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G. F. Wieczorek · G. S. Mossa · B. A. Morgan

Regional debris-flow distribution and preliminary risk assessment from severe storm events in the Appalachian Blue Ridge Province, USA

Abstract Storms of high-intensity rainfall, including hurricanes, occur about once every 3 years in small areas of the mountains of the eastern United States posing a high debris-flow hazard. Reported casualties and monetary losses are often an insufficient and inadequate means for comparing the impact from debris flows. A simple GIS technique was used to characterize the distribution and density of debris flows for making a preliminary assessment of risk of impact on roads. This technique was used for comparison of three major severe storms resulting in numerous debris flows: August 10–17, 1940, near Deep Gap, North Carolina; August 19–20, 1969, in Nelson County, Virginia; and June 27, 1995, in Madison County, Virginia. Based on the criteria of the number of debris flows and area covered by debris flows, the August 19–20, 1969, Nelson County, Virginia, event was the most severe of the three storms and posed the greatest risk of debris-flow impact on roads.

Keywords Debris-flow hazard · Impact and risk · Intense rainfall · North Carolina · Virginia · United States

Introduction

Historically severe storm events with high-intensity, long-duration rainfall have triggered numerous shallow, rapidly moving landslides, i.e. debris flows, resulting in casualties and property damage in small parts of the Appalachian Mountains of the eastern United States. Hurricanes, downgraded to tropical storms or depressions after coming inland, typically can have irregular paths and result in heavy amounts of rainfall. Clark (1987) reported 51 historical storm events that triggered debris flows between 1844 and 1985, south of the glacial border in the Blue Ridge and Valley and Ridge Provinces of the Appalachian Mountains from Georgia to Pennsylvania. This number of events is equivalent, on average, to about one storm every three years. Only a few of these storms and the resulting hazardous impacts from debris flows have been well documented (Hack and Goodlet 1960; Williams and Guy 1973; Kochel 1987; Gryta and Bartholomew 1989; Jacobson 1993; Wieczorek et al. 2000).

For individual storms, the number of casualties or estimates of economic damage are often the only available means for comparing the magnitude of impact of different events, and even these are generally not sufficiently accurate for distinguishing the differences between flood and debris-flow damage. In fact, the damage estimates from floods and landslides in catastrophic storms prepared by the US Federal Emergency Management Agency (FEMA) prior to the time of a Federal Disaster Declaration by the President of the United States are usually estimates based on preliminary information available immediately following a storm before detailed damage assessments can be made (Ellen et al. 1988).

The object of this paper is to develop techniques for characterizing debris-flow distribution and density in order to compare debris-flow impact as an evaluation of preliminary risk for different storm events. These methods were applied to three major storms in the Blue Ridge Mountains of North Carolina and Virginia that triggered abundant debris flows.

Major debris-flow storm events in the Blue Ridge

During August 1940, the southeastern United States experienced two major storms that caused damage of about US$30 million (US Geological Survey 1949). The first and larger of these two storms occurred during the week of August 10–17, 1940, when the southeastern states of Georgia, Tennessee, North Carolina, and Virginia were subjected to damages inflicted by a severe hurricane. Twenty-six people were reportedly killed in North Carolina during this storm where flooding in many rivers was at a historical maximum (US Geological Survey 1949). The track of the storm was highly erratic, coming ashore near Savannah, Georgia, passing through Atlanta, Georgia, then swinging in a broad western arc west of Knoxville, Tennessee, then easterly across North Carolina and southern Virginia (Fig. 1). One of the most significant features associated with this storm was the large number of shallow debris flows in steep forested terrain that traveled into small valleys with streams and rivers along the Blue Ridge in North Carolina (Fig. 2A). The center of the storm with

