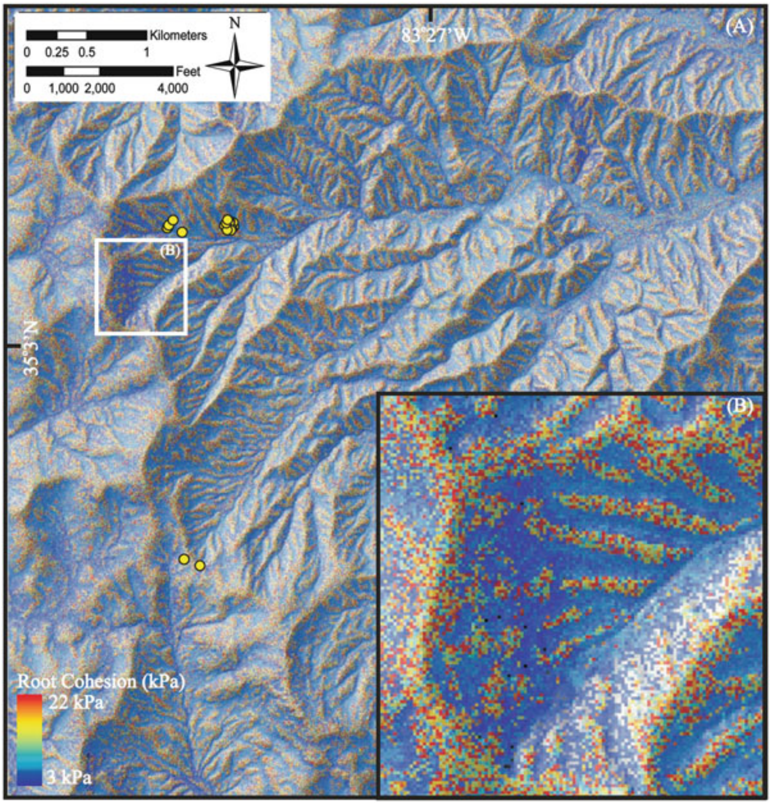

Fig. 9.23 Spatial model of the distribution of root cohesion across Coweeta Hydrological Laboratory in Macon County, North Carolina. *Yellow dots* represent the locations of pits and trenches sampled by Hales et al. (2009). The model is constructed by calculating profile curvature across the catchment. Root apparent cohesion values were assigned using a random uniform distribution of values for each topographic class (nose or hollow)

the area on August 13–14, 1940. The Deep Gap area is a highly dissected erosional reentrant on the BRE that coincides with the surface traces of west-northwest trending ductile thrust faults and topographic lineaments that transect the BRE. Figure 9.7 shows the Deep Gap study on the steep slopes of the BRE, and the landslide initiation sites identified on the landslide hazard maps of Watauga County (Wooten et al. 2008a).

Our approach was to determine the relative spatial frequency of debris flows that initiated on forested slopes versus unforested slopes. As part of landslide hazard mapping in Watauga County (Wooten et al. 2008a), September 29, 1940 vintage black and white aerial photographs (Fig. 9.7) were scanned and georegistered for use in GIS to identify and map the debris flow initiation sites and tracks. Approximately 10 % of the nearly 2100 debris flows, debris slides and blowouts identified as being triggered by the 1940 event were field verified. In this current study, forested slopes were defined as closed canopy, mixed conifer and hardwood

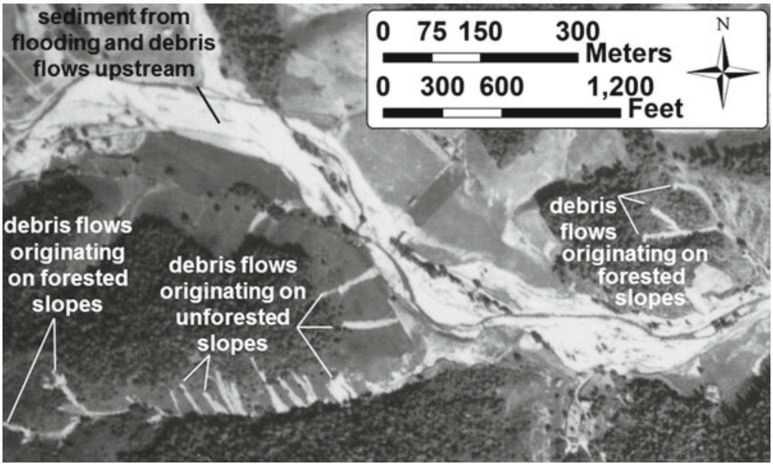

Fig. 9.24 Excerpt of a September 29, 1940 aerial photograph showing examples of August 13–14, 1940 debris flow initiation sites on forested and unforested slopes within the Deep Gap study area (Fig. 9.7). Analysis of 629 debris flow sites in the Deep Gap study area showed a nearly five-fold increase in debris flow initiation sites on unforested slopes over those on forested slopes

forest that were readily identifiable on the aerial photos by the dark color and distinct textural contrasts of foliage. Unforested slopes were defined as open areas that included grasses, shrubs, agricultural fields, areas of recently harvested timber, but also included small areas containing, isolated stands of trees, or bare earth. In general, the unforested slopes occurred in areas more readily suited for clearing and agriculture such as in valleys and toe slopes. Figure 9.7 shows the mapped forested and unforested slopes in the study area. Figure 9.24 shows examples of debris flows originating of forested vs. unforested slopes on 1940 aerial photography of the Deep Gap area.

Potential sources of error include misinterpreting the type of vegetation present at initiation sites and in mapping vegetation patterns. Individual photographs were georegistered, not ortho-rectified; therefore, planimetric areas of the map unit polygons are approximate give the high relief of the area. The numbers of debris flows within forested slopes may be underestimated because they were obscured by the forest canopy. The scoured tracks of debris flows, and sediment deposited in second and third order drainages by debris flows and flood waters obscured the vegetation types present prior to the storm event.

The results of the analysis are given in Table 9.2. Within the 78.2 km^2 study area, 629 debris flow initiation sites were mapped for an average of 8.0 initiation sites/km^2, and a total track area of 18.7 km^2 (1,870 ha). Forested slopes accounted for approximately 63.9 km^2 of the total area, whereas unforested slopes made up a significantly smaller area at approximately 14.3 km^2. On forested slopes there were 234 initiation sites representing 38.4 % of the total sites, resulting in an average of 3.8 sites per km^2. In contrast, 263 sites occurred on unforested slopes yielding an average of 19.5 sites per km^2, nearly a fivefold increase over those on forested

Table 9.2 Tabulated results from the Deep Gap area vegetation and debris flow study. Analysis of 629 debris flow sites in the Deep Gap study area showed a nearly fivefold increase in debris flow initiation sites on unforested slopes over those on forested slopes

	Area km^2	Number of debris flows	Percentage of total debris flows	Average debris flow frequency per km^2
Study area	78.2	629	100	8.0
Forested area	63.9	242	38.4	3.8
Unforested area	14.3	279	44.4	19.5
Boundary of forested – unforested area	–	108	17.2	–

slopes. Interestingly, 108 initiation sites (17.2 % of the total) were mapped as being on the boundary between forested and unforested slopes. This occurrence may reflect a change in slope conditions near the boundaries of forested and cleared land, perhaps the forested land being steeper and less suited for clearing and agriculture. Although there were several potential sources of error in the assessment, the nearly five-fold difference in the frequency of debris flows on unforested slopes over that on forested slopes supports the concept that deep rooted vegetation provides a greater stabilizing influence on slopes than shallow rooted vegetation.

