Role of debris flows in long-term landscape denudation in the central Appalachians of Virginia

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ABSTRACT

Four major storms that triggered debris flows in the Virginia–West Virginia Appalachians provide new insights into the role of high-magnitude, low-frequency floods in long-term denudation and landscape evolution in mountainous terrain. Storm denudation in the Blue Ridge Mountain drainage basins is approximately an order of magnitude greater compared to basins located in the mountains of the Valley and Ridge province. This difference is probably the result of higher storm rainfall from the Blue Ridge storms. Radiocarbon dating of debris-flow deposits in the Blue Ridge indicates a debris-flow return interval of not more than 2–4 k.y. in mountainous river basins. This finding, combined with measurements of basin denudation, suggests that approximately half of the long-term denudation from mechanical load occurs episodically by debris-flow processes. Although floods of moderate magnitude are largely responsible for mobilizing sediment in low-gradient streams, our data suggest that high-magnitude, low-frequency events are the most significant component in delivering coarse-grained regolith from mountainous hollows and channels to the lowland floodplains.

Keywords: denudation, debris flows, geomorphic work, geomorphic effectiveness, Appalachian Mountains.

INTRODUCTION

For decades geologists have debated the effectiveness of catastrophic storms in modifying the landscape. Landscape modification has traditionally been quantified by the volume of sediment transported during an event (geomorphic work; Wolman and Miller, 1960) or by the ability of an event to affect the shape or form of a landscape (geomorphic effectiveness; Wolman and Gerson, 1978). Researchers have found that large-magnitude, infrequent events transport only a small fraction of the total annual sediment load in large, lower-gradient river basins (e.g., Wolman and Miller, 1960; Moss and Kochel, 1978). In contrast, studies of smaller mountainous river basins have documented that large-magnitude events are effective in transporting sediment and denuding the landscape (Hack and Goodlett, 1960; Williams and Guy, 1973; Kochel, 1987, 1988, 1990; Jacobson et al., 1989; Miller, 1990; Eaton, 1999) and that a significant amount of long-term denudation is achieved during these events. Studies of four severe storm events that initiated debris-flow activity in the Virginia–West Virginia Appalachians provide information that can be used to assess the impact of large floods on geomorphic work in the area (Hack and Goodlett, 1960; Williams and Guy, 1973; Jacobson, 1993; Wieczorek et al., 2000). The research reported here combines new data on debris-flow frequency and denudation from catastrophic flooding to assess the importance of debris flows in long-term landscape denudation.

RATES OF DENUDATION IN THE CENTRAL APPALACHIANS

The rates of Appalachian erosion are within the same order of magnitude as the continental United States average. Judson and Ritter (1964) reported denudation rates attributed to chemical and mechanical loads of 4.1 cm/k.y. for the southern Atlantic basins and 4.8 cm/k.y. for the northern Atlantic basins. Hack (1979) summarized denudation rates on rivers draining the Appalachians as ranging from 0.5 to 4.8 cm/k.y. However, some concern exists over using historic sediment-load data to predict long-term denudation rates because of accelerated sediment yields from European settlement (Trimble, 1969; Meade, 1982). Trimble (1969) estimated that modern stream sediment loads may be a full order of magnitude higher than prehistoric levels despite aggressive controls on soil erosion implemented during the twentieth century. Contrary to concerns of Trimble and other researchers, several lines of evidence indicate that average modern rates of denudation approximate Cenozoic rates. The supporting data are based on studies of the volume of sediment deposited in, or offshore of, the Atlantic Coastal Plain (Mathews, 1975; Poag and Sevon, 1989; Pazzaglia and Brandon, 1996) and on findings of parallel rates of continental uplift and denudation (Durrant, 1978; Zimmerman, 1979).

Several studies of denudation rates of small Appalachian river basins (e.g., Wolman, 1967; Cleaves et al., 1970; Berry, 1977; Osterkamp and Costa, 1986) show erosion rates that vary over orders of magnitude from the mean regional denudation rate. With the exception of Berry's work that was conducted in an experimental forest, these other measurements are from urbanizing basins where soil disturbance is substantial and probably do not reflect long-term conditions.

DENUDATION FROM INDIVIDUAL CATASTROPHIC STORMS

Four major storms that triggered numerous debris flows struck the central Appalachians of Virginia and West Virginia in the last half of the twentieth century. They include two storms in the Blue Ridge Mountains of Virginia and two storms in mountainous terrain of the Valley and Ridge province in western Virginia and eastern West Virginia (Fig. 1).