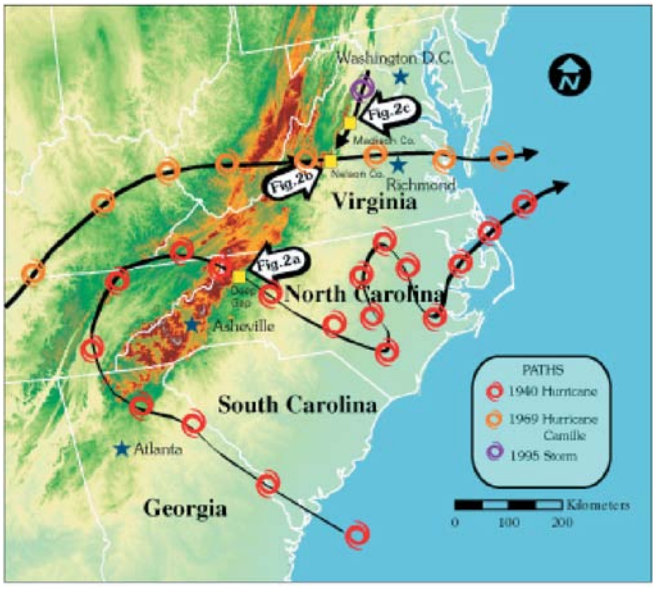

Fig. 1 Shaded relief map of southeastern United States showing storm tracks and study areas (*yellow boxes*) of debris-flow events in Deep Gap, North Carolina, Nelson County, Virginia, and Madison County, Virginia

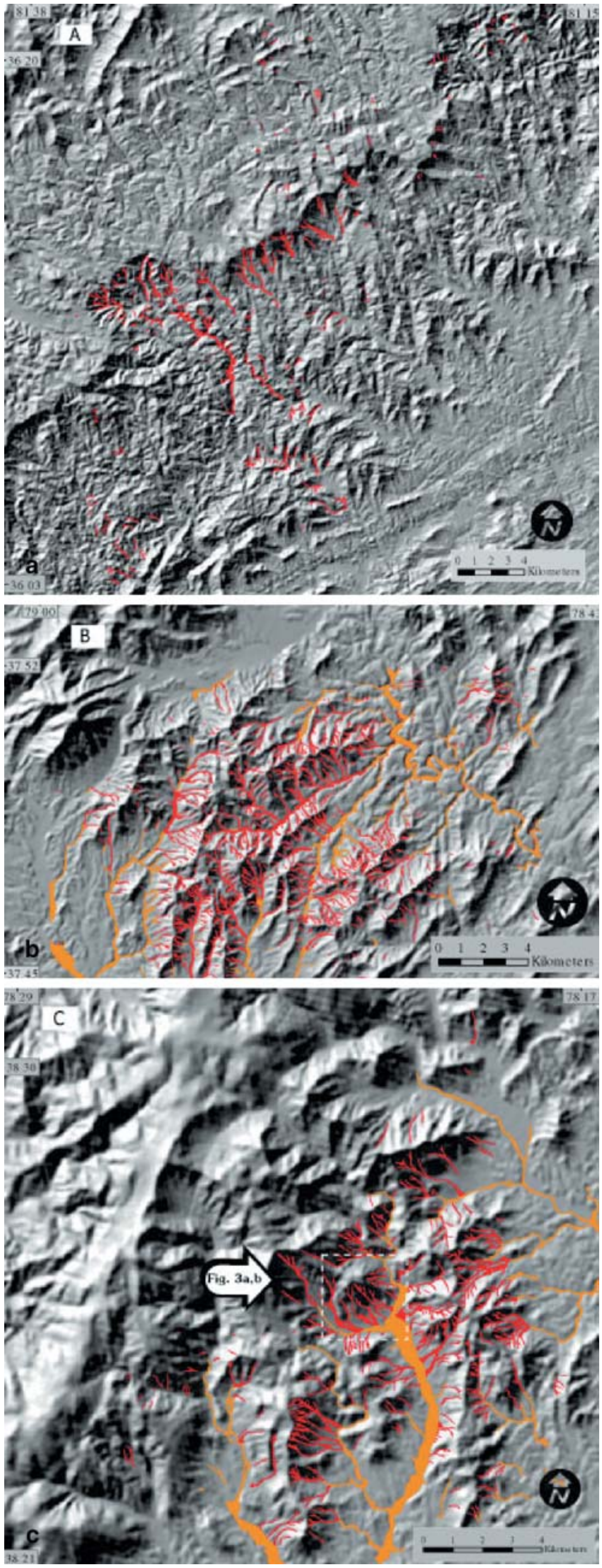

Fig. 2 Shaded relief maps with inventories of debris flows (*red*) and flooding (*orange*) in Blue Ridge storms: **A** Deep Gap, North Carolina, August 10–17, 1940 storm, **B** Nelson County, Virginia, August 19–20, 1969, and **C** Madison County, Virginia, June 27, 1995. Maps originally prepared at 1:24,000-scale. *White dashed lines* indicate area shown in Fig. 3