9.9 Debris Flows Effects on Landscape and Forest Structure

Debris flows, in contrast with most other disturbances such as wind, fire, ice, insects and diseases in the SAH remove not only the forest, but the soil and land beneath the forest. Debris flows remove vegetation, scour surface soil, and disrupt aquatic ecosystems, creating linear canopy gaps and early successional habitats along their tracks. As noted in the Introduction chapter (Greenberg et al., Chap. 1) landslides (debris flows) can facilitate species diversity and lead to persistent patches of early successional vegetation in older forests (Seiwa et al. 2013). Debris flows evacuate sediment from their initiation zones and along their scoured paths in upland areas, and deposit it in their run out zones in footslope drainage valleys and channels, commonly in areas of older debris flow deposits (Fig. 9.5). The development of landslide geodatabases and the mapping of debris flows in a GIS (Bauer et al. 2012; Witt and Heller 2014; Crawford 2014) provide the framework for studying the geo-spatial and temporal aspects forest recovery from documented historical debris flow event in the SAH.

An individual debris flow may initiate with soil volumes on the order 10^1–10^2 m^3, but with entrainment and bulking of soil along its path, it may erode and transport in excess of 10^3–10^4 m^3 of soil. Vegetation recovery can begin rapidly in the depositional (i.e., run out) zones of debris flows. Even in the case of catastrophic events like the 11.4 km-long, 122 ha debris flow that resulted from the August 1916 failure of the Lake Toxaway Dam tree growth (pitch pine) began in boulder deposits the following year (Wooten et al. 2003a, b). Sediment from individual debris flows has a relatively short term negative impact on aquatic ecosystems. A positive aspect of debris flow activity over the long term is that in some areas of western North Carolina accumulated deposition in footslope areas leads to the formation of productive forest soils (Neary et al. 1986) at centennial and millennial time frames. Vegetative recovery in the steep, high elevation, upper portions of debris flow tracks, commonly scoured to bedrock (Fig. 9.12), would generally be slower than in debris deposition zones in the lower reaches of drainages and foot slope area (Fig. 9.5).

Major debris flow events induced by tropical cyclones can disturb large areas over multiple watersheds. Mapped debris flows from the August 13–14, 1940 event disturbed a minimum of 368 ha of riparian area in Watauga County not accounting for the large volume of sediment transported downstream below the BRE into Wilkes and Caldwell Counties. Mapped debris flows from Hurricane Camille in the Virginia Blue Ridge Mountains and Piedmont account for a minimum of 1,200 ha of disturbed riparian area, nearly every first and second order drainage in some watersheds. Smaller, though spatially concentrated events such as the Balsam Mountain debris flows triggered by a July 14–15, 2011 thunderstorm resulted in near source disturbances on the order of 13 ha. Impacts from this localized, but intense, storm event extended over 13 km downstream from the debris flow initiation sites.

9.10 Methods and Approaches to Debris Flow Susceptibility Mapping and Modeling

Quantitative methods for landslide hazard mapping geared toward debris flow mapping and susceptibility modeling are well established, readily available, and are continually being improved. Slope stability assessments are important not only for forest and watershed management, but are critical to help protect public health and safety on forest lands and at the interface of forest lands with private property in areas downslope from upland forests (Collins 2014; US Department of Agriculture 2014).

Physically-based computerized models that use a limit-equilibrium approach to slope stability analysis governed by variations of the infinite slope model incorporated into a GIS platform have been developed and in use since the 1990s. In evaluating the computer programs SINMAP (Pack et al. 1998) and SHALSTAB (Montgomery and Dietrich 1994) for use in the North Carolina landslide hazard mapping program Witt et al. (2007a) found the output results to be very similar. SINMAP has been used in North Carolina to model debris flow susceptibility at the county level (Fig. 9.17) (Witt et al. 2007a; Wooten et al. 2007). Modeling using SINMAP coupled with a GIS-based hydrologic routing model and field mapping of debris flows and deposits have been used together to model potential debris flow pathways (Fuemmeler et al. 2008; Witt et al. 2008). These steady-state hydrologic models can be used to forecast the spatial distribution of unstable slopes and landslide occurrence. Models that incorporate transient hydrologic responses (Baum et al. 2002) have the capability to assess spatial and temporal slope stability for varying precipitation scenarios. Morrissey et al. (2004) found such an approach useful in attempting to simulate the locations and timing of debris flow from the 1995 event in Madison County, Virginia.

Next generation models that are being developed and tested include the RHESSys (Regional HydroEcological Simulation System) model in which ecohydrological and geomorphic inputs are coupled to simulate spatial and temporal slope stability. The RHESSys model has undergone development and successfully applied at the watershed scale at the Coweeta Hydrologic Laboratory (Band et al. 2011). Development and application a hydro-mechanical model HILLSOPE FS2 (Lu et al. 2010) that incorporates soil capillary tension to model stability at the hillslope scale is to be tested in western North Carolina (Lewis et al. 2013) on the Nantahala National Forest and Coweeta Hydrologic Laboratory in Macon County, and at the Bent Creek Experimental Forest in Buncombe County. A hydrologic model used with a high elevation rain gage network to predict flood response and debris flow initiation has been applied to GSMNP and adjoining area of western North Carolina (Tao and Barros 2014).

The performance of models used to map slope instability at various spatial scales is highly dependent on the quality of the geologic, soil, geotechnical, hydrologic, and vegetative input parameters, and the quality of the landslide mapping and data used to calibrate them and evaluate their results (Witt et al. 2007b). Landslide and landslide deposit inventories are important not only for identifying areas affected by recent and past landslide activity, but serve as important means to calibrate debris flow susceptibility and run out models. Quality digital elevation data are critical to model performance. Where available 6 m- or higher (e.g., 1 m) pixel resolution LiDAR digital elevation models improve model results over standard 10 or 30 m digital elevation models. These models do not substitute for site-specific stability assessments by qualified earth scientists, but they provide a means for planning purposes to identify potentially at-risk areas where on-site analyses are warranted.

9.11 Summary

The term landslide refers to a variety of gravity-driven movements of soil or rock materials downslope. Landslides may be swift and catastrophic (i.e., rockfalls and debris flows) or may travel slowly and incrementally downslope (i.e., soil slides). Debris flows, the dominant landslide processes in the SAH, are a water-laden (i.e., liquefied) mass of rock fragments and coarse grained soil (debris). Debris flows can attain speeds in excess of 50 km per hour and are capable of destroying or damaging everything in their paths.

Debris flows originate on steep mountain slopes, mainly in areas of convergent topography known as colluvial hollows. Debris flows initiate when the shear stresses on a hillslope exceed the frictional and cohesion shear strength of the hillslope material, which is composed of soil, rock fragments, and roots. Many interrelated, chiefly geologic, factors contribute to debris flow occurrence, including steep slopes, landforms (i.e., their influence on rainfall patterns, runoff and infiltration in convergent topography), bedrock types and structure, soil types (i.e., mechanical and hydrologic properties), and vegetation (i.e., evapotranspiration and root cohesion). Excessive rainfall leading to elevated pore-water pressures (i.e., decreased shear strength) is the primary trigger for debris flows, especially when antecedent moisture conditions are high.

Debris flows and other forms of mass wasting are natural processes of landscape evolution in the SAH. The present landscape includes many remnants of prehistoric (Pleistocene and older) debris flow deposits. Native American and early European settlements were confined mainly to valleys and some mountain footslope areas that include debris flow run-out zones. In the twentieth and twenty-first centuries, however, anthropogenic influences on the landscape have increased the frequency of mass wasting for a given storm event above historical natural levels through changes in vegetation and disturbances on mountain slopes. Where forests with deeply rooted trees have been replaced with agricultural and pasture lands that have shallow-rooted grasses, crops, and shrubs, the stabilizing effects of precipitation interception, evapotranspiration and root cohesion by vegetation have been reduced. In the latter part of the twentieth century increased development on steep mountain slopes has resulted in ground-disturbing human activity where debris flows initiate. Poorly constructed and maintained cut and fill slopes are the primary destabilizing influences that increase the susceptibility of mountain slopes to debris flow initiation. This upslope development pattern combined with increased development in footslope areas within debris flow run-out zones has increased the overall societal risk from damaging debris flows.

