ELSEVIER

Geomorphology 37 (2001) 135–148

GEOMORPHOLOGY

www.elsevier.nl/locate/geomorph

Sediment budgets for two mountainous basins affected by a catastrophic storm: Blue Ridge Mountains, Virginia

Gregory S. Springer [*], Heather Shroyer Dowdy, L. Scott Eaton

Department of Geology and Environmental Studies, James Madison University, Harrisonburg, VA 22807, USA

Received 15 October 1999; received in revised form 24 August 2000; accepted 25 August 2000

Abstract

On June 27th, 1995, a catastrophic storm generated thousands of slope failures in mountainous portions of Madison County, VA, USA. Within a 129-km^2 area, 16-h rainfall totals reached 775 mm. Using direct field measurements, sediment budgets were constructed for two drainage basins impacted by the event, Teal and Jenkins Hollows. Lengthwise distributions of channel erosion and deposition were examined by taking measurements within incremental 30-m-long channel segments. Comparison of sediment budgets reveals that the two hollows responded very differently to the storm event. These differences are largely due to differences in soil types, failure volumes, and natures of the resulting flows. Within Jenkins Hollow, the kinetic energy of a 4200-m^3, liquefied slope failure scoured the channel of virtually all sediment and vegetation and resulted in a sediment retention rate of 5%. In contrast, slope failures that reached the central channel of Teal Hollow failed to generate a large flow track and erosion features are coupled with deposition features. The sediment retention rate in Teal Hollow was 27%. Single storm denudation rates for the basins exceed the regional 1 ka area-normalized denudation rate of 25.5 mm ka^{-1}; denudation was 27 mm in Teal Hollow and >38 mm in Jenkins Hollow. Following catastrophic events, considerable attention has been paid to those channels dramatically modified by debris flows. The high denudation rate for Teal Hollow, attributed to liquefaction of fine-grained soils easily transported as washload, suggests that extremely high denudation rates are possible even in low-order mountainous basins that appear relatively undisturbed by catastrophic storms. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: sediment budget; debris flow; denudation; Blue Ridge mountains

---

1. Introduction

A growing body of literature suggests that mobilized slope failures associated with high magnitude storms determine channel forms in low-order mountainous basins and transport the bulk of sediments in such channels (Hack and Goodlet, 1960; Williams and Guy, 1973; Dietrich and Dunne, 1978; Pierson, 1980; Benda, 1990; Benda and Dunne, 1997; Cenderelli and Kite, 1998). Slope failure-generated flows can scour channels to bedrock and may be more important than fluvial processes in many mountainous, low-order basins (Howard, 1998). Within the Blue Ridge Mountains of Virginia, the recurrence interval for slope failures generated by catastrophic

---

[*] Corresponding author. Present address: Department of Earth Resources, Colorado State University, Fort Collins, CO 80523-1482, USA.

E-mail address: laramide@bedrockstreams.org (G.S. Springer).

PII: S0169-555X(00)00066-0

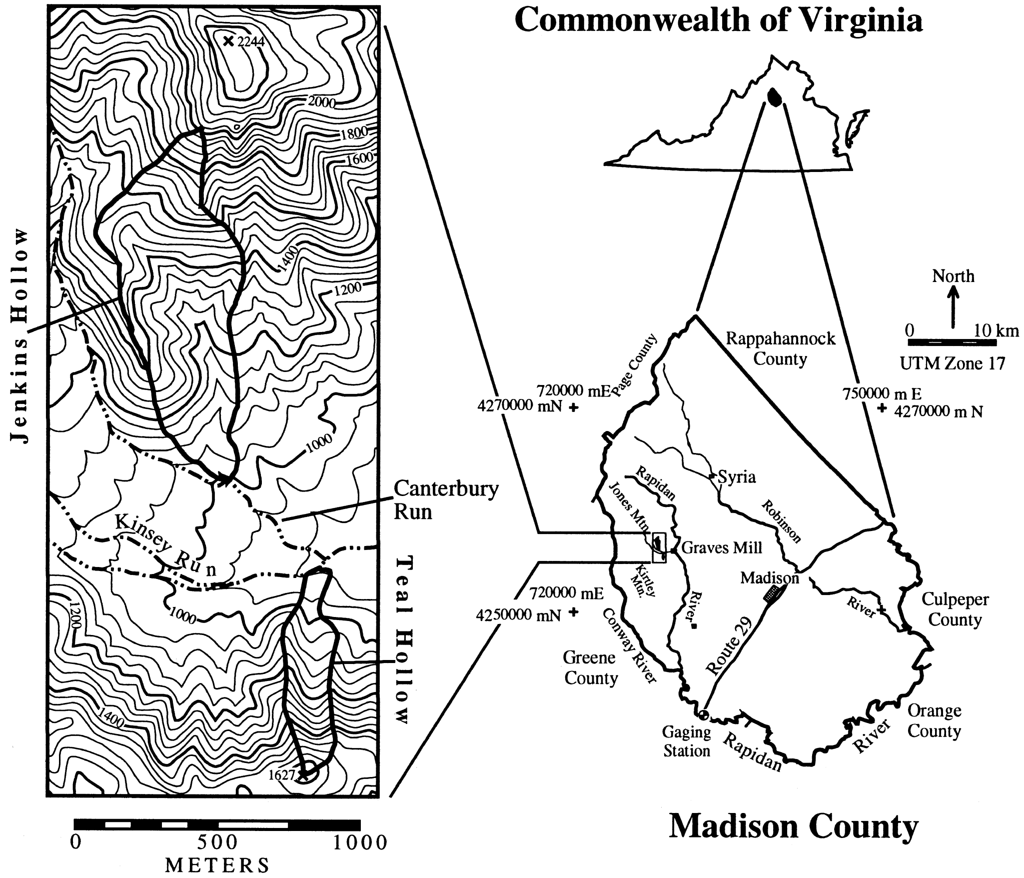

Fig. 1. Location and topography of study area.

storms has been reported as 3 to 4 ka by Kochel (1987) and 2 ka by Eaton and McGeehin (1997).