intense rainfall passed between the cities of Boone and Wilkesboro, North Carolina between 06:00 (morning) and 12:00 (noon) on August 14 dropping a maximum of 254 mm of rain within 6 h at Laurel Springs (sta. 436A); this had been preceded by 86 mm of rain on August 13 (US Geological Survey 1949). The source areas of debris flows were in thin, saturated soil overlying bedrock on steep slopes. According to field observations, the size of debris flows varied from about 2 m wide and 12 or 15 m long to 60 or 90 m wide and 400 to 800 m long (US Geological Survey 1949). Many of the larger debris flows continued down the mountainsides into the stream valleys removing trees and structures in their path. In this paper, we refer to this area of debris flows as Deep Gap, North Carolina, after a town on the Blue Ridge Parkway near the center of the area (Fig. 2A).

On the night of August 19–20, 1969, the remnants of Hurricane Camille, moving eastward across the Appalachian Mountains from the Gulf Coast, stalled against a high-pressure system in central Virginia (Fig. 1). Within the 8-h period of the storm, at least 710 mm of rain fell and produced abundant debris flows and severe floods that claimed 150 lives, most of them in Nelson County, Virginia (Fig. 2B). This storm caused extensive damage to roads, bridges, communication systems, houses, farms, and livestock (Simpson and Simpson 1970). The damage to property was estimated at more than US$116 million in Nelson County (Gao 1992). The preliminary storm effects in Nelson County were examined by the Virginia Division of Mineral Resources (1969), Webb et al. (1970), DeAngelis and Nelson (1969), and Camp and Miller (1970). Subsequently, more comprehensive studies of the erosion and depositional characteristics (Williams and Guy 1973), recurrence of debris-flow activity using radiocarbon dating of ancient debris-flow deposits (Kochel 1987), and geotechnical properties of debris flows (Auer 1989) were undertaken. Statistical analyses of geological and hydrological factors affecting debris flows in the Nelson County storm were done by Terranova (1987) and Gryta and Bartholomew (1989). Gryta and Bartholomew (1989) prepared a contour map showing the density of the number of debris-flow source areas within each 1-km radius circle. Gao (1992) used GIS techniques to develop a landslide susceptibility map for a portion of Nelson County.

During the last week of June 1995, a series of unusually intense, wet, tropical type storms struck parts of the Blue Ridge Mountains in central Virginia. These storms initiated debris flows and floods in several widely separated parts of the Blue Ridge. On June 27, an intense storm cell triggered abundant, damaging debris flows in northwestern Madison County (Fig. 1), resulting in one fatality, destroying buildings, bridges, and roads, killing livestock, and inundating crops (Morgan et al. 1999a; Wieczorek et al. 2000). Total damage from the June storms throughout the Blue Ridge region of Virginia was estimated at over US$100 million, although no estimate was individually made for damage from the June 27 storm in Madison County. The Madison County area affected by the June 27, 1995, storm is within the upper drainage basins of the Conway, Rapidan, and Robinson Rivers on the eastern slopes of the mountainous Blue Ridge (Fig. 2C). Although no official rain gages operated in this debris-flow area during the storm, according to local residents, the rain began in early morning at about 2:00 on June 27 and persisted until 6:00; after a brief respite, a continuous, high intensity rainfall resumed around 10:00 and lasted until 16:00. During this second part of the storm, local residents measured rainfall with intensities of 25 to 100 mm/h lasting for several consecutive hours. A maximum of 770 mm was reported by two different residents near Graves Mill. During the most intense part of the storm (10:00 to 14:00 on June 27), hundreds of shallow rock, debris, or earth slides mobilized into debris flows (Wieczorek et al. 2000). Downstream of the confluence of the Conway and Rapidan Rivers, near Ruckersville, the flood on the Rapidan River peaked shortly before 16:00, destroying the stream gaging station. The reconstructed crest of the flood on the Rapidan River in Madison County was greatly in excess of a 500-year flood, with a discharge per unit area, 10.2 $m^3s^{-1}km^{-2}$, approximating the maximum historic value reported for the United States east of the Mississippi River (Smith et al. 1996). This discharge was enhanced by large volumes of sediment and organic debris, i.e. tree trunks, dislodged from hillsides by shallow landslides and delivered by debris flows to the flooding streams and rivers within the Conway and Rapidan watersheds.