Debris flows remove vegetation, remove surface soil and vegetation, and disrupt aquatic ecosystems, creating linear canopy gaps and early successional habitats along their tracks. The area affected by an individual debris flow originating on forested slopes ranges from less than 10 m^2 to 13.8 ha (2004 Peeks Creek debris flow). Coalescing debris flows can impact areas on the order of 16.5 ha or more. Human activity resulted in the largest area affected by a single debris flow in this study where the failure of the Lake Toxaway dam in 1916 disturbed a minimum of 122 ha along the Toxaway River in North and South Carolina. Recovery of areas impacted by debris flows to pre-disturbance conditions can be on decadal and centennial time scales. Vegetative recovery in the steep upper portions of debris flow tracks, commonly scoured to bedrock, would generally be slower than in debris deposition zones in the lower reaches of drainages and foot slope area.

In 1940, 1969 and 1985, each of three tropical cyclones that passed over the SAH generated thousands of documented debris flows. Given the magnitude of the July 15–16, 1916 storm, it is reasonable to conclude that this event triggered thousands of debris flows, bringing the total to four tropical cyclones that have had the greatest impacts on the SAH over the last century. The average frequency of these major events is about 25 years. Where documented by mapping, these catastrophic storms disrupt forest structure and/or hydrologic systems over areas ranging from about 368 to 1,200 ha. Major storms that have each generated hundreds of reported landslides in the SAH have occurred 10 times from 1924 to 2013 for an average frequency of about 9 years. Where documented by mapping, these major storms disrupt forest structure and/or hydrologic systems over areas ranging from about 70 to 600 ha. Collectively these catastrophic and major storms have an average frequency of 7 years over the period 1916–2013.

Sixteen smaller-scale storms that generated less than a hundred of debris flows have a maximum average frequency of 7–8 years over the period from 1876 to 2013. These smaller storms that have induced debris flows are undoubtedly more frequent, and many have not been recorded in the literature. Where documented by mapping, these lesser storms disrupt forest structure and/or hydrologic systems over areas ranging from about 1.4 to 50 ha. Taken together, the 31 landslide events documented here over the period from 1876 to 2013 have an average frequency of about 4 years.

Debris flow occurrence is strongly correlated with antecedent precipitation and rainfall intensity (i.e., rainfall rate and duration). Looking forward, should climate change result in increased occurrences of high intensity rainfall through more frequent storms, or less frequent, but higher intensity storms, then an increased frequency of debris flows and other forms of mass-wasting should be expected in the SAH (see Dale et al. Chap. 13). With regard to the difficulties and uncertainties in predicting the affects that climate change scenarios will have on landslide occurrence, Sidle and Ochiai (2006) conclude that a higher priority should be given to understanding the interactions between land use and landslides, and applying this knowledge in managing mountainous and unstable terrain. Given the importance of the stabilizing influences of forest cover, healthy forests on mountain slopes are critical in mitigating the impacts of recurring landslide events. Reducing losses from landslides are important from the perspectives of ecosystem and infrastructure integrity, but most importantly from the standpoint of public safety.

Quantitative methods for landslide hazard assessment geared toward debris flow mapping and susceptibility modeling are well established, readily available, and are continually being improved. Landslide and landslide deposit inventories are important not only for identifying areas affected by recent and past landslide activity, but serve as important means to calibrate landslide models. These models do not substitute for site-specific stability assessments by qualified earth scientists, but provide a means at the planning level to identify potentially at-risk areas where detailed on-site analyses are warranted. The interdisciplinary technical and scientific capacity exists now to investigate, analyze, identify and delineate landslide prone areas of the landscape with increasing reliability. The March 22, 2014 landslide near Oso, Washington that killed 41 people is yet another reminder of the destructive power of landslides of all types, and the ongoing need to identify and map landslide hazard zones in mountain slopes.

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References

Abernethy, B., & Rutherfurd, I. D. (2001). The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological Processes, 15*, 63–79.

Albaugh, T. J., Allen, H. L., Dougherty, P. M., Kress, L. W., & King, J. S. (1998). Leaf area and above- and below-ground growth responses of loblolly pine to nutrient and water additions. *Forest Science, 44*, 317–328.

Bailey, J. F., Patterson, J. L., & Paulhus, J. L. H. (1975). Hurricane Agnes rainfall and floods June-July 1972. *United States Geological Survey, 924*, 403.

Band, L. E., Hwang, T., Hales, T. C., Vose, J. M., & Ford, C. R. (2011). Ecosystem processes at the watershed scale: Mapping and modeling ecohydrological controls of landslides. *Geomorphology, 137*, 159–167.

Bartholomew, M. J. (1977). Geology of the Greenfield and Sherando quadrangles, Virginia. *Virginia Division of Mineral Resources, 4*, 43. Charlottesville: Virginia Division of Mineral Resources.

Bauer, J. B., Wooten, R. M., Gillon, K. A., Douglas, T. J., Fuemmeler, S. J., Witt, A. C., & Latham, R. S. (2010). *Your country is falling apart: Response to recent landslides by the North Carolina Geological Survey*. Charleston: Abstract Association of Environmental and Engineering Geologists.

Bauer, J. B., Fuemmeler, S. F., Wooten, R. M., Witt, A. C., Gillon, K. A., & Douglas, T. J. (2012). Landslide hazard mapping in North Carolina – Overview and improvements to the program. In E. Eberhardt et al. (Eds.), *Landslides and engineered slopes: Protecting society through improved understanding. 11th International symposium on landslides and 2nd North American symposium on landslides, June 2–8 2012*. Banff.

Baum, R. L., Savage, W. Z., & Godt, J. W. (2002). *TRIGRS – A Fortran program for transient rainfall infiltration and grid-based regional slope-stability analysis* (US Geological Survey open-file report 02–424). Reston: US Geological Survey.

Bell, W. M. (1916). *The North Carolina flood: July 14,15,16, 1916* (pp. 1–86). Charlotte: Ramsey Library at University of North Carolina Asheville special collections.

Bogucki, D. J. (1976). Debris slides in the Mt. LeConte area, Great Smoky Mountains National Park, USA. *Geografiska Annaler, 58A*, 179–191.

Bryant, B., & Reed, J. C., Jr. (1970). *Geology of the Grandfather Mountain window and vicinity. North Carolina and Tennessee* (US Geological Survey Professional paper 615). Washington, DC: US Government Printing Office.

Bryant, L., Mauldon, M., & Mitchell, J. K. (2003). *Geotechnical problems with pyritic rock and soil* (pp. 1–88). Blacksburg: Center for Geotechnical Practice and Research, Virginia Polytechnic Institute and State University.

Burrows, M. T., Schoeman, D. S., Richardson, A. J., Molinos, J. G., Hoffmann, A., Buckley, L. B., Moore, P. J., Brown, C. J., Bruno, J. F., Duarte, C. M., Halpern, B. S., Hoegh-Guldberg, O., Kappel, C. V., Kiessling, W., O'Connor, M. I., Pandolfi, J. M., Parmesan, C., Sydeman, W. J., Ferrier, S., Williams, K. J., & Poloczanska, E. S. (2014). Geographical limits to species-range shifts are suggested by climate velocity. *Nature, 507*, 492–496.