Storms of the Blue Ridge

In the late evening of August 19, 1969, the remnants of Hurricane Camille crossed the Blue Ridge Mountains from the west and stalled in the rugged foothills of Nelson County, Virginia. As much as 711 mm of rain fell over a 7–8 h period during the early morning hours of August 20 (Camp and Miller, 1970), although one unofficial reading of nearly 1020 mm of rainfall was made at a single locality (Simpson and Simpson, 1970). The deluge triggered thousands of debris flows and killed more than 125 people, ~1% of the county's population. Williams and Guy (1973) measured net losses of sediment in three basins; mean denudation was 4.3 cm (Table 1).

The June 27, 1995, storm centered over the Rapidan River basin in Madison County, Virginia, developed from the combination of a stalled cold front and westward-flowing, moisture-laden air moving toward the eastern slopes of the Blue Ridge Mountains (Smith et al., 1996). Maximum rainfall totals for the storm system reached 775 mm during a 16 h period. The deluge triggered more than 1000 debris flows (Figs. 1 and 2), and flooding in the region was catastrophic. In the region of maximum rainfall, Springer et al. (2001) measured sediment losses from two drainage basins <1 km^2 in area. Mean basin denudation from the storm was 2.7 cm (Table 1).

Later that evening the North Fork of the Moormans River in western Albemarle County, located 45 km southwest of the Rapidan Basin, was also affected by the storm system. The rainfall exceeded 279 mm (Morgan and Wieczorek, 1996), but may have been as great as 635 mm (Carlton Frazier, 1996, personal commun.). Nearly 100 debris flows were documented in a much smaller area (13 km^2) relative to the Rapidan Basin (100 km^2). The debris-flow surges partially filled the Sugar Hollow Reservoir, reducing its holding capacity by 15%, translating to a minimum value of 0.9 cm of denudation (Table 1). This denudation value is a minimum, because ~50% of the upland regolith is composed of silt- and clay-sized particles, suggesting that much of the debris-flow material may have been flushed beyond the reservoir dam.

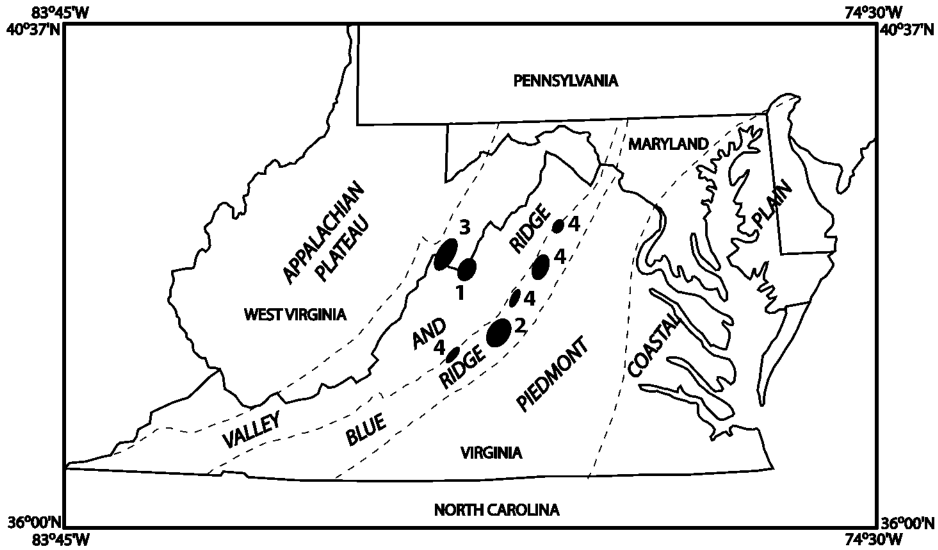

Figure 1. Areas affected by debris-flow events in Virginia and West Virginia from 1949 to 1996. 1—June 17–18, 1949, storm in western Virginia and eastern West Virginia; 2—August 19–20, 1969, storm in western Nelson County, Virginia; 3—November 3–5, 1985, storm in western Virginia and eastern West Virginia; 4—June 27, 1995, Rapidan storm in several counties bordering Blue Ridge Mountains.

Storms of the Valley and Ridge Province

Catastrophic storms struck the Valley and Ridge province along the West Virginia–Virginia border in 1949 and 1985 (Fig. 1). The June 1949 storm was the result of convective storm cells limited to only a few mountainous basins. The torrential rainfall produced as much as 229 mm of rainfall in western Virginia and >380 mm in eastern West Virginia (Stringfield and Smith, 1956) and triggered dozens of debris slides and flows (Hack and Goodlett, 1960). The November 1985 storm covered a much larger area, and was noted for rainfall at a moderate intensity and a long duration of three days. The storm produced as much as 250 mm of rain, and was dominated primarily by two low-pressure systems and, to a lesser extent, the remnants of Hurricane Juan (Colucci et al., 1993). This storm initiated thousands of debris flows and occurred over the same region as areas affected by the 1949 deluge. Cenderelli and Kite (1998) examined drainage basins affected by either the 1949 flood or the 1985 flood for the geomorphic effects of debris flows on channel morphology. Two basins affected by the 1949 storm were denuded by an average of 0.2 cm, and similar values were noted for basins surveyed from the 1985 storm (Table 1).