Although officially operated rain gages were generally not available in the regions of debris flows of these storms, some useful measurements were collected. Comparative rainfall for the three storm events was: 254 mm within 6 h for Deep Gap; 711 mm within 8 h for Nelson County; and 775 mm within 14 h for Madison County. In terms of rainfall intensity-duration characteristics, which are closely related to the triggering of debris flows (e.g., Wieczorek et al. 2000), the Nelson County storm had a much higher average hourly intensity (89 mm/h), than either the Madison County (55 mm/h) or Deep Gap (42 mm/h) storms.

Study areas

These three areas of severe storm events in Deep Gap, North Carolina; Nelson County, Virginia; and Madison County, Virginia are similar in several ways. These areas are all located inland from the Atlantic coastline near the crest of the Blue Ridge Mountains (Fig. 1). Each of these areas is rural and sparsely populated. They are primarily agricultural (grazing, orchards, vineyards) with forest cover in the higher steeper terrain. The population is relatively low in these areas without any major cities, e.g. the population of Nelson County was about 12,000 at the time of the August 1969 storm and is currently 14,500. The relatively few and widely distributed structures throughout the areas are mostly individual houses and farm structures. Only a few main highways cross through the areas; the majority of roads are 2-lane highways or farm roads. In terms of total elevation difference and slope gradient, the topography was comparable for the three storm areas. Total topographic relief in these three areas ranges from 460 to 790 m, with the Deep Gap region having the highest total difference in relief and Nelson County the lowest, although Nelson County has steeper more dissected slopes. In the region near Deep Gap, North Carolina, the bedrock consists mostly of Neoproterozoic gneiss and schist. In both Nelson County and Madison County, the bedrock consists of Mesoproterozoic quartzo-feldspathic gneisses of mostly granitic composition. Although prehistoric evidence of debris flows has been found in Nelson County (Kochel 1987) and Madison County (Eaton et al. 2003), no historic debris flows have been reported in these three areas since settlement in the early 1800s.

Methods

For each of the three study areas, inventory maps of debris flows were prepared at a scale of 1:24,000 from interpretation of similar scale aerial photographs taken shortly after each storm. The inventory maps were subsequently scanned and digitized using GIS methods to determine the number of and area covered by debris flows. Evaluation of the areas where debris flows impacted roads also allowed a preliminary evaluation of risk of impact on roads. These techniques were developed to allow a direct comparison of the severity of density of debris flows and storm impacts and to suggest means of better evaluating the degree of risk posed by debris flows in future storms.

Debris-flow inventories

In the Deep Gap study area, aerial photographs (scale 1:20,000) of the devastated area taken by the Department of Agriculture on September 27, 1940, were used to prepare an inventory of landslides at a scale of 1:24,000 (Fig. 2A). For the 1969 Nelson County storm we used a previously published 1:24,000-scale debris-flow inventory of the 1969 Nelson County storm event (Morgan et al. 1999b) prepared from interpretation of aerial photography taken on August 25, 1969 (1:24,000) and on April 27, 1971 (1:40,000) (Fig. 2B). No significant storms occurred during this interval between the two sets of aerial photographs. Field examination of debris-flow features in Nelson County during 1999 generally verified the inventory and, despite the period of 30 years since the storm event, many source areas and paths of debris flows could still be recognized by contrasts in topography or vegetative differences. In Madison County, color infrared stereo photographs of approximately 1:18,000-scale taken in August 1995 were used to prepare an inventory map of debris flows and flooding at a scale of 1:24,000 (Morgan et al. 1999a) (Fig. 2C). These photographs taken about 2 months after the storm, but without any intervening storms during this period, displayed details of the initial slides, debris-flow channels and deposits on fans. We conducted field studies in Madison County to verify the inventory map and to quantitatively characterize debris-flow features on about half of the mapped sites, including size of initial slides, slope steepness, deposit thickness, and boulder size on depositional fans (Morgan et al. 1997).