Clark, G. M. (1987). Debris slide and debris flow historical events in the Appalachians south of the glacial border. In J. E. Costa & G. F. Wieczorek (Eds.), *Debris flows, avalanches: Process, recognition, and mitigation* (Reviews of engineering geology, Vol. 7, pp. 125–138). Boulder: Geological Society of America.

Clark, G. M. (1993). Quaternary geology and geomorphology of part of the Inner Piedmont of the southern Appalachians in the Columbus Promontory upland area, southwestern North Carolina and northwestern South Carolina. In T. L. Davis, R. D. Hatcher Jr (Eds.), *Studies of Inner Piedmont geology with a focus on the Columbus Promontory*. Field trip guidebook. Raleigh: Carolina Geological Society.

Clark, G. M., Ryan, P. T., Jr., & Drumm, E. C. (1987). Debris slides and debris flows on Anakeesta Ridge, Great Smoky Mountains National Park, Tennessee. In A. Schultz & C. Southworth (Eds.), *Landslides of eastern North America* (US Geological Survey Circular 1008, pp. 18–19). Washington, DC: US Government Printing Office.

Clingman, T.L. (1877). Water spouts. In J. Nichols (Ed.), *Selections from the speeches and writings of the Honourable Thomas L. Clingman of North Carolina with Additions and Explanatory Notes*. Raleigh: Afro-Americana Imprint.

Collins, T. K. (2008). Debris flows caused by failure of fill slopes: Early detection, warning, and loss prevention. *Landslides, 5*, 107–119.

Collins, T. K. (2014). Supplemental report geologic hazards assessment, plan revision Nantahala and Pisgah National Forests. http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3793002.pdf34p. Accessed 14 July 2014.

Crawford, M. M. (2014). Kentucky Geological Survey landslide inventory: From design to application. *Kentucky Geological Survey Information Circle, 31*, 18.

Crozier, M. J., Vaughan, E. E., & Tippett, J. M. (1990). Relative instability of colluvium-filled bedrock depressions. *Earth Surface Processes and Landforms, 15*, 329–339.

Cruden, D. M., & Varnes, D. J. (1996). Landslide types and processes. In A. K. Turner & R. L. Schuster (Eds.), *Landslides investigation and mitigation* (Special report (National Research Council (U.S.). Transportation Research Board), 247). Washington, DC: National Academy Press.

D'Odorico, P., & Fagherazzi, S. (2003). A probabilistic model of rainfall-triggered shallow landslides in hollows: A long-term analysis. *Water Resources Research, 39*, 1262.

Eaton, L. S., & Reynolds, S. H. (2002). Trends in vegetation recovery of the Kinsey Run Debris Fan, Madison County, Virginia. *Abstracts with Programs- Geological Society of America, 34*, 8.

Eaton, L. S., Morgan, B. A., Kochel, R. C., & Howard, A. D. (2003a). Quaternary deposits and landscape evolution of the central Blue Ridge of Virginia. *Geomorphology, 46*, 139–154.

Eaton, L. S., Morgan, B. A., Kochel, R. C., & Howard, A. D. (2003b). Role of debris flows in long-term landscape denudation in the central Appalachians of Virginia. *Geology, 31*(4), 339–342.

Eaton, L. S., Bailey, C. M., Gilmer, A. K. (2004). The debris flows of Madison County, Virginia. In *Virginia geological field conference guidebook 34th Annual Virginia Geology Field Conference.* Harrisonburg.

Eschner, A. R., & Patrick, J. H. (1982). Debris avalanches in eastern upland forests. *Journal of Forestry, 80*, 343–347.

Ford, C. R., Laseter, S. H., Swank, W. T., & Vose, J. M. (2011). Can forest management be used to sustain water-based ecosystem services in the face of climate change? *Ecological Applications, 21*, 2049–2067.

Ford, C. R., Elliott, K. J., Clinton, B. D., Kloeppel, B. D., & Vose, J. M. (2012). Forest dynamics following eastern hemlock mortality in the southern Appalachians. *Oikos, 121*, 523–536.

Fuemmeler, S. J., Douglas, T. J., Bauer, J. B., Wooten, R. M., Latham, R. S., Witt, A. C., & Gillon, K. A. (2008). Landslide hazard mapping, methodology and examples from North Carolina. In *Abstracts with programs*, Charlotte (Vol. 40, p. 12). Boulder: Geological Society of America.

Fuhrmann, C. M., Konrad, C. E., III, & Band, L. E. (2008). Climatological perspectives on the rainfall characteristics associated with landslides in western North Carolina. *Physical Geography, 29*, 289–305.

Gabet, E. J., & Dunne, T. (2003). A stochastic sediment delivery model for a steep Mediterranean landscape. *Water Resources Research, 39*, 9.

Genet, M., Stokes, A., Salin, F., Mickovski, S. B., Fourcaud, T., Dumail, J.-F., & van Beek, R. (2005). The influence of cellulose content on tensile strength of tree roots. *Plant and Soil, 278*, 1–9.

Gibbs, M. (2013). NC Department of Transportation damage report, NCDOT Div 14. Rockslide conference, Haywood Community College, Clyde, 5 June 2001.

Gillon, K. A., Wooten, R. M., Latham, R. L., Witt, A. W., Douglas, T. J., Bauer, J. B., & Fuemmeler, S. J. (2009). Integrating GIS-based geologic mapping, LiDAR-based lineament analysis and site specific rock slope data to delineate a zone of existing and potential rock slope instability located along the Grandfather Mountain Window-Linville Falls shear zone contact, southern Appalachian Mountains, Watauga County, North Carolina. In 43rd US rock mechanics symposium and 4th US-Can rock mechanics symposium 28 June–1 July 2009 (p. 13), 181, Asheville.

Godt, J. W. (1997). *Digital representation of landslide overview map of the conterminous United States. Open-File Report 97–289, scale 1:4,000,000*. Reston: US Geological Survey.

Godt, J. W., Baum, R. L., & Lu, N. (2009). Landsliding in partially saturated materials. *Geophysical Research Letters, 36*, L02403.

Grant, W. H. (1988). Debris avalanches and the origin of first-order streams. In W. T. Swank & D. A. Crossley Jr. (Eds.), *Ecological studies* (Forest hydrology and ecology at Coweeta, Vol. 6, pp. 103–110). New York: Springer.

Gryta, J. J., & Bartholomew, M. J. (1983). Debris-avalanche type features in Watauga County, North Carolina. In S. E. Lewis (Ed.), *Carolina Geological Society guidebook* (pp. 1–22). Boone: North Carolina Division of Land Resources, 21–23 October, article 5.

Gryta, J. J., & Bartholomew, M. J. (1989). Factors influencing the distribution of debris avalanches associated with the 1969 Hurricane Camille in Nelson County, Virginia. In A. P. Schultz & R. W. Jibson (Eds.), *Landslide processes of the eastern United States and Puerto Rico* (Special paper (Geological Society of America), 236, pp. 15–28). Boulder: Geological Society of America.

Hack, J. T. (1982). *Physiographic divisions and differential uplift in the Piedmont and Blue Ridge* (US Geological Survey professional paper, 1265). Washington, DC: US Government Printing Office.

Hack, J. T., & Goodlett, J. C. (1960). *Geomorphology and forest ecology of a mountain region in the Central Appalachians* (US Geological Survey professional paper, 347). Washington, DC: US Government Printing Office.

Hales, T. C., & Miniat, C. F. (2015). Root reinforcement and slope stability dynamically adjust to soil moisture. *Earth Surface Process and Landforms.*

Hales, T. C., Ford, C. R., Hwang, T., Vose, J. M., & Band, L. E. (2009). Topographic and ecologic controls on root reinforcement. *Journal of Geophysical Research, 114*, F03013.