The importance of catastrophic, storm-generated slope failures as geomorphic agents in the Ap-

Table 1
Drainage basin morphometries and storm denudation rates

Basin	Area ($\times 10^3$ m^2)	Relief (m)	Drainage density (km km^{-2})	Relief ratio	Basin shape	Ruggedness (km km^{-3})	Storm denudation rate (mm m^{-2})
Jenkins Hollow	356	305	5.3	0.257	0.234	17	> 38
Teal Hollow	92	215	5.0	0.468	0.196	23	27
Jenkins Hollow sub-basins							
Sub-basin I	26	85	4.2	0.770	0.365	49	–
Sub-basin II	36	91	3.3	0.758	0.688	36	–
Sub-basin III	128	238	4.7	0.395	0.344	20	65
Sub-basin IV	22	128	8.5	0.688	0.187	66	–
Sub-basin V	38	134	6.0	0.589	0.261	45	–

palachians of North America is shown by single-storm denudation rates reported by Williams and Guy (1973) and herein. The former reported that the Camille storm of 1969 generated single-storm denudation rates as great as 44 mm within mountainous basins of Nelson County, VA. Given an estimated regional denudation rate of 25.5 mm ka^{-1} (Judson and Ritter, 1964), one might conclude that sediment transport rates are comparatively minor except for catastrophic events. However, sediment production and chemical weathering during intervening periods are an integral part of landscape evolution (Dietrich and Dunne, 1978) and soil genesis and texture may play an important role in determining the distribution of slope failures in a mountain basin (Graham and Buol, 1990; Graham et al., 1990).

Despite the recognized importance of catastrophic flows, the relationships between channel form and flow processes are poorly understood. Benda (1990) examined the role of various processes in delivering sediment to mountainous streams in Oregon, but only Cenderelli and Kite (1998) presented detailed information about the lengthwise distribution of erosion and deposition in channels impacted by debris flows. Such studies are needed to assess the true role of catastrophic slope failures in creating channel forms and transporting sediment in mountainous basins. This paper examines and compares the

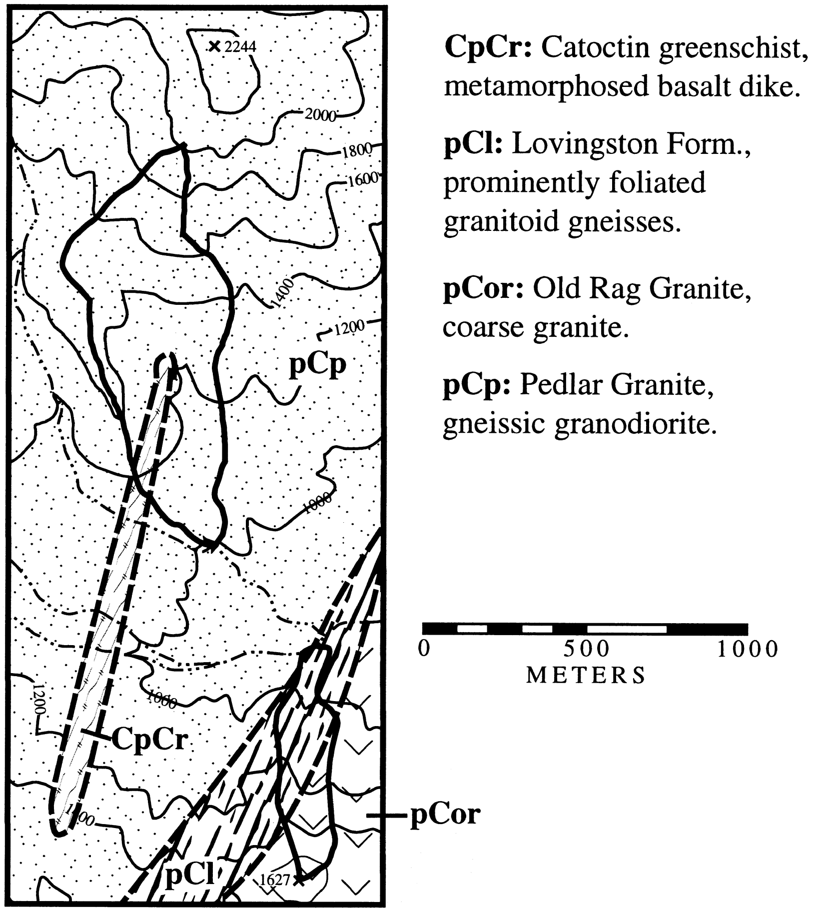

Fig. 2. Bedrock geology of study area. Modified from Allen (1963).

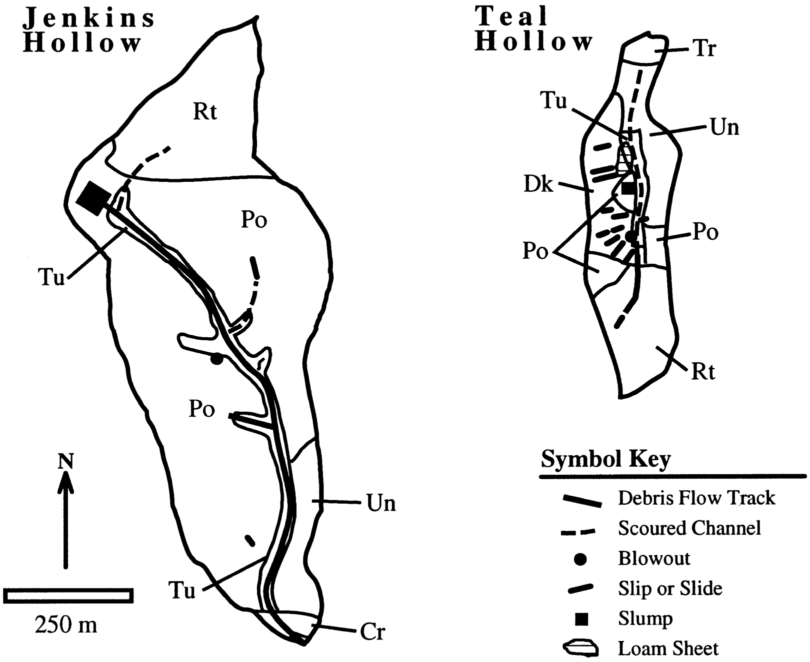

Fig. 3. Soils map of study area. Soil series symbols are explained in Table 2. Modified from Elder and Pettry (1975).

lengthwise distributions of erosion and deposition within two hollows impacted by a catastrophic storm in 1995 within Madison County, VA.