The preparation of these debris-flow inventories depended on experience with photo interpretation and mapping of debris flows in the Blue Ridge. Criteria for identifying areas of debris flows include high spectral reflectance values, that is “bright tones” in the photographs caused by exposure of the bare ground from recent removal of vegetation by debris flows. Evidence of removal of trees by debris flows, especially in thick forests, shows distinctly the debris-flow source areas, travel paths, and evidence of deposition on lower slopes at distinct toes on lower slope where the debris flows terminated. The inventory maps that were prepared showed the entire debris flow from the initial source area to the final point of deposition and did not distinguish between debris-flow source, track and deposit areas. Accurate depiction of small debris flows less than 60 m long and only 10 m wide, on a 1:24,000-scale base map proved to be difficult. Additionally, small debris flows, which did not remove the tree cover, could not be easily recognized on aerial photos and therefore the inventory map and total number of mapped debris flows underestimates the total number of individual debris-flow events. In several instances, debris flows appeared to grade into downstream floods and/or hyperconcentrated stream flows, and debris flow cut-off points were occasionally designated somewhat arbitrarily. Field checking in these areas shortly after the storm events provided some additional identification of small landslides and better characterization of some debris flow/flood boundaries. Without the ability to examine the dated features of the 1940 Deep Gap area, flood boundaries were not easily distinguished and consequently were not mapped (Fig. 2A).

Size and number of debris flows

Rectangular boundaries were selected to incorporate the debris flows included in each inventory map. The maps were then divided into a network of individual 1-km^2 cells, although many cells did not include any debris flows because of the irregular distribution of debris flows. Based on the inventory maps, the areas encompassing the debris flows (km^2) and the total number of cells within each of the three study areas was 966, 330, and 270, for the Deep Gap, Nelson County, and Madison County storms, respectively.

The density or number of debris flows within each cell were tabulated by two different methods. The first and simplest method consisted of counting only the number of points of initial debris-flow source areas within each cell (e.g., blue dots on Fig. 3). The second method of evaluation determined the number of debris-flow paths within a cell by adding those from source areas within the cell and those paths that entered from another adjacent cell. This second evaluation resulted in a slightly larger debris-flow count reflecting the fact that many individual source areas produced debris flows that coalesced or converged into a common debris-flow path, which traveled long distances, passing through many different cells. This transit from one cell to another applies particularly to debris flows of large volume that continued to flow through high-order channels. For example, the largest debris flow in the June 27, 1995, Madison County storm, which had an estimated volume of about 57,000 m^3, traveled about 3 km, and consequently, had a flow path running through parts of six different cells. An example of these different counts of the number of debris flows is illustrated in Fig. 3 with the corresponding values listed in Table 1.

The process of evaluating debris-flow density for each of these three storms was quantified in yet another way. We used GIS polygonal measurements to determine the area covered by debris flows within each respective cell. These measurements combined initial source, travel path and depositional areas of each debris flow. Although the recognition of some small sites of debris-flow initiation is possible, the measurement of total debris-flow area per cell minimizes the significance of smaller individual debris-flow features that may have been missed in the mapping and maximizes the importance of individually large debris flows. An example of these three different debris-flow distribution measures for several individual grid cells in the Madison County storm shown in Fig. 3 are listed in Table 1. These measurements permitted several types of comparisons of the debris-flow distribution and density for the three different storms. The total number of points of debris-flow initiation, number of debris-flow