Hales, T. C., Scharer, K. M., & Wooten, R. M. (2011). Southern Appalachian hillslope erosion rates measured by soil and detrital radiocarbon in hollows. *Geomorphology, 138*, 121–129.

Hales, T. C., Cole-Hawthorne, C., Lovell, L., & Evans, S. (2013). Assessing the accuracy of simple field based root strength measurements. *Plant and Soil, 372*, 553–56.

Hansen, A. J., Neilson, R. P., Dale, V. H., Flather, C. H., Iverson, L. R., Currie, D. J., Shafer, S., Cook, R., & Bartlein, P. J. (2001). Global change in forests: Responses of species, communities, and biomes. *BioScience, 51*, 765–779.

Hatcher, R. D., Jr. (1989). Tectonic synthesis of the US Appalachians. In R. D. Hatcher Jr., W. A. Thomas, & G. W. Viele (Eds.), *The Appalachian-Ouachita orogen in the United States, vol F-2*. Boulder: Geological Society of America.

Hatcher, R. D., Jr. (2010). The Appalachian orogen: A brief summary. In R. P. Tollo, M. J. Bartholomew, J. P. Hibbard, & P. M. Karabinos (Eds.), *From Rodinia to Pangea: The lithotectonic record of the Appalachian region* (Memoir (Geological Society of America), 206, pp. 1–19). Boulder: Geological Society of America.

Heller, M.J., Hancock, G. S., & Carter, M. W. (2014). Structure and geomorphology at the Blue Ridge-Valley and Ridge boundary near Big Levels, Virginia. In *Abstracts with programs*, Geological Society of America Southeast Sect 46:12, Blacksburg. Boulder: Geological Society of America.

Henry, A. J. (1916). Floods in the east Gulf and South Atlantic states, July 1916. *Monthly Weather Review, 44*, 431–498.

Hibbard, J., van Stall, C., Rankin, D., & Williams, H. (2006). *Lithotectonic map of the Appalachian orogen (south), Canada-United States of America* (Map (Geological Survey of Canada), 2069A). Ottawa: Geological Survey of Canada. scale 1:1500000.

Holmes, J. S. (1917). Some notes on the occurrence of landslides. *Journal of the Elisha Mitchell Society, 33*, 100–105.

Hwang, T., Hales, T. C., Miniat, C. F., Vose, J. M., Bolstad, P. V., Miles, B., & Price, K. (2015). Simulating vegetation controls on hurricane-induced shallow landslides with a distributed eco-hydrological model. *J of Geophysical Research-Biogeosciences*. doi:10.1002/2014JG002824.

Jacobson, R. B. (Ed.). (1993). *Geomorphic studies of the storm and flood of November 3–5, 1985, in the Upper Potomac and Cheat River Basins in West Virginia and Virginia* (187p). Bulletin 1981. Reston: US Geological Survey.

Joslin, J. D., Wolfe, M. H., & Hanson, P. J. (2000). Effects of altered water regimes on forest root systems. *New Phytologist, 147*, 117–129.

Judson, S., & Ritter, D. F. (1964). Rates of regional denudation in the United States. *Journal of Geophysical Research, 69*, 3395–3401.

Keim, R. F., & Skaugset, A. R. (2003). Modelling effects of forest canopies on slope stability. *Hydrological Process, 17*, 1457–1467.

Keyes, M. R., & Grier, C. C. (1981). Above- and below-ground net production in 40-year-old Douglas-fir stands on low and high productivity sites. *Canadian Journal of Forest Research, 11*, 599–605.

Kochel, R. C. (1987). Holocene debris flows in central Virginia. In J. E. Costa & G. F. Wieczorek (Eds.), *Debris flows, avalanches: Process, recognition, and mitigation* (Review in engineering geology, 7, pp. 139–155). Boulder: Geological Society of America.

Kochel, R. C. (1990). Humid fans of the Appalachian Mountains. In A. H. Rachocki & M. Church (Eds.), *Alluvial fans: A field approach* (pp. 109–129). New York: Wiley.

Kochel, R. C., & Johnson, R. A. (1984). Geomorphology, sedimentology, and depositional processes of humid- temperate alluvial fans in central Virginia. In E. Koster & R. Steel (Eds.), *Gravels and conglomerates* (Canadian Society of Petroleum Geologists, 10, pp. 109–122). Calgary: Canadian Society of Petroleum Geologists.

Latham, R. S., Wooten, R., Witt, A. C., & Brame, S. (2006). Investigation of the Peeks Creek debris flow of September 2004, Macon County, North Carolina. *14th annual David S. Snipes/Clemson hydrogeology symposium field trip guidebook*. Clemson: Clemson University.

Latham, R. S., Wooten, R. M., Cattanach, B. L., Merschat, C. E., & Bozdog, G. N. (2009). Rock slope stability analysis along the North Carolina section of the Blue Ridge Parkway: Using a geographic information system (GIS) to integrate site data and digital geologic maps. *43rd US rock mechanics symposium and 4th US-Canadian rock mechanics symposium* (p. 12). American Rock Mechanics Association, 28 June–1 July 2009, 171.

Lee, L. G., Tanner, P. A., Horne, C. S., & Greer, S. (2011). The Qualla Boundary flash flood of 14 and 15 July 2011. http://www.erh.noaa.gov/er/gsp/localdat/cases/2011/14JulyQuallaBoundaryFF. Accessed 14 July 2014.

Leigh, D. (2009). Geomorphic assessment of the Ferrebee Memorial Park at Bridge 3 along the Nantahala River, US Highway 74, Swain County North Carolina, unpublished report. In T. Benyshek (Ed.), *Archeological deep testing and geomorphic study for the proposed replacement of bridge 3 across the Nantahala River*, TIP-4286, Swain County, North Carolina, Appendix 1:11.

Lewis, Y. W., Wayllace, A., Lu, N., Godt, J. W., & Wooten, R. M. (2013). Hydro-mechanical properties and stability analysis of four landslide-prone hillslopes. In: *Abstracts with programs*, Denver, 27–30 Oct 2013 (Vol. 45, p. 720). Boulder: Geological Society of America.

Lu, N., Godt, J. W., & Wu, D. T. (2010). A closed-form equation for effective stress in variably saturated soil. *Water Resources Research, 46*, 5.

Mazza, N. A., & Wieczorek, G. F. (1997). A volumetric sediment analysis for Kinsey Run debris flow, triggered during an extreme storm event, Madison, County, Virginia. In *Abstracts with programs* (p. 64). Geological Society of America, Northeast section, 29:1. Boulder: Geological Society of America.

Miller, D. K., Barros, A. P., Lee, L., Wilson, A. M., & Wooten, R. (2012). Weather conditions leading to the Gunter Fork Trail debris flows of 14–15 July. In: Abstract, 2011 Great Smoky Mountain Science Colloquium, 22 Mar 2011.

Mills, H. H. (1982). Long-term episodic deposition on mountain foot slopes in the Blue Ridge Province of North Carolina; evidence from relative-age dating. *Southeastern Geology, 23*, 123–128.

Mills, H. H. (1998). Surficial deposits and landforms on the south and west piedmont slopes of Roan Mountain, Mitchell County, North Carolina. In *Southeastern Friends of the Pleistocene 1998 Field Trip Guidebook* (pp. 9–34), Boone.

Mills, H. H., & Allison, J. B. (1995a). Weathering rinds and the evolution of Piedmont slopes in the southern Blue Ridge Mountains. *Journal of Geology, 103*, 379–394.

Mills, H. H., & Allison, J. B. (1995b). Controls on the variation of fan-surface age in the Blue Ridge Mountains of Haywood County, North Carolina. *Physical Geography, 15*, 465–480.