2. Study area

Two small mountainous basins, Jenkins and Teal Hollows, were examined for this study (Fig. 1). Drainage basin morphometries for each hollow are given in Table 1. The hollows lie on the eastern margin of the Blue Ridge Mountains of central Virginia within the east–west trending valley of Kinsey Run, a tributary of the Rapidan River. Local relief varies between 300 and 700 m, and slope angles in headwater basins commonly exceed 25°. Alluvial fans, many of which are highly elongated, lie in valley bottoms and adjacent to the flood plains of

Table 2
Characteristics of soil series

Series[a]	Order	Particle size(s)	Origin
Colluvial Land (Cr)	Inceptisol	Clay to boulder	Recent alluvial and colluvial deposits
Dyke (Dk)	Ultisol	Clay loam	Residual soils modilized by colluvial processes
Porters (Po)	Ultisol	Stoney loam	Colluvial soils derived from crystalline bedrock units
Rock Land (Rt)	Inceptisol	Diamict	Colluvial deposits
Trego (Tr)	Ultisol	Loam	Weathering of alluvial fan deposits
Tusquitee (Tu)	Ultisol	Stoney loam	Weathering of alluvial fan deposits
Unison (Un)	Ultisol	Clay loam	Weathering of alluvial fan deposits

[a] From Elder and Pettry (1975).

large streams. Hillslopes are reforested by mature hardwood forests of maple and oak. Valley bottoms adjacent to Kinsey Run have largely been cleared for pasture lands. The terminal fan of Jenkins Hollow is pasture while ~50% of the Teal Hollow fan is forested.

Locally, the bedrock is Precambrian-age, quartzofeldspathic metamorphic rocks and intrusives (Allen, 1963). Jenkins Hollow is underlain by lightly metamorphosed, sparsely fractured Pedlar Granite, a prominent ridge-forming unit (Fig. 2). Teal Hollow is underlain by prominently foliated granitoid gneisses of the Lovingston Formation (Fig. 2). Within the examined hollows, soil types vary from Ultisols to bouldery Inceptisols within the axes and side slopes of hollows (Fig. 3). Descriptions of selected soils are given in Table 2.

3. The storm event and geomorphic response in small basins

On June 27th, 1995, upslope winds fed moist air to a series of storm cells along the eastern slopes of the Blue Ridge Mountains in western Madison County. Maximum 16-h precipitation totals were as high as 775 mm; sustained rainfall intensities reached 200 mm. The vast majority of precipitation came in the form of rain. Maximum rainfall totals were centered in the Rapidan River Basin where peak runoff rate was 10.17 $m^3 s^{-1} km^{-2}$ (Smith et al., 1996). Unfortunately, no discharge estimates are available for Jenkins or Teal Hollows. However, rainfall distribution maps by Smith et al. (1996) and Morgan et al. (1997) indicate that the two basins received a minimum of 600 mm of precipitation during the event. Actual precipitation totals for the hollows may exceed 700 mm. Smith et al. (1996) reported that topography played a major role in generating intense rainfall along particular mountain slopes; the distribution of rainfall and associated slope failures was not random.

Slope failures generated by the event included: (1) planar slips and slides, (2) slumps, (3) in-channel debris flows, and (4) blowouts. The majority of debris flows were not generated by in-channel processes but liquefaction of slumps as they entered channels from planar hillsides (Morgan et al., 1997; Wieczorek et al., 1997). Blowouts, storm-generated springs with pronounced headscarps, were numerous. Headward-eroding blowouts appeared to have also triggered larger failures by undercutting slopes or liquefying adjacent soil. After the storm, the failure heads of some large flow tracks preserved soil pipes with diameters as great as 0.6 m. Large flow tracks were created within low-order basins that experienced voluminous slumps; the channels were completely reamed of vegetation and scoured to bedrock or saprolite. Many debris flow tracks exhibit superelevation scars, some as high as 20 m.

Within small basins, such as Teal Hollow, many central channels did not develop large flow tracks but were nonetheless significantly disturbed by the storm. Channels were widened and incised, and flooding of adjacent slopes and flood plains produced a complex suite of low volume deposits; deposition was discontinuous and generally associated with tree jams. Deposition atop the alluvial fans of small basins (area < 1 km^2) was common although minor. Fan heads were entrenched as much as 5 m. The largest volumes of sediment were deposited upon the alluvial fans of larger basins (area > 1 km^2), where multiple drainage basins converge and valley widths increase dramatically, and atop floodplains.

4. Research impetus, hypotheses, and methodology

Recognizance of Teal Hollow, whose forest canopy appeared unbroken, revealed a dozen slope failures and dramatic channel widening and incision but minimal deposition. Further investigation revealed that other basins displayed similar responses to the storm despite the absence of large flow tracks or disturbed canopies; qualitative evidence suggested that some low-order basins experienced extremely high erosion rates regardless of whether a dramatic flow track was formed. As a result of these observations, a program of research was begun to test the following hypotheses: (i) erosion rates in catastrophically impacted low-order basins with flow tracks are comparable to those in impacted basins lacking flow tracks; (ii) the spatial patterns, volumes, and controls of erosion and deposition in channels impacted by large slope failures are fundamentally different than those within channels not impacted by debris flows.

The only means by which to test our research hypotheses was to perform detailed sediment budgets of channels impacted by the storm. Air photography could not be used because of the intact forest canopy of Teal Hollow. Measurements began in September 1995 and proceeded until August 1996. The labor-intensive process of measuring all recognized erosion and deposition features resulted in an estimated 1000 man-hours being spent in the field. Time constraints imposed by our measurement technique meant that sediment budgets were not completed for all five Jenkins Hollow sub-basins.

The central channel of each hollow was divided into 30-m (slope distance) segments. Within each segment, erosion and deposition features were measured using fiberglass tapes and graduated Jacobs staffs. Where necessary to calculate erosion of side slopes and channel bottoms, channel cross-sections were reconstructed by extrapolating side slopes into the channel using a method described by Cenderelli (1994). The difference between the reconstructed channel shape and post-storm channel was taken as the cross-sectional area eroded during the storm event. To obtain volumes, the cross-sectional area was multiplied by the length of the channel for which that particular cross-section was appropriate. It was often necessary to measure multiple cross-sections in an individual segment, particularly within segments with superelevation scars.