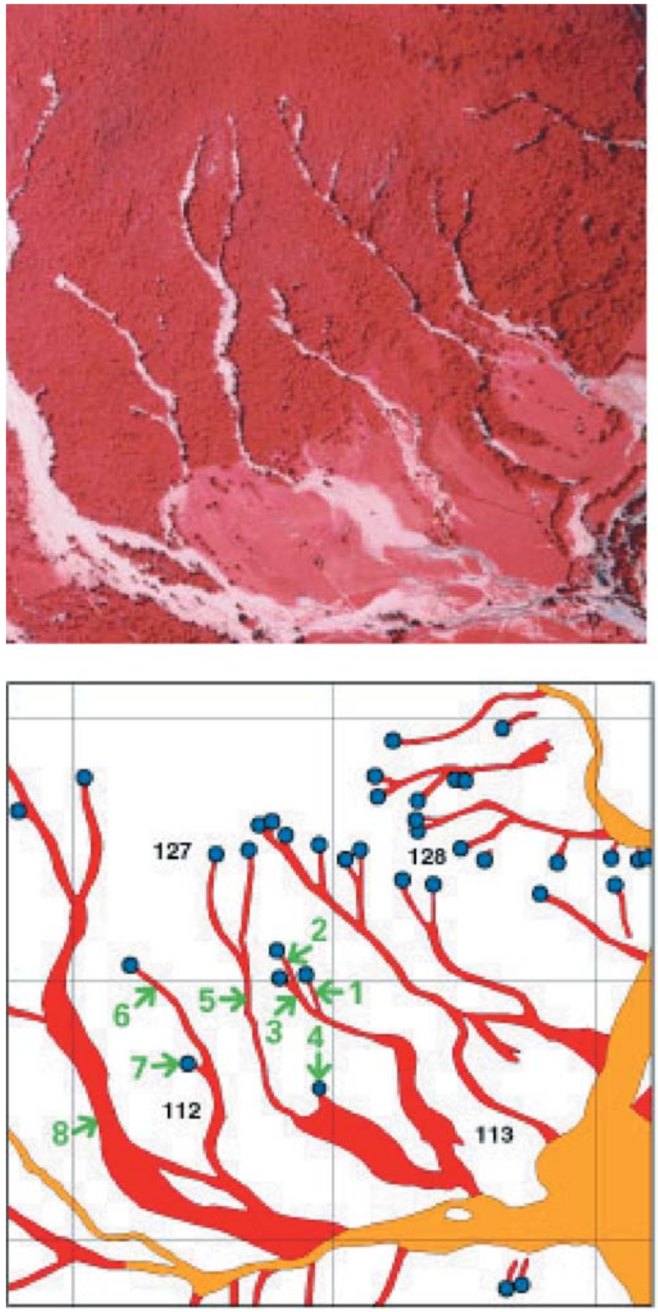

Fig. 3 Example of debris-flows within grid cells in Madison County in June 27, 1995 storm: **A** Infrared photograph of debris flows (highly reflective light color), and **B** outlines of four cells (#'s 112, 113, 127, 128), of 1 km^2 each, showing debris-flow source initiation points (*blue dots*), debris-flow paths (*red*), and flooding (*orange*). *Green arrows* identify the total number of debris flow paths within cell #112 equal to 8

Table 1 Characterization of debris flows for four grid cells in 1995 Madison County storm shown in Fig. 3

Grid cell no.	Debris-flow initiation points	Total number of debris-flow paths	Area (km^2) of debris flows
112	3	8	0.231
113	0	4	0.193
127	11	11	0.065
128	18	18	0.095

Table 2 Comparison of debris-flows for three storms in the Blue Ridge

	1940 Deep Gap, NC	1969 Nelson Co., VA	1995 Madison Co., VA
Total number of cells (km^2) in study area	966	330	270
Sum of all points of debris-flow initiation in all cells	763	3793	629
Sum of all debris-flow paths as counted in individual cells	1,024	4,509	874
Maximum debris-flows paths per individual (1 km^2) cell	25	86	35
Number of cells (km^2) with debris flows	232	262	123
Percentage of cells with debris flows in study area	24.0	79.4	45.6
Total area (km^2) of debris flows	6.53	13.3	6.26
Maximum area (km^2) covered by debris flows per individual (1 km^2) cell	0.25	0.26	0.23

Table 3 Comparison of debris-flow impact on roads for three storms in the Blue Ridge

