Landslides (2006) 3: 95–106
DOI: 10.1007/s10346-005-0029-5
Received: 4 June 2005
Accepted: 11 November 2005
Published online: 10 January 2006

Gerald F. Wieczorek · L. Scott Eaton · Thomas M. Yanosky · Eric J. Turner

Hurricane-induced landslide activity on an alluvial fan along Meadow Run, Shenandoah Valley, Virginia (eastern USA)

Abstract Although intense rainfall and localized flooding occurred as Hurricane Isabel tracked inland northwestardly across the Blue Ridge Mountains of central Virginia on September 18–19, 2003, few landslides occurred. However, the hurricane reactivated a dormant landslide along a bluff of an incised alluvial fan along Meadow Run on the western flanks of the Blue Ridge Mountains. Subsequent monitoring showed retrogressive movement involving several landslide blocks for the next several months. Using dendrochronology, aerial photography, and stream discharge records revealed periods of landslide activity. The annual variation of growth rings on trees within the landslide suggested previous slope instability in 1937, 1972, 1993, 1997, and 1999, which correlated with periods of local flood events. The avulsive and migrating nature of Meadow Run, combined with strong erosional force potential during flood stages, indicates that landslides are common along the bluff-channel bank interface, locally posing landslide hazards to relatively few structures within this farming region.

Keywords Landslides · Hurricane Isabel · Dendrochronology · Retrogressive · Stream erosion · USA · Virginia · Shenandoah Valley

Introduction

Landslides triggered by severe storms have been examined along the Blue Ridge Mountains of central Virginia. A severe landslide event occurred on the night of August 19–20, 1969, when the remnants of Hurricane Camille, moved eastward across the Appalachian Mountains from the Gulf Coast, and stalled against a high-pressure system in Nelson County along the Blue Ridge in central Virginia. Within the 8-h period of the storm, at least 71.0 cm of rain fell producing several thousand debris flows and severe floods that claimed 150 lives (Williams and Guy 1973; Kochel 1987; Wieczorek et al. 2004). On June 27, 1995, an intense tropical type storm cell dropped up to 77.5 mcm of rain in 14 h causing flooding and triggering of about a thousand, damaging debris flows in northwestern Madison County of the Blue Ridge Mountains resulting in one death and destruction of buildings, bridges, and roads (Morgan et al. 1999; Wieczorek et al. 2000). Radiocarbon dating of prehistoric debris-flow events in the Madison County region revealed that debris-flow activity has recurred since 25000 YBP and on the average the events have recurred at least every 2500 years (Eaton et al. 2003).

Historic and recent landslide activity was examined along Meadow Run, a stream that emerges from the western flank of the Blue Ridge Mountains of Virginia into the Shenandoah Valley, northeast of the town of Crimora (Fig. 1). Currently, in this general farming region only relatively few structures are exposed to landslide hazards. Meadow Run flows across an alluvial fan primarily during periods of high runoff and enters the South River, a tributary of the South Fork of the Shenandoah River. The Pleistocene-Quaternary alluvial fan is composed of fresh and weathered silt, sand, gravel, and cobbles derived from quartzites, sandstones, and phyllites of the Antietam and Harpers Formations of the Chilhowee Group (Early Cambrian age) (Fig. 2) (Morgan et al. 2003). The largely forested alluvial fan is underlain by the Shady Dolomite (Early to Middle Cambrian age), which has limited exposure as saprolite, along the banks and thalweg of the stream channel.

This section of the Blue Ridge Mountains contains numerous alluvial fans that build and coalesce along its western flank. The fan complex of Meadow Run has several topographically higher banks and escarpments situated above the active stream channel, suggesting past periods of incision and lateral migration of the stream (Fig. 3). Currently, Meadow Run flows near and against one of these higher fan escarpments, or bluffs, that reach up to 20 m in height. In several locations stream migration and undercutting of these bluffs and higher fan surfaces has destabilized slopes and banks along Meadow Run. Additionally, instability also exists within the stream channel. Aerial photography shows that the stream has varied in its positions since 1937 through a series of stream avulsions, and has taken on both single and double thread channel patterns during this period (Fig. 3) (Peebles and Eaton 2004). The lateral migration zone of these incised streams is approximately 250 m wide along the western edge of the alluvial fan (Fig. 3).

Observations of several landslides of differing ages along the bluffs of Meadow Run raised the question of whether the ages and potential causes of these landslides could be accurately determined. The hypothesis is that high stream flow in Meadow Run causes erosion at the toe of the alluvial bluffs, initiating slope movement. The timing of slope failures was investigated using dendrochronologic techniques, which documented events of tree tilting and sprouting due to rotation during the landslide movement. The study then examined discharge records of the South River to ascertain local or regional high magnitude storms that produced flooding, and if these events coincided with the dendrochronologic record of slope movements at Meadow Run.

Landslide activity along Meadow Run

A dormant landslide composed of two different aged sections were roughly distinguishable on the basis of revegetation and slope modification along the banks on the northeastern side of Meadow Run. Beginning in 2002, the authors examined these two adjacent landslides, the apparently younger upstream landslide (UL) had a steep fresh-looking main scarp and sparse vegetative cover (Fig. 4), whereas the older downstream landslide (DL) had a slightly gentler slope and contained well-established, denser vegetative cover (Fig. 5). In March of 2003, a topographic map of the two adjacent landslides (Fig. 6) was compiled from field surveys.