During measurement, depositional and erosional features were classified according to their (i) position relative to the channel, (ii) sedimentological and particle size characteristics, and (iii) inferred genesis. Erosion was attributed to (i) slope failure, or (ii) scour. Slope failures were characterized as either slumps, slides/slips, or blowouts. If erosion generated by flood waters or debris flows lay outside the concave channel cross-section, the erosion was recorded as channel side-slope erosion rather than in-channel erosion. Particular attention was paid to recognizing scour that occurred during superelevation of transient debris flows. Such scour was classified as channel-side slope erosion attributable to superelevating masses. Based upon sediment structure and texture, deposition was attributed to processes associated with either streamflow, debris flow, or slope failure. Field data was recorded on standardized worksheets. Data was compiled and manipulated within Microsoft Excel® and statistically analyzed using the PC-based SAS statistical package (SAS Institute, 1994).

5. Post-event hollow morphologies

5.1. Morphology of Jenkins Hollow

The 2nd order Jenkins Hollow catchment consists of five distinct sub-basins (Table 1; Fig. 4). The 1-km-long central channel of Jenkins Hollow was scoured of virtually all sediment and vegetation. The sediment budget for Jenkins Hollow includes only sub-basin III, the channel downstream of the junction of sub-basins III and IV, and zero-order hillslopes along the channel (Fig. 4). Measurements began at the confluence of Jenkins Hollow with Canterbury Run (Fig. 1). To facilitate description and subsequent discussions, the hollow was divided into three reaches (failure zone, main channel, and fan), each of which is described below.

5.1.1. Failure zone

The flow track in Jenkins Hollow heads within a 45-m-wide and 45-m-long slump (Fig. 4). The ~4200-m^3 failure occurred adjacent to a hillslope convergence within a planar portion of the hillside whose undisturbed surface slope is 21°. Prior to sloughing, lateral margins of the failure were sharp and the headscarp attained heights of 5 m. The undulating failure surface lies within saprolite. The failed material consisted of loamy diamicton and 0 to 0.5 m of saprolite. Cobbles and small boulders are present atop the contact between the saprolite and overlying regolith.

5.1.2. Main channel

The main channel extends 710 m from the slope failure to the basin's alluvial fan. Along the channel, gradient decreases rapidly and erosion of channel side slopes was common; the channel was widened by as much as 5 m. Four superelevations were found along the channel, the highest of which rises 6 m above the channel bed.

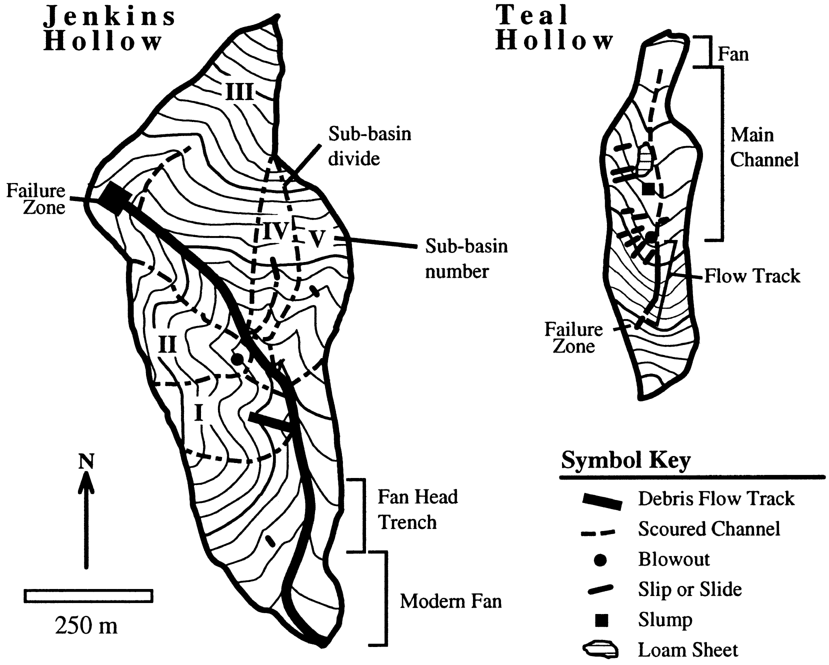

Fig. 4. Location of slope failures in Jenkins and Teal Hollows. Reach names are discussed in text.

5.1.3. Fan

At the downstream end of the main channel, the stream channel gradually narrows and deepens to form a fan head trench. The trench lies between the valley wall and western margin of an ~ 0.1-km^2, ancient alluvial fan once fed by Jenkins Hollow (Fig. 1). Within the trench, the channel was incised by the 1995 event to bedrock and saprolite; and at least one debris flow superelevated and created minor sediment (< 5 m^3) and profuse woody debris deposits atop the older fan. Severe slope and channel erosion occurred where the flow reentered the gully from atop 3- to 6-m high walls. Downstream of the trench, scour pockets were found atop much of the fan surface and the channel was deepened by as much as 2.5 m.

5.2. Morphology of Teal Hollow

Slope failures and channel scour significantly altered the valley bottom of Teal Hollow. Within Teal Hollow, the channel can be subdivided into four distinct reaches characterized by different channel forms, gradients, and dominant processes (Fig. 4). As with Jenkins Hollow, reach names are merely descriptive and do not represent an attempt to subdivide flow tracks into categorical zones (e.g., Bogucki, 1976; Pierson, 1985; Cenderelli and Kite, 1998); subdivision of the hollow into reaches (failure zone, flow track, main channel, and fan) facilitates description and subsequent discussions. Each reach is described below.

5.2.1. Failure zone

The most headward erosion feature within Teal Hollow is an irregular, 20-m-long, 53-m^3 debris slide scar within a 35° slope of bouldery sandy loam (Fig. 4). The failure lies at the base of a boulder-mantled slope of colluvium along the western margin of a topographic convergence. The failure surface lies atop diamicton and saprolite.

Upslope of the failure, clasts with intermediate axes of 1.5 m are found, and coarse material comprises a significant fraction of the matrix-supported regolith. Numerous arcuate, 0.1- to 0.3-m-high scarps upslope of the failure indicate that much of the hillslope experienced minor sliding although only the base of the slope failed. Within just the disturbed area, individual boulder volumes approach 10 m^3 and regolith volume may exceed 250 m^3. We speculate that had the larger volume of material failed, the central channel of Teal Hollow would have been completely scoured of vegetation; a dramatic flow track would have been formed.