Trends of Basin Denudation

The data from several studies (Williams and Guy, 1973; Cenderelli and Kite, 1998; Springer et al., 2001) were used to determine whether denudation values in the Blue Ridge and Valley and Ridge could be influenced by meteorologic, physiographic, or geologic factors. The correlations of denudation with physiography and geology were extremely low and were probably due to a very limited data set. The highest correlation was found between denudation and storm rainfall totals (R^2 =

TABLE 1. SUMMARY OF BASIN DENUDATION

Event	Basin	Location	Area (km^2)	Volume of sediment eroded (m^3)	Mean basin denudation (cm)
1949	Austin Run*	Valley and Ridge	9.71	20,900	0.22
1949	Kisamore Run*	Valley and Ridge	5.01	8500	0.17
1969	Willis Cove†	Blue Ridge	4.08	173,488	4.25
1969	Ginseng Hollow†	Blue Ridge	1.75	88,727	5.07
1969	Polly Wright Cove†	Blue Ridge	2.47	87,707	3.55
1985	Twin Run*	Valley and Ridge	17.48	13,900	0.08
1985	Gravel Lick Run*	Valley and Ridge	1.78	3300	0.19
1995	Jenkins Hollow§	Blue Ridge	0.40	13,364	3.36
1995	Teal Hollow§	Blue Ridge	0.12	2492	2.03
1995	Sugar Hollow#	Blue Ridge	29.5	544,000	0.92**

*Cenderelli and Kite, 1998.
†Williams and Guy, 1973.
§Springer et al., 2001.
#Eaton, 1999.
**Minimum value reported.

Figure 2. Photograph of Kirtley Mountain, western Madison County, Virginia, following Madison County 1995 storm. Debris-flow activity affected and denuded numerous low-order drainages. Arrows denote houses for scale.

0.71) (Fig. 3). The Blue Ridge basins have received more rainfall during recent debris-flow events than the Valley and Ridge basins, presumably resulting in the greater denudation. Rainfall intensity is also a factor that influences denudation. Work by Wieczorek et al. (2000) showed a threshold of rainfall intensity and duration for triggering debris flows in the Blue Ridge, i.e., 70 mm/h for 2 h.

FREQUENCY OF CATASTROPHIC EVENTS

No published work exists on debris-flow frequency of small mountainous basins in the Valley and Ridge province. Clark (1987) found no published reports of historic debris-flow activity in the province prior to 1949. However, debris-flow frequency data exist for two Blue Ridge storm sites. Kochel (1987) estimated that debris-flow activity in several low-order basins in Nelson County affected by Hurricane Camille had a recurrence interval of not more than 3 k.y. Work by Eaton and McGeehin (1997) and Eaton et al. (2001) included 39 radiometric carbon dates that originated from debris-flow, slope-wash, and fluvial deposits and paleosols in the Upper Rapidan Basin of western Madison County, Virginia. The research shows a recurrence interval of debris-flow activity of not more than 2500 yr since the onset of the Wisconsinan glacial maximum.

Although debris-flow return intervals are on the order of thousands of years for individual first-order drainage basins, the probability of debris-flow activity increases substantially as the size of the area considered increases. In the central Virginia–eastern West Virginia region, eight separate localities have been affected by debris flows over a 50 yr period (Fig. 1). During this period, storms producing debris flows in the much larger region of the Appalachian Mountains of Virginia and West Virginia (Hack and Goodlett, 1960; Williams and Guy, 1973; Jacobson et al., 1989; Morgan and Wieczorek, 1996; Wieczorek et al., 2000) have recurred at ~10–15 yr intervals. It is uncertain whether this average recurrence is typical over the entire historic period of ~300 yr because debris flows occur in mountainous regions that were sparsely populated during this period and thus were often undocumented.

If the entire unglaciated terrain of the Appalachians is considered, historical debris-flow activity shows a frequency of one event about every 3–7 yr (Clark, 1987; Kochel, 1990). Clark's study showed that a large proportion of Appalachian debris-flow activity has occurred in the Appalachian Mountains in Tennessee and North Carolina. Although no published studies exist on the frequency of debris-flow activity in this region, Clark's study suggests that either activity is much higher in the southern Appalachians than in other areas, or there is better documentation of debris-flow events in the southern region.