	1940 Deep Gap, NC	1969 Nelson Co., VA	1995 Madison Co., VA
Total area (km^2) of roads	10.160	4.378	3.23
Total cells with roads	735	217	213
Total cells in study area (km^2)	966	330	270
Percentage of cells with roads	76.1	65.8	78.9
Percentage of road area per total study area	1.05	1.33	1.20
Total area (m^2) of roads impacted by debris flows	149,018	253,485	94,986
Percentage of road area impacted by debris flows	1.47	5.79	2.94
Total cells with roads impacted by debris flows	70	95	54
Percentage of road cells impacted by debris flows	9.52	43.78	25.35
Maximum road area (m^2) impacted by debris flows in an individual (1 km^2) cell	14,420	13,454	7,065

paths passing through each cell, as well as the total area affected by the debris flows of the three different storms can be compared in Table 2.

Evaluation of debris-flow impact on roads

Larsen and Parks (1997) evaluated the correlation between roads and landslide distribution in Puerto Rico as a partial measure of landslide risk. To compare risk posed by these three Blue Ridge storm events, we measured the area of roads that would have been affected by debris flows. Although this analysis was based on roads represented on current (1997) digital versions of US Geological Survey 1:24,000-scale topographic maps, the subsequent change in roads since the storm events is probably minimal because of the relatively small population growth in these rural areas. For this general assessment we did not distinguish the different types of roads identified, e.g. highways versus farm roads, but simply evaluated the extent of area (polygonal) covered by each road, assuming that each road was about 10 m wide. In the case of wider highways with two lanes of travel in each direction, the width of each road was effectively doubled by the size of the road polygon on the map. We then evaluated what partial size (and percentage) of the road area per cell would be impacted by the debris flows in a theoretical repeat of each respective storm event with the current topographic map. The results of this type of risk assessment (Table 3) do not evaluate the number of people using each roadway per unit of time, which could be used to more fully assess the landslide risk, but it gives some comparative measure of the risk that might be posed to roads in each of these three storms.

Results

A comparison of the values in Table 2 demonstrates that all three debris-flow measures of debris-flow density from the 1969 Nelson County, Virginia storm were far more significant than from either of the other two storms. Gryta and Bartholomew (1987) mapped at a smaller scale than 1:24,000 a few widely scattered debris flows outside the area of the inventory map (Morgan et al. 1999b); consequently they were omitted from our analyses. This increased the evaluation of the percentage of cells (Table 2) with debris flows in Nelson County study area; however, this was not the most important factor for comparison of the storm events. Not only was a greater relative area impacted by debris flows (number of cells—262 km^2), but the total number of debris flows (4509) and the total area covered by debris flows (13.3 km^2) was much greater in Nelson County than in either of the two other storm events. In addition, the maximum number of debris flows per cell (86) was several times greater in Nelson County than in either of the other two events. These comparisons suggest that the Nelson County event posed debris-flow hazards several times greater than the other two events. Interestingly, the comparison of the maximum area covered by debris flows within an individual cell is almost equal, approximately 0.25 km^2, for each of the three storm events. This suggests that under the severest of conditions for these three storms, where debris flows can be generated, a maximum of about 25% of the area of a 1 km^2 cell can be impacted, perhaps reflecting a comparable hazard for the generation and travel of debris flows dependent upon the influence of a similar topography and lithology within these areas of the Blue Ridge.

Comparison of the percentage of road area within the total storm grid area (Table 3) shows that the three storm areas have about the same road density (~1% of the area). Likewise, the percentage of cells with roads (Table 3) was fairly similar, varying from 66 to 78% for the three regions, with Madison having the highest and Nelson the lowest percentages. The percentage of roadways impacted by debris flows in Nelson County (5.79%) was greater than Madison County (2.94%) and Deep Gap (1.47%). Thus, despite the fact that Nelson County had the lowest percentage of grid cells with roads (65.8%), the percentage of road cells impacted by debris flows for Nelson County (44%) was much greater than for Madison County (25%) or Deep Gap (10%) because Nelson County had the highest number of and greatest area covered by debris flows (Table 2). Presumably, more developed areas in the Blue Ridge, such as near Asheville, North Carolina, a city with a population of 69,000, would have a greater percentage of road area per grid cell and consequently could have significantly higher degree of risk in similar severe storm events.