5.2.2. Flow track

The gradient is 28° immediately downhill of the slide scar and decreases to 17° over a distance of 180 m. The plan and profile of the flow track is highly variable, and this reflects the poor ability of a small debris flow to scour a coarse substrate while simultaneously removing vegetation. The forest canopy remains unbroken above the flow track, but a few small trees were entrained by the flow. Nowhere along the flow track did the flow scour to bedrock or saprolite. The maximum width of the track never exceeded 4 m, and the depth of scour was generally < 0.6 m. The flow track ends abruptly where a large boulder wedged against tree boles and significant deposition occurred.

5.2.3. Main channel

An abrupt change in channel form and gradient occurs 60 m downstream of the tree dam where the channel passes over massive boulders and bedrock outcrops. Below this point, the post-event channel widens from 4 m to as much as 10 m and many soil slips and a blowout enter from the valley wall. Resistance and damming associated with trees resulted in complex branching of the channel and irregular patches of deposition across much of the valley bottom. Ten soil slips reached the valley bottom within the main channel. None of the smaller slips generated significant deposition on the valley bottom and all failed along planar saprolite surfaces. Many of the failure surfaces ramp up to pre-event surfaces at the toe of the failure.

5.2.4. Fan

The transition from the rectangular channel to fan surface is abrupt. Flood waters diverged at the apex of the 60-m-long fan. Sediment was principally deposited on the east side of the fan as coarse, imbricated bars behind small dams of woody debris and tree boles. Scour was most pronounced downstream of sediment bars. Net sediment deposition atop the fan was only 4 m^3. However, the terminus of the fan was truncated to form a 3-m high scarp by lateral migration of Kinsey Run; and an unknown volume

Table 3
Contributions of sediment by landforms

Feature	Erosion (E; m^3)	Deposition (D; m^3)	Net (m^3)	Retention (D/E)
(a) Jenkins Hollow				
Channel	5793 (0.41)[a]	724 (1.00)	−4893 (0.37)	0.13
Slope	3998 (0.28)	2 (0.00)[b]	−4082 (0.31)	0.00
Slide $n = 1$[c]	90 (0.01)	0 (0.00)	−90 (0.00)	0.00
Blowout $n = 0$	0 (0.00)	0 (0.00)	0 (0.00)	0.00
Slump $n = 1$	4224 (0.30)	0 (0.00)	−4224 (0.32)	0.00
Totals	14,105 (1.00)	726 (1.00)	−13,379 (1.00)	0.05
(b) Teal Hollow				
Channel	1173 (0.35)[a]	427 (0.47)	−746 (0.30)	0.36
Slope	11 (0.00)	2 (0.00)	−9 (0.00)	0.18
Slide $n = 12$	1670 (0.49)	466 (0.52)	−1204 (0.48)	0.28
Blowout $n = 1$	517 (0.15)	0 (0.00)	−517 (0.21)	0.00
Slump $n = 1$	30 (0.01)	8 (0.01)	−22 (0.01)	0.27
Totals	3401 (1.00)	903 (1.00)	−2497 (1.00)	0.27

[a] Fraction of column total.

[b] Rounding reduces many ratio values to zero.

[c] Observed number of features.

of event-generated sediment was eroded from the Teal Hollow fan by Kinsey Run.

6. Results of sediment budgets

The lengthwise distributions of erosion and deposition within Jenkins and Teal Hollows is depicted as histograms in Figs. 5 and 6. Volumes of sediment erosion and deposition are summarized in Table 3. Dividing net cubic meters of sediment loss by drainage area yields storm-generated denudation values for each hollow (Williams and Guy, 1973). The value for Jenkins Hollow must be reported as a minimal value because of our failure to measure erosional features within sub-basins I, II, IV, and V. For Jenkins Hollow, the denudation rate is therefore reported as > 38 mm. The denudation rate for Teal Hollow is calculated as 27 mm. The geomorphic significance of the storm is apparent given a regional denudation rate of 25.5 mm ka^{-1} reported by Judson and Ritter (1964); the equivalent of more than 1000 years of geomorphic work was accomplished in a mere 16 h.

Sources of sediment differed significantly between the two hollows. The channel and channel side slopes contributed 69% of the sediment mobilized in Jenkins Hollow (Table 3). Within Teal Hollow, only 35% of the sediment was from the channel and channel side slopes. Slope failures supplied the remaining sediment volumes. While the slump in Jenkins Hollow was large, it contributed only 30% of the sediment mobilized in the hollow. However, the liquefied slump generated much of the erosion seen in Fig. 5. Channel erosion was minor upstream of the failure (not shown), but downstream of the failure channel erosion was significant and channel side slopes were eroded as the debris flow scoured banks and superelevated. Indeed, sediment contribution by side slopes was volumetrically greater than that of the channel for the first 300 m of the debris flow (Fig. 5). Channel scour eventually became predomi-