DISCUSSION

In low-relief landscapes such as the Piedmont, debris flows are rare, both because of low slope gradients and relief, and because of lesser orographic forcing of extreme rainfall. In contrast, researchers (e.g., Kochel, 1987, 1988; Jacobson et al., 1989; Miller, 1990) proposed that high-magnitude events significantly modify high-relief landscapes, but lacked the quantitative data necessary to definitively test their hypotheses. The data reported in this paper suggest that geomorphic work and effectiveness in mountainous terrain are achieved largely by high-magnitude, infrequent events. For the following discussion, mechanical load is assumed to be the primary contributor to landscape denudation during large floods, because the chemical load removed during a short time interval must be very small.

In Nelson County, Kochel (1987) estimated an average debris-flow frequency of not more than 3500 yr. The estimated long-term mechanical denudation rate in Nelson County is 2.6 cm/k.y. (Judson and Ritter, 1964); 9.1 cm of mechanical denudation would occur during a 3500 yr period. Erosion values from the 1969 Hurricane Camille storm indicate that the landscape was denuded on average 4.3 cm (Table 1), i.e., 47% of the expected amount of

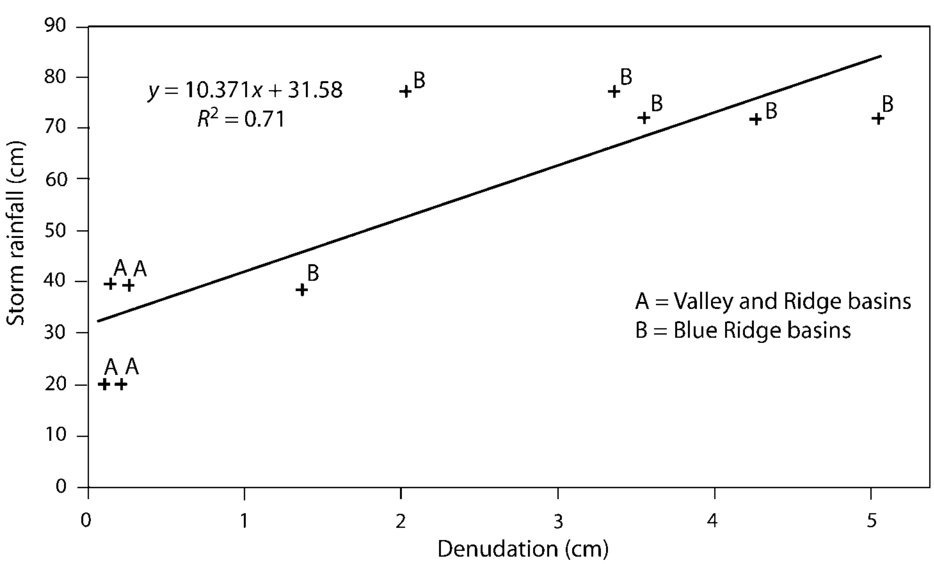

Figure 3. Plot of storm event rainfall total vs. denudation for mountainous drainage basins in Blue Ridge and Valley and Ridge provinces.

sediment transport–caused denudation (9.1 cm) over 3500 yr. Nearly half of the long-term denudation is attributable to debris-flow activity. For the 1995 Madison County storm, the projected basin-denudation rate attributed to mechanical load is 2.1 cm/k.y. (Judson and Ritter, 1964), i.e., 5.3 cm for the 2500 yr increment between debris flows (Eaton, 1999). During the Madison County storm an average of 3.3 cm was removed from the studied basins, i.e., 63% of the denudation expected over a 2500 yr period.

In the Appalachians, and probably other mountainous terrains located in humid-temperate climates, the role of high-magnitude events on geomorphic effectiveness and landscape evolution arguably has been underestimated. The presence of coarse bedload stored in upland channels, porous regolith that mantles the slopes, and densely vegetated terrain marginalizes the effectiveness of frequent, low-magnitude storms in mobilizing sediment. In contrast, high-magnitude events trigger debris flows, which incise streams, export sediment from the uplands, and deposit regolith onto debris fans or into lowland stream channels and floodplains. Many of the upland channels affected by debris flows described in this paper have been slow to recover; they continue to maintain a greater hydraulic geometry than required for frequent, low-magnitude storms. Throughout much of the Appalachians, the ubiquity of specific landforms and deposits, including debris fans and levees, boulder bars and terraces, remarkably wide linear alluvial valleys that originate at the terminus of debris fans, and single-channel floodplains that become braided during catastrophic flooding, suggests that geomorphic work and effectiveness in mountainous terrain are achieved largely by high-magnitude, infrequent events. Future research in similar terrains and climates will help test this model.

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