Mills, H. H. & Grainger, D. E. (2002). Cosmogenic isotope burial dating reveals 1.5 million-year-old fan deposit in Blue Ridge Mountains of North Carolina. In *Abstracts with programs* (pp. A–32), Geological Society of America, 34, Lexington. Boulder: Geological Society of America.

Mills, H. H., Brakenridge, R. G., Jacobson, R. B., Newell, W. L., Pavich, M. J., & Pomeroy, J. S. (1987). Appalachian mountains and plateaus. In W. L. Graf (Ed.), *Geomorphic systems of North America* (Centennial special, Vol. 2, pp. 5–50). Boulder: Geological Society of America.

Montgomery, D. R., & Dietrich, W. E. (1994). A physically based model for the topographic control on shallow landsliding. *Water Resources Research, 30*, 1153–1171.

Morgan, G. A., & Wieczorek, G. F. (1996). *Debris flows and landslides resulting from the June 27, 1995 storm in the North Fork Moormans River, Shennandoah National Park, Virginia*. US Geological Survey Open-File Report 96-503. 10p map scale 1:24000. Reston: US Geological Survey.

Morgan, B. A., Wieczorek, G. F., Campbell, R. H., & Gori, P. L. (1997). *Map showing debris-flow hazards in areas affected by the June 27, 1995 storm in Madison County, Virginia*. US Geological Survey Open File Report 97-438. map scale 1:24,000. Reston: US Geological Survey.

Morgan, B. A., Iovine, G., Chirico, P., & Wieczorek, G. F. (1999a). *Map Inventory of debris flows and floods in the Lovingston and Horseshoe Mountain, Virginia, 7.5-minute quadrangles, from the August 19–20, 1969, storm in Nelson County, Virginia*. US Geological Survey Open-File Report 99-0518. Reston: US Geological Survey.

Morgan, B. A., Wieczorek, G. F., & Campbell, R. H. (1999b). *Map of rainfall, debris flows, and flood effects of the June 27, 1995, storm in Madison County, Virginia*. US Geological Survey Investigations Series Map I-2623A. map scale 1:24,000. Reston: US Geological Survey.

Morrissey, M. M., Wieczorek, G. F., & Morgan, B. A. (2004). Transient hazard model using rada data for predicting debris flows in Madison County, Virginia. *Environmental and Engineering Geoscience, 5*, 285–296.

Myers, E. W. (1902). A study of the southern river floods of May and June 1901. *Engineering News and American Railway Journal, 48*, 102–104.

Neary, D. G., & Swift, L. W., Jr. (1987). Rainfall thresholds for triggering a debris avalanching event in the southern Appalachian Mountains. In J. E. Costa & G. F. Wieczorek (Eds.), *Debris flows, avalanches: Process, recognition, and mitigation* (Geological Society of America Review Engineering Geology, Vol. 7, pp. 81–92).

Neary, D. G., Swift, L. W., Jr., Manning, D. M., & Burns, R. G. (1986). Debris avalanching in the southern Appalachians: An influence on forest soil formation. *Soil Science Society of America Journal, 50*, 465–471.

O'Loughlin, C., & Watson, A. J. (1979). Root wood strength deterioration in Pinus radiata after clearfelling. *New Zealand Journal of Forestry Science, 9*, 284–293.

Otteman, R. (2001). *Using GIS to model debris flow susceptibility for the Bent Creek Experimental Forest near Asheville, North Carolina*. Thesis, Greenville: East Carolina University.

Ownby, S. E., Miller, C. F., Berquist, P. J., Carrigan, C. W., Wooden, J. L., & Fullagar, P. D. (2004). U-Pb geochronology and geochemistry of a portion of the Mars Hill terrane, North Carolina–Tennessee: Constraints on origin, history, and tectonic assembly. In R. P. Tollo, J. McLelland, & M. J. Bartholomew (Eds.), *Proterozoic tectonic evolution of the Grenville orogen in North*

America (Memoir (Geological Society of America), 197, pp. 609–632). Boulder: Geological Society of America.

Pack, R. T., Tarboton, D. G., & Goodwin, C. N. (1998). *Terrain stability mapping with SINMAP, technical description and users guide for version 1.00, 4114-0*. Terratech Consulting Ltd, Salmon Arm, British Columbia.

Pollen, N., & Simon, A. (2005). Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. *Water Resources Research, 41*, W07025.

Pomeroy, J. S. (1980). Storm-induced debris avalanching and related phenomena in the Johnstown area, Pennsylvania, with references to other studies in the Appalachians. *US Geological Survey Professional Paper, 1191*, 24.

Pomeroy, J. S. (1984). Storm-induced slope movements at East Brady, northwestern Pennsylvania. *US Geological Survey Bulletin, 1618*, 16.

Pomeroy, J. S. (1991). Map showing late 1977 debris avalanches southwest of Asheville, western North Carolina. US Geological Survey open file report 91–334, map scale 1:24,000.

Pontrelli, M. D., Bryan, G., & Fritsch, J. M. (1999). The Madison County, Virginia, flash flood of 27 June 1995. *Weather and Forecast, 14*, 384–404.

Reneau, S. L., & Dietrich, W. E. (1987). The importance of hollows in debris flow studies; Examples from Marin County, California. In J. E. Costa, G. F. Wieczorek (Eds.), *Debris flows/avalanches: Process, recognition, and mitigation*: *Vol. 7. Reviews in engineering geology* (pp. 165–180). Boulder: Geological Society of America.

Roering, J. J., Schmidt, K. M., Stock, J. D., Dietrich, W. E., & Montgomery, D. R. (2003). Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range. *Canadian Geotechnical Journal, 40*, 237–253.

Roth, D. M. (2015). Tropical Cyclone Rainfall in the Southeastern United States Tropical Rainfall Point Maxima. Available via http://www.hpc.ncep.noaa.gov/tropical/rain/tcmaxima.html, Hydrometeorological Prediction Center, United States National Oceanic and Atmospheric Administration, National Weather Service. Accessed 7 Feb 2015.

Sakals, M. E., & Sidle, R. C. (2004). A spatial and temporal model of root cohesion in forest soils. *Canadian Journal of Forest Research, 34*, 950–958.

Sas, R. J., & Eaton, L. S., Jr. (2008). Quartzite terrains, geologic controls, and basin denudation by debris flows: Their role in long term landscape evolution in the central Appalachians. *Landslides, 5*, 97–106.

Schmidt, K., Roering, J. J., Stock, J. D., Dietrich, W. E., Montgomery, D. R., & Schaub, T. (2001). The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. *Canadian Geotechnical Journal, 38*, 995–1024.

Schneider, R. H. (1973). *Debris slides and related flood damage resulting from Hurricane Camille 19–20 August, and subsequent storm, 5–6 September, 1969 in the Spring Creek drainage basin, Greenbrier County, West Virginia*. Dissertation, University of Tennessee.

Schrader, F. E. (1945). *Notable local floods of 1939; Part 2. Flood of July 5, 1939 in eastern Kentucky*: *US Geological Survey water-supply paper no 967-B* (pp. 41–59). Washington DC: US Government Printing Office.

Schwarz, M., Cohen, D., & Or, D. (2010). Root-soil mechanical interactions during pullout and failure of root bundles. *Journal of Geophysical Research, 115*, F04035. doi:10.1029/2009JF001603.

Scott, R. C. Jr. (1972). *Geomorphic significance of debris avalanching in the Appalachian Blue Ridge Mountains*. Dissertation, University of Georgia.

Seiwa, K., Miwa, Y., Akasaka, S., Kanno, H., Tomita, M., Saitoh, T., Ueno, N., Kimura, M., Hasegawa, Y., Konno, M., & Masaka, K. (2013). Landslide-facilitated species diversity in a beech-dominant forest. *Ecological Research, 28*, 29–41.