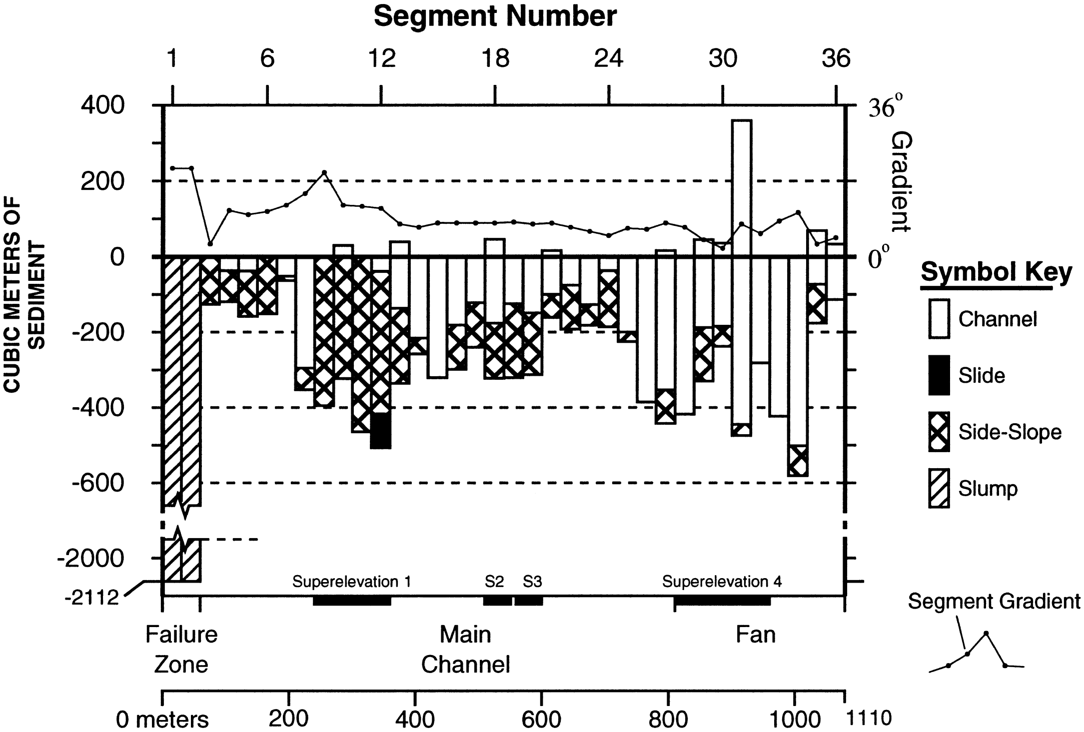

Fig. 5. Histogram depicting lengthwise distribution of erosion and deposition in Jenkins Hollow. Positive bars represent deposition. Negative bars represent erosion. Patterns indicate whether the volume was associated with a particular landscape feature.

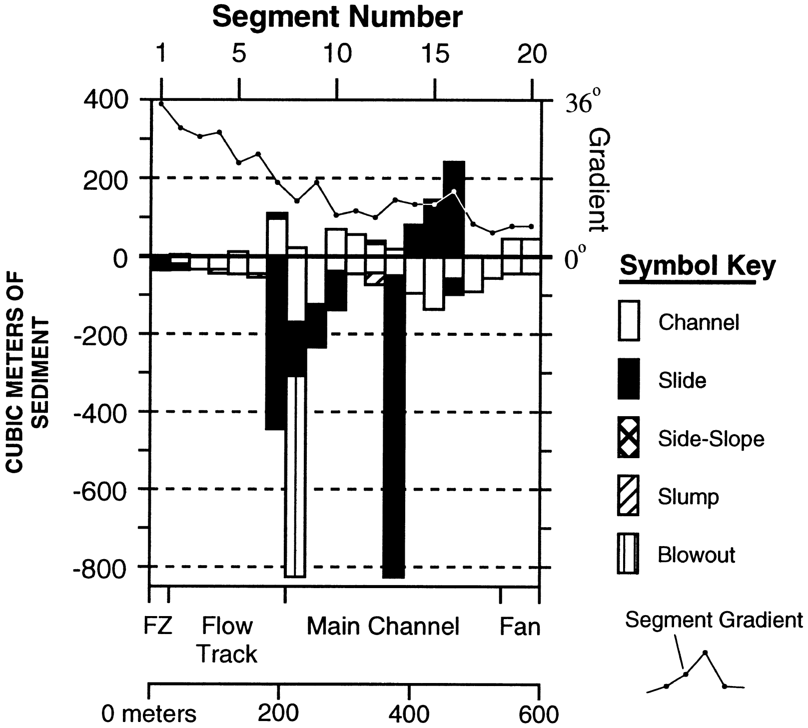

Fig. 6. Histogram depicting lengthwise distribution of erosion and deposition in Teal Hollow. Positive bars represent deposition. Negative bars represent erosion. Patterns indicate whether the volume was associated with a particular landscape feature.

nant as the channel widened; superelevations became smaller and erodible alluvium volumes increased as the flow attenuated. Given the known rainfall totals, in-channel flow may have been further promoted by liquefaction. Indeed, a general lack of levees and diamicton deposits suggests that the flow quickly evolved into a hyperconcentrated slurry.

Within Teal Hollow, the volumetric importance of slope failures (slides, slumps, and blowouts) in mobilizing sediment is clearly evident in Fig. 6; this relationship is best seen in Table 3. As with Jenkins Hollow, channel erosion in Teal Hollow was strongly influenced by slope failures. Downstream of the largest slope failures, channel erosion and deposition increased (Fig. 6). Increases in erosion are attributed to direct scour by liquefied failures and confinement of channel flow by the transient masses. Deposition was engendered by woody debris traps and tree boles. Aside from a large lobe of silt loam generated by two large parallel slips, all deposits in Teal Hollow were comprised of sediment coarser than medium sand. The paucity of fine-grained deposits attests to the ability of flood waters and liquefied failures to transport soil-derived, fine-grained sediment in a high gradient setting and suggests a mechanism whereby comparatively small soil slips could generate high net sediment losses during the storm.

7. Statistical analysis

For the accumulated segment data, Pearson correlation coefficients were calculated between such independent and dependent variables as channel gradient and volume of sediment eroded within the channel. The abbreviated results of these calculations for Jenkins Hollow are presented in Table 4 with correlations significant at a level of $\alpha = 0.10$. The correlations merely confirm the relationships seen in Fig. 5. Namely, side-slope erosion is negatively correlated with distance from the failure where the channel is narrow and shallowly underlain by

Table 4
Pearson correlation table for selected variables

	Total erosion	In-channel erosion	Side-slope erosion	Total deposition	Net erosion or deposition
Segment gradient	0.3040[a] (0.0805)[b]	−0.1552 (0.3807)	0.5008 (0.0026)	−0.1361 (0.4428)	0.36781 (0.0324)
Superelevation (Yes or No)	0.4435 (0.0086)	−0.0161 (0.9277)	0.4887 (0.0034)	0.2727 (0.1186)	0.3042 (0.0803)
Distance from failure	0.2583 (0.1403)	0.5739 (0.0004)	−0.4259 (0.0120)	0.3012 (0.0835)	0.1131 (0.5243)
Previous segment gradient	0.1881 (0.2867)	−0.3821 (0.0257)	0.6630 (0.0001)	−0.2862 (0.1008)	0.3238 (0.0618)

[a] Pearson correlation coefficient (r).
[b] Significance level.

bedrock. Channel erosion predominated in the downstream reaches where the channel is wide and alluvium is thickest. Hence, channel erosion is positively correlated with distance.