Discussion

The validity of such debris-flow storm event comparisons depends in part on the accuracy of the interpretation of aerial photography and detailed field mapping. Using similar scale photography taken shortly after the storms and preparing an inventory map at the same scale improves the basis for comparison, even though the number of identified individual debris-flow source points may differ between interpretation and mapping from aerial photographs made by different people, especially if many of the debris flows are too small for recognition under heavy vegetation. During the Nelson County storm, for example, the maximum number of debris flows per cell (86) was 2 to 3 times greater than for the other two storms; however, the maximum area of impact within one cell was similar for all three storms (~0.25 km^2), indicating that many more small debris flows were identified within individual cells in Nelson County. The total area covered by debris flows is perhaps the best criteria for comparison of storm impact. However, the delineation of the boundary between the end of debris flows and beginning of floods can be subjective and influence the measures of debris-flow area. Whereas we had the opportunity for detailed examination and mapping of debris flows in Madison County, we did not have the same ability to distinguish and verify these differences in the other two storm events because of the length of time since the events.

Although storm-triggered debris-flow events occur frequently worldwide, no general methods have been developed for comparing the regional distribution and density of debris flows in different storms. The distribution and density of debris flows in some storm areas have been evaluated by contouring the number of debris flows with isohyetal lines (e.g. Campbell 1973; Govi and Sorzana 1980; Coe and Godt 2001). Govi and Sorzana (1980) characterized 22 storms triggering debris flows during a 30-year period in northern Italy and characterized them by determining a density measure (number of debris flows per square kilometer) with a particularly high value (maximum of 80–90/km^2) observed for a storm on August 7, 1978. Crosta and Frattini (2000) compared debris-flow density with the rainfall intensity of storms. This information is graphically illustrative and useful for evaluating the relationship between points where debris flows initiate and other important factors related to debris-flow initiation, such as degree of slope, nature of soils and rocks, and intensity and duration of rainfall. Other methods have also been developed for evaluating landslides hazards on a geomorphological and historical basis (e.g., Carrara et al. 2003).

Conclusions

Storms in the southeastern United States, particularly hurricanes, which commonly are downgraded to tropical storms or depressions after coming ashore, can have very irregular paths traveling over large parts of the country. Such tropical storms frequently release intense rainfall that in mountainous areas can generate severe debris-flows many days after the hurricanes have come ashore. Consequently, the hazards and risks posed by debris flows from such storms are difficult to predict in advance either spatially or temporally.

Many severe storms have historically caused debris flows and flooding in the southeastern United States. A comparison of three of the most severe storms in the Blue Ridge Mountains of North Carolina and Virginia shows that measures of distribution and density of debris flows can be used as a basis for comparison of the magnitude of the impact of individual storm events and as a means for better evaluating debris-flow hazards and risks. In the cases of these three storm events, a maximum of about 25% of the area of a 1-km^2 grid cell was impacted by debris flows. Although these three storm regions were basically rural agricultural areas with relatively low populations, a repeat of a similar storm event in more populated regions in the Blue Ridge could pose significantly higher risks.

Using the density of roads impacted by debris flows as a measure of the risk posed by each storm showed that as much as about 45% of the cells with roads could be affected. Consequently, in more developed and densely populated mountainous areas, such storms might impact a greater percentage of road area depending on the road location.

Of the three Blue Ridge storm events, the August 19–20, 1969, Nelson County storm was clearly the most severe in triggering more debris flows and covering the largest area. Likewise, the amount of road area impacted by debris flows and the number of cells with impacted roads was highest for the Nelson County event. Although no details exist for distinguishing which of the 150 deaths occurred from flooding or debris flows, all measures of debris-flow impact were much greater for the Nelson County storm than for the other two storms.

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G. F. Wieczorek (✉)
US Geological Survey,
National Center,
MS 926A, Reston, VA 20192, USA
e-mail: gwieczor@usgs.gov

G. S. Mossa
Dept. of Geology & Geophysics,
University of Bari,
Via Orabona, 4-70125 Bari, Italy

B. A. Morgan
US Geological Survey,
MS 926A, Reston, VA 20192, USA