Selby, M. J. (1993). *Hillslope materials and processes*. Oxford: Oxford University Press.

Sidle, R. C., & Ochiai, H. (2006). Landslides: Processes, prediction and land use. *American Geophysical Union, Water Resources Monograph, 18*, 312.

Sidle, R. C., Ziegler, A. D., Negishi, J. N., Nik, A. R., Siew, R., & Turkelboom, F. (2006). Erosion processes in steep terrain-Truths, myths, and uncertainties related to forest management in southeast Asia. *Forest Ecology and Management, 224*, 199–225.

Silver, T. (2003). *Mount Mitchell and the Black Mountains: An environmental history of the highest peaks in eastern America*. Chapel Hill: University of North Carolina Press.

Simpson, P. S., & Simpson, J. H. (1970). *Torn land*. Lynchburg: JP Bell Co.

Soller, D. R., & Mills, H. H. (1991). Surficial geology and geomorphology. In J. W. Horton & V. A. Zullo (Eds.), *The geology of the Carolinas* (pp. 290–308). Knoxville: University of Tennessee Press.

Southworth, S., Schultz, A., Aleinkoff, J. N., & Merschat, A. J. (2012). *Geologic map of the Great Smoky Mountains National Park region, Tennessee and North Carolina*: Scientific investigations map 2997, scale 1:100,000. Reston: US Geological Survey.

Tao, J., & Barros, A. P. (2014). Coupled prediction of flood response and debris flow initiation during warm- and cold-season events in the southern Appalachians, USA. *Hydrology Earth System Sciences, 18*, 367–388.

Tao, J., Wilson, A. M., Barros, A. P., Wooten, R. M. (2012). *Using a spatially dense, high elevation rain gauge network and a hydrologic model to enhance predictability of landslides in the southern Appalachians*: *Abstracts with programs (p. 420) 44:7*, Charlotte. Boulder: Geological Society of America.

Tennessee Valley Authority. (1940). *Floods of August 1940 in Tennessee River Basin*. Report no. 0-243-67S. Knoxville: TVA Water Control Planning Department, Hydraulic Data Division.

Tennessee Valley Authority. (1964). *Floods on the French Broad River, Davidson River, King Creek, Nicholson Creek in the vicinity of Brevard, NC*. Report no. 0–6373. Knoxville: TVA Water Control Planning Department, Hydraulic Data Division.

Turner, M. G., Pearson, S. M., Bolstad, P. V., & Wear, D. N. (2003). Effects of land-cover change on spatial pattern of forest communities in the southern Appalachian Mountains (USA). *Landscape Ecology, 18*, 449–464.

US Department of Agriculture. (1902). *Message from the President of the United States transmitting a report of the Secretary of Agriculture in relation to the forests, rivers, and mountains of the southern Appalachian region*. Washington, DC: Government Printing Office.

US Department of Agriculture – Forest Service. (2014). Assessment for the Nantahala and Pisgah National Forests. http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3793034.pdf. Accessed 14 July 2014.

US Geological Survey. (1949). *Floods of August 1940 in the southeastern states. US Geological Survey water supply paper 1066*. Washington, DC: US Government Printing Office

Waldron, L. J. (1977). The shear resistance of root-permeated homogeneous and stratified soil. *Journal of the Soil Science Society of America, 41*, 843–849.

White, P. S., Collins, B., & Wein, G. (2011). Natural disturbances and early successional habitats. In C. H. Greenberg, F. R. Thompson III, & B. S. Collins (Eds.), *Sustaining Young Forest Communities: Ecology and management of early successional habitats in the Central Hardwood Region, USA*. New York: Springer.

Whittecar, G. R., & Ryter, D. W. (1992). Boulder streams, debris fans, and Pleistocene climate change in the Blue Ridge Mountains of Central Virginia. *Journal of Geology, 100*, 487–494.

Wieczorek, G. F., Gori, P. L., Campbell, R. H., & Morgan, B. A. (1995). *Landslide and debris-flow hazards caused by the June 27, 1995, storm in Madison County, Virginia (includes discussion of mitigation options)*: *US Geological Survey open-file report 95-822*. Reston: US Geological Survey.

Wieczorek, G. F., Morgan, B. A., & Campbell, R. H. (2000). Debris flow hazards in the Blue Ridge of Central Virginia. *Environmental and Engineering Geoscience, VI*, 3–23.

Wieczorek, G. F., Mossa, G. S., & Morgan, B. A. (2004). Regional debris flow distribution and preliminary risk assessment from severe storm events in the Appalachian Blue Ridge Province, USA. *Landslides, 1*, 53–59.

Wieczorek, G. F., Eaton, L. S., Morgan, B. A., Wooten, R. M., & Morrissey, M. (2009). *An examination of selected historical rainfall-induced debris-flow events within the central and southern Appalachian Mountains of the eastern United States*: US Geological Survey open-file report 2009-1155. Reston: US Geological Survey.

Williams, G. P., & Guy, H. P. (1971). Debris-avalanches; A geomorphic hazard. In D. R. Coates (Ed.), *Environmental geomorphology, 1st annual geomorphology symposia series* (pp. 25–46). Binghamton State University of New York Publication in Geomorphology.

Williams, G. P., & Guy, H. P. (1973). *Erosional and depositional aspects of Hurricane Camille in Virginia, 1969*. US Geological Survey prof paper 804.

Winandy, J. E., & Rowell, R. M. (2005). Chemistry of wood strength. In R. M. Rowell (Ed.), *Handbook of wood chemistry and wood composites* (pp. 303–347). Boca Raton: CRC Press.

Witt, A. C. (2005). A brief history of debris flow occurrence in the French Broad River Watershed, western North Carolina. *The North Carolina Geographer, 13*, 58–82.

Witt, A. C., & Heller, M. J. (2012). Landslide hazard mapping in Page County, Virginia: GIS processes and preliminary findings. In *Abstracts with programs* (p. 467): Geological Society of America 44:7, Charlotte. Boulder: Geological Society of America.

Witt, A. C., & Heller, M. J. (2013). Development of a landslide hazard mapping project in Page County, Virginia: Preliminary results and methods. 13th annual technical forum on geohazards in transportation in the Appalachian Region, 31 July–1 August 2013, Harrisonburg.

Witt, A. C., & Heller, M. J. (2014). Landslide hazard mapping in Page County, Virginia: Processes, results and lessons learned. In *Abstract with programs* (p. 23). Geological Society of America 46, Blacksburg. Boulder: Geological Society of America.

Witt, A. C., Smith, M. S., Latham, R. S., Douglas, T. J., Gillon, K. A., Fuemmeler, S. J., Bauer, J. B., & Wooten, R. M. (2007a). Life, death and landslides: the August 13–14, 1940 storm event in Watauga County, North Carolina. In *Abstract with programs* (p. 76). Geological Society of America Southeast Section 39, Savannah. Boulder: Geological Society of America.

Witt, A. C., Wooten, R. M., Latham, R. S., Fuemmeler, S. J., Gillon, K. A., Douglas, T. J., & Bauer, J. B. (2007b). A comparative study of two GIS slope stability models for use in the North Carolina landslide hazard mapping program. In V. R. Schaefer, R. L. Schuster, A. K. Turner (Eds.), *Conference presentations 1st North America landslide conference*, Vail Colo, Association of Engneering and Environmental Geologist Special Publication, Vail.

Witt, A. C., Wooten, R. M., Gillon, K. A., Latham, R. S., Douglas, T. J., Fuemmeler, S. J., & Bauer, J. B. (2008). Using an observational database in the preliminary statistical analysis of debris flow run out and its application to inundation modeling in Watauga County, North Carolina, USA. 33rd international geological congress, 6–14 Aug 2008, Oslo.