The only statistically significant correlation between dependent and independent variables observed in Teal Hollow was between channel gradient and channel erosion. Interestingly, the correlation was negative ($r = -0.4281$) with a significance level of 0.0675 ($n = 18$). This counterintuitive result reflects the nature of statistics as much as the processes at work in Teal Hollow. The small debris flow from atop the hollow created minor channel scour in steep portions of the basin, while hyperconcentrated flood waters supplied by the valley side slopes scoured the central channel atop the comparatively low gradient valley bottom.

Analysis of covariance models were created using the data for Jenkins Hollow. The analyses used the independent and dependent variables shown in Table 4 as well as others. While R^2 values as high as 0.69 (at a significance level of 0.001) were attained, the models only confirmed the patterns seen in Fig. 5. Linear correlations and analysis of covariance models may support our interpretations of the data, but they offer no quantitative insight into the underlying processes at work.

8. Discussion

The principal differences between the two hollows are (i) failure volumes, (ii) number of failures, (iii) geomorphic setting of failures, (iv) texture of failed materials, and (v) length of runout. The slump in Jenkins Hollow was both voluminous and at high relief within the basin. As the slump entered a high gradient reach, its potential energy was rapidly converted to scour-enhancing kinetic energy. The mean size of track-generating slope failures in the area is 377 m^3 (Morgan et al., 1997). At least three soil slips met or exceeded this value within Teal Hollow; failure sizes do not appear to have precluded development of flow tracks. However, the soil slips lay at comparatively low relief and were broad and shallow. Failure depths rarely reached 1 m. The fine-grained texture of the soils and shallow depth of failure may have enhanced liquefaction and conversion of failed material to hyperconcentrated flows.

All but one of the soil slips in Teal Hollow occurred in silty soils of the Dyke Series (Fig. 3). The Dyke Series is described as a colluvial soil (Elder and Pettry, 1975). Similar soils elsewhere in the Blue Ridge Mountains originate as residual soils upon interfluves and move downslope by creep and mass wasting (Graham and Buol, 1990; Graham et al., 1990). The Dyke Series soils lie atop the Lovingston Gneiss (Figs. 2 and 3), but this series also lies atop the Pedlar and Old Rag granites in adjacent low-order basins that contain many soil slips; soil morphology appears to have played a role in determining whether a particular slope failed. The small number of slope failures in Jenkins Hollow suggests that soils there were less susceptible to mass wasting and that possibility merits further study. Given that both hollows lie within the area of maximum rainfall totals, these observations challenge the conclusion of Morgan et al. (1997) that rainfall totals and intensities alone controlled the distribution of slope failures.

Storm-generated denudation values for Jenkins and Teal Hollows are comparable to the values of 44 mm reported by Williams and Guy (1973). Within sub-basin III of Jenkins Hollow, in which the failure zone lies, a negligible fraction of sediment was contributed by the channel; and the denudation rate is calculated as 65 mm. Sub-basin III is roughly the same size as Teal Hollow where the denudation rate was 27 mm. Hence, the denudation rate in sub-basin III was 2.4 times greater than that of Teal Hollow. The denudation rate in Teal Hollow nonetheless exceeds the regional denudation rate of 25.5 mm ka^{-1}. This fact suggests that sediment budgets for catastrophic storms may need to consider more than the erosion and deposition associated with dramatic flow tracks.

Cenderelli and Kite (1998) presented histograms of lengthwise erosion and deposition along four debris flow tracks in the Appalachian Mountains of West Virginia. The distribution of erosion within Jenkins Hollow resembled the lengthwise distribution of erosion in the upstream reaches of the three comparable debris flow tracks studied by Cenderelli and Kite (1988) (see their Fig. 10). As a result of long runout lengths, Cenderelli and Kite observed deposits containing 57–81% of the debris flow-mobilized sediments, principally in terminal deposition zones. The deposition zones began between 1200 and 2000 m downstream of the failure zones and accounted for no less than 86% of all sediments deposited. This contrasts with the values of 5% and 27% reported herein.

The failure zone within Jenkins Hollow lies 1050 m upstream of Canterbury Run. During the storm, streamflow within Canterbury Run was a ~30-m-wide torrent at its junction with Jenkins Hollow. As a result, there is no recognized deposition zone and no deposition in Canterbury Run directly attributable to Jenkins Hollow. Low sediment retention within Jenkins Hollow is attributable to an insufficient runout length within which the debris flow could dissipate its potential energy, low flow viscosity due to incorporation of flood waters caused by the extremely high rainfall intensities and totals, and the storm-generated competence of Canterbury Run. This suggests that drainage network organization may play a significant role in determining long-term storage volumes of sediment in the upstream portions of river basins. For instance, long pathways may ensure high retention rates and episodic aggradation of headwater streams by debris flows, whereas networks with low bifurcation ratios or small tributaries debauching directly into large streams may foster transport of sediment downstream to alluvial flood plains. Benda (1990) reported that the majority of debris flows in the Oregon Coast Range come to rest in 3rd-to-5th order channels.

In addition to runout length, the magnitude of catastrophic storms and their debris flows must certainly play a role in determining whether low-order fans experience significant deposition. Within a week of the 27 June 1995 storm, two other catastrophic storms struck drainage basins within 60 km of the Madison County event. These storms generated one debris flow near Front Royal and approximately a dozen along the Moorman River in western Ablemarle County. Inquiries with local residents with rain gages suggest that these storms generated less than 400 mm of precipitation. The lower precipitation totals may explain why the associated debris flow came to rest on slopes as great as 20° and debris flows generated large lobate fans within low-order hollows. When interpreting the flood history of a region, we should keep in mind that a wide spectrum of storm intensities and durations are possible. As a result, particular classes of storms may be recorded as depositional units on different landforms; well-developed low-order fans do not necessarily record all catastrophic storms equally; and fan stratigraphy must therefore be interpreted with some caution. Within the Rapidan River Basin, the 1995 event was characterized by erosion of fan surfaces and therefore left a paltry record on such surfaces.

9. Conclusions

Lengthwise distributions of erosion and deposition differed dramatically between the two hollows as did the sources of erosion and deposition. Within Jenkins Hollow, erosion was principally accomplished by a debris flow and confined to a central channel and channel side slopes (Fig. 5). Within Teal Hollow, erosion was highly variable and intimately related to individual slope failures (Fig. 6). Deposition was minor in both hollows, although Teal Hollow retained a larger fraction of mobilized sediments (Table 3). The paucity of channel deposits in Jenkins Hollow contrasts with the coarse deposits in Teal Hollow. The latter deposits reflect the inability of shallow hyperconcentrated stream flow within wide portions of the valley bottom to ream the channel of large resistence elements such as trees. The deposits also reflect the comparatively low kinetic energy of the small debris flow. The lack of a terminal deposition zone in Jenkins Hollow and at the end of other nearby flow tracks can be explained by long runout lengths, low viscosities of flows, and many flows debauching directly into high-order streams.

Although the forest canopy was only minimally disturbed within Teal Hollow, its storm-generated denudation rate of 27 mm exceeds the regional long-term rate of 25.5 mm ka^{-1} (Judson and Ritter, 1964). The denudation rate in Jenkins Hollow was more than 1.4 times greater than that of Teal Hollow; but within a sub-basin of similar size to Teal Hollow, the denudation rate was 65 mm or 2.4 times greater. Thus, the catastrophic June 1995 storm was a significant geomorphic agent in both hollows. That the denudation rate in Teal Hollow was 40% of the rate in Jenkins Hollow suggests that single-storm erosion rates may be comparable between basins with different morphologies and storm responses. The high denudation rates may be attributed to short runout lengths and the nature of flows generated by slope failures. As a result, fans of low-order mountainous basins may not record all catastrophic storms or slope failures equally.

Acknowledgements

The authors thank Cullen Sherwood for his verbal support of this research. We thank Mr. Jenkins for access to his property and the National Park Service for access to Shenandoah National Park. We thank the reviewers and editors of this paper for their significant improvements to the manuscript. The data was largely collected as part of a senior Honor's thesis by HSD; additional data was collected by Susan Teal whom we thank. HSD wishes to thank the Waynesboro Gem and Mineral Society for a grant award that assisted this research. GSS thanks Christine McVie for her assistance to this project.

References

Allen, R.M., 1963. Geology and mineral resources of Greene and Madison Counties, Bulletin vol. 78. Virginia Division of Mineral Resources, Charlottesville, VA, 102 pp.

Benda, L., 1990. The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA. Earth Surf. Processes Landforms 15, 457–466.

Benda, L., Dunne, T., 1997. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. Water Resour. Res. 33, 2849–2863.

Bogucki, D.J., 1976. Debris slides in the Mt. Le Conte Area, Great Smokey Mountains National Park, USA. Geograkiska Annaler 58, 179–191.

Cenderelli, D.A., 1994. Erosional aspects of four debris-flow impacted channels on North Fork Mountain, eastern West Virginia. MS Thesis, West Virginia University, Morgantown, 124 pp.

Cenderelli, D.A., Kite, J.S., 1998. Geomorphic effects of large debris flows on channel morphology at North Fork Mountain, eastern West Virginia, USA. Earth Surf. Processes Landforms 23, 1–19.

Dietrich, W.E., Dunne, T., 1978. Sediment budget for a small catchment in mountainous terrain. Z. Geomorphol. Suppl. 29, 191–206.

Eaton, L.S., McGeehin, J.P., 1997. Frequency of debris flows and their role in long term landscape evolution in the central Blue Ridge, Virginia. GSA Abstr. Programs 29 (6), A–410.

Elder, J.H., Pettry, D.E., 1975. Soil Survey of Madison County, Virginia. USDA Soil Conservation Service, Washington, DC, 127 pp.

Graham, R.C., Buol, S.W., 1990. Soil–geomorphic relations on the Blue Ridge front: II. Soil characteristics and pedogenesis. Soil Sci. Soc. Am. J. 54, 1367–1377.

Graham, R.C., Daniels, R.B., Buol, S.W., 1990. Soil–geomorphic relations on the Blue Ridge front: I. Regolith types and slope processes. Soil Sci. Soc. Am. J. 54, 1362–1367.

Hack, J.T., Goodlett, J.C., 1960. Geomorphology and forest ecology of a forested region in the central Appalachians. US Geol. Survey Prof. Paper 347, 66 pp.

Howard, A.D., 1998. Long profile development of bedrock channels: interaction between weathering, mass wasting, bed erosion, and sediment production. In: Wohl, E.E., Tinkler, K. (Eds.), Bedrock Channels. Am. Geophys. Union Water Resource Monograph vol. 107, pp. 297–320.

Judson, S., Ritter, D.F., 1964. Rates of regional denudation in the United States. J. Geophys. Res. 69, 3395–3401.

Kochel, R.C., 1987. Holocene debris flows in central Virginia. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris Flow Avalanches: Process, Recognition, and Mitigation. Geol. Soc. Am., Rev. Engr. Geol. vol. 7, pp. 139–155.

Morgan, B.A., Wieczorek, G.F., Campbell, R.H., Gori, P.L., 1997. Debris-flow hazards in areas affected by the June 27, 1995 storm in Madison County, Virginia. US Geol. Survey Open File Report 97-438, 12 pp.

Pierson, T.C., 1980. Erosion and deposition by debris flows at Mount Thomas, North Canterbury, New Zealand. Earth Surf. Processes Landforms 5, 227–247.

Pierson, T.C., 1985. Initiation and flow behaviour of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington. Geol. Soc. Am. Bull. 96, 1056–1069.

SAS Institute, 1994. JMP and Statistical and Graphics Guide. SAS Institute, Cary, NC, 580 pp.

Smith, J.A., Baeck, M.L., Steiner, M., Miller, A.J., 1996. Catastrophic rainfall from an upslope thunderstorm in the central Appalachians: the Rapidan storm of June 27, 1995. Water Resour. Res. 32, 3099–3113.

Wieczorek, G.F., Mandrone, G., DeCola, L., 1997. The influence of hillslope shape on debris-flow initiation. In: Cheng-lung, C. (Ed.), Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Proc. of First Inter. Conf., Water Resourc. Eng. Div., ASCE, San Francisco, 7–9 August, pp. 21–31.

Williams, G.P., Guy, H.P., 1973. Erosional and depositional aspects of Hurricane Camille in Virginia, 1969. US Geol. Survey Prof. Paper 804, 80 pp.