Witt, A. C., Wooten, R. M., Gillon, K. A., Douglas, T. J., Fuemmeler, S. F., & Bauer, J. B. (2012). Determining potential debris flow inundation zones for an emergency response using LAHARZ: The Ghost Town debris flow, Maggie Valley, North Carolina, USA. In E. Eberhardt, C. Froes, A. K. Turner, S. Leroueil (Eds.), *Landslides and engineered slopes: Protecting society through improved understanding*, 11th international symposium on landslides and 2nd North America symposium on landslides, 2–8 June 2012, Banff.

Witt, A. C., Heller, M. J., & Eaton, L. S. (in press). *Slope movement hazard maps of Page County, Virginia*. Division of Geology and Mineral Resources, 3 sheets, map scale 1:48,000. Charlottesville: Virginia Department of Mines Minerals and Energy.

Wooten, R. M., Latham, R. S. (2004). *Report on the May 5–7, 2003 debris flows on slopes underlain by sulfidic bedrock of the Wehutty, Nantahala, and Copper Hill Formations, Swain County, North Carolina*. North Carolina Geological Survey Report of Investigations to North Carolina Division of Emergency Management. Raleigh: North Carolina Geological Survey.

Wooten, R. M., Latham, R. S. (2006). *August 31, 2006 Embankment Failure – Debris Flow at the Cascades Development, Haywood County, North Carolina*. North Carolina Geological Survey report of Investigation to Haywood County Erosion and Sedimentation Control Officer. Raleigh: North Carolina Geological Survey.

Wooten, R. M., Carter, M. W., & Merschat, C. E. (2003a). Geology of Gorges State Park. *North Carolina Geological Survey Information Circular, 31*, 60.

Wooten, R. M., Merschat, C. E., & Carter, M. W. (2003b). *Map of slope movements and related surficial deposits, Gorges State Park, Transylvania County, North Carolina*. North Carolina Geological Survey Geologic Map Series 10-B, map scale 1:12,000. Raleigh: North Carolina Geological Survey.

Wooten, R. M., Latham, R. S., Clinton, B. D., Reid, J. C., & Idol, T. (2004). The August 13, 1916 Lake Toxaway dam failure in Gorges State Park, Transylvania County, North Carolina: A retrospective from the geologic record. In Poster, 12th annual David W. Snipes Clemson University hydrogeology symposium, Clemson University.

Wooten, R. M., Reid, J. C., Latham, R. S., Medina, M. A., Bechtel, R., & Clark, T. W. (2005). An overview of the North Carolina Geological Survey's geologic hazards program – phase I: In Proceedings of 56th highway geological symposium, Wilmington, NC, 4–6 May 2005.

Wooten, R. M., Latham, R. S., Witt, A. C., Fuemmeler, S. J., Gillon, K. A., Douglas, T. J., & Bauer, J. B. (2006). *Slope movement hazard maps of Macon County, North Carolina*, North Carolina Geological Survey, Geologic Hazard Map Series 1, 3 sheets, map scale 1:48,000. Raleigh: North Carolina Geological Survey.

Wooten, R. M., Latham, R. S., Witt, A. C., Gillon, K. A., Douglas, T. J., Fuemmeler, S. J., Bauer, J. B., & Reid, J. C. (2007). Landslide hazards and landslide hazard mapping in North Carolina. In V. R. Schaefer, R. L. Schuster, A. K. Turner (Eds.), 1st North America landslide conference, Association of Engineering and Environmental Geologist Special Publication 23 (pp. 458–471), Vail.

Wooten, R. M., Gillon, K. A., Witt, A. C., Latham, R. S., Douglas, T. J., Bauer, J. B., Fuemmeler, S. J., & Lee, L. G. (2008a). Geologic, geomorphic, and meteorological aspects of debris flows triggered by Hurricanes Frances and Ivan during September 2004 in the southern Appalachian Mountains of Macon County, North Carolina (southeastern USA). *Landslides, 5*, 31–44.

Wooten, R. M., Witt, A. C., Gillon, K. A., Douglas, T. J., Latham, R. S., Fuemmeler, S. J., & Bauer, J. B. (2008b). *Slope movement hazard maps of Watauga County, North Carolina*. North Carolina Geological Survey Geologic Hazard Map series 3, 4 sheets, map scale 1:36,000. Raleigh: North Carolina Geological Survey.

Wooten, R. M., Gillon, K. A., Douglas, T. J., Witt, A. C., Bauer, J. B., & Fuemmeler, S. J. (2009a). *Report on the Bear Trail debris flow of January 7, 2009a*. North Carolina Geological Survey Report of investigation to Haywood County Erosion and Sedimentation Control Officer. Raleigh: North Carolina Geological Survey.

Wooten, R. M., Witt, A. C., Gillon, K. A., Douglas, T. J., Fuemmeler, S. J., Bauer, J. B., & Latham, R. S. (2009b). *Slope movement hazard maps of Buncombe County, North Carolina*. North Carolina Geological Survey Geologic Hazard Map Series 4, 3 sheets, map scale 1:52,000. Raleigh: North Carolina Geological Survey.

Wooten, R. M., Latham, R. S., Gillon, K. A., Bauer, J. B., Merschat, C. E., & Carter, M. W. (2010a). Stop 3- Lake Toxaway Dam. In J. Gill-Shaler (Ed.), From the Atlantic to the Appalachians and Back!, 2010, Annual meeting, fieldtrip #1 guidebook, Association of Environmental and Engineering Geologist, Charleston.

Wooten, R. M., Witt, A. C., Douglas, T. J., Gillon, K. A., Fuemmeler, S. J., Bauer, J. B., Latham, R. S., & Nickerson, J. G. (2010b). The North Carolina Landslide Program: 3864 km^2 mapped and 6,042 landslide features later – Findings and observations. In *Abstracts with programs*, 2010. Annual meeting, Association of Environmental and Engineering Geologists, Charleston. Denver: Association of Environmental and Engineering Geologists.

Wooten, R. M., Witt, A. C., Douglas, T. J., Fuemmeler, S. J., Bauer, J. B., Gillon, K. A., & Latham, R. S. (2011). *Digital data and maps of the slope movement hazards for Henderson County, North Carolina*. North Carolina Geological Survey Digital Data Series Geologic Hazard Map Series 5 (DDS-GHMS-5). Raleigh: North Carolina Geological Survey.

Wooten, R. M., Douglas, T. J., Bauer, J. B., Fuemmeler, S. J., Gillon, K. G., Witt, A. C., & Latham, R. S. (2012). Geologic, geomorphic and geotechnical aspects of debris flow initiation sites in the Blue Ridge Mountains of western North Carolina at study locations in Buncombe, Haywood, Henderson, Jackson, Macon, Transylvania and Watauga Counties. In *Abstracts with programs* (p. 147), Charlotte. Boulder: Geological Society of America 44.

Wooten, R. M., Cattanach, B. L., Bozdog, G. N., & Bullard, A. R. (2014). The North Carolina Geological Survey's response to landslide events in 2012 and 2013 in the Blue Ridge Mountains of western North Carolina: Using a geodatabase, LiDAR and ortho-imagery in a geographic information system to augment field investigations and map production. In *Abstract with programs* (p. 23): Geological Society of America Southeast Sect 46, Blacksburg. Boulder: Geological Society of America.

Young, C. H. (1973). Investigation of landslides resulting from severe storm. USDA Forest Service in-house report, 11 June 1973, Nat For in North Carolina, Asheville.

Zeedyk, W. D. (1973). *Storm and flood report – National Forests in North Carolina*. USDA Forest Service in-house report, 13 June 1976 Nat For in North Carolina, Asheville.