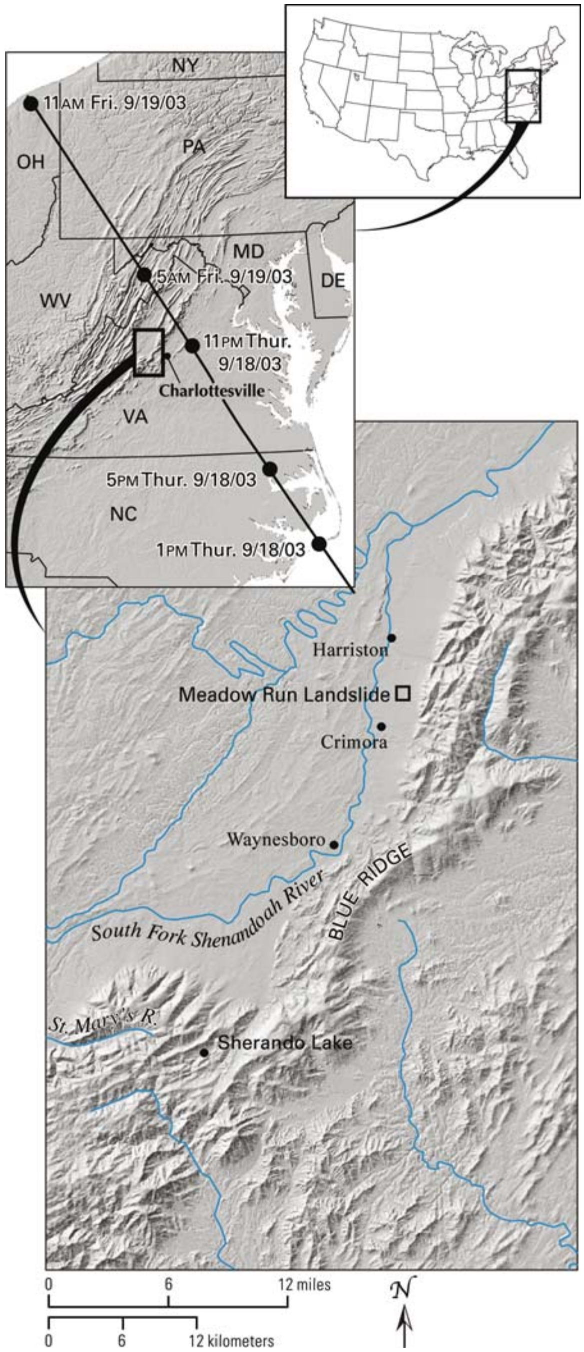

Fig. 1 Northwesterly path of Hurricane Isabel, September 18–19, 2003, across Eastern United States. The location of the Meadow Run landslide in Virginia (VA) is northeast of Crimora and west of the Blue Ridge Mountains

These two landslides are composed of predominantly earth (soil) from alluvial deposits without apparent bedding, although a small exposure of degraded bedrock (saprolite) was visible near the stream bed–hillslope interface of the lower northwestern scarp of UL (Fig. 7). Geotechnical laboratory soil tests (Table 1) found that the landslide materials were slightly plastic, clayey sands and clayey gravelly sands, classified as SP-SC, according to the Unified Soil Classification.

Tilting of trees and slope surfaces on these two landslides indicates that rotation was the dominant type of slope movement; hence, these two landslides are termed earth slumps, according to the landslide classification system of Cruden and Varnes (1996). The activity of movement of these two earth slumps was investigated by examining the timing of tree rotation, trunk resprouting, and growth of new trees determined from dendrochronology.

Dendrochronology

The absolute age of a tree establishes a minimum age of the surface upon which it grows. Damage to the roots or crown sometimes causes sustained periods of reduced radial growth that can be used to determine the year of damage (Yanosky 1983). If partially uprooted and tilted, some trees produce asymmetric radial growth (reaction wood) along the axis of lean that can be used to ascertain the approximate year of the event. The age of a sprout arising from a tilted trunk similarly can be used to estimate when the tree tilted (Sigafoos 1964). Thus, trees may preserve evidence of episodic events such as flooding, erosion and sedimentation, slope failure, insect damage, and fire (Hupp 1988; Yanosky and Jarrett 2002). Increment cores were collected from selected trees growing on scarp surfaces to determine their ages and to detect growth asymmetries caused by the partial uprooting or rotation of woody stems resulting from episodic surficial processes. In some instances small trees or sprouts were cut with a saw. The locations of most sampled trees within the two landslides are shown on Fig. 6a.

A white oak (*Quercus alba*) with a nearly horizontal trunk grows near the head of the main scarp of DL (#1 on Fig. 6a). This tree germinated about 1850 and supports a basal sprout that in turn has been rotated and tilted relative to the vertical (Fig. 8). To determine when the parent tree was tilted, and thus when the initial episode of slope instability probably occurred, rings along opposite radii perpendicular to the axis of lean were measured to the nearest 0.01 mm. Radial growth declined in 1937 and for the next 40 years thereafter ranged only from 25 to 50% of pre-1936 growth. This abrupt and sustained growth decline most likely resulted when the tree was partly uprooted during an episode of slope instability. The center ring of the basal sprout formed in 1940 but the sprout could be slightly older because its base has been subsumed by growth of the trunk. A similar sprout from a tilted black gum (*Nyssa sylvatica*) just downgradient from the oak (#2 on Fig. 6a) began to grow no later than 1941. Thus, evidence preserved in the wood of the oak and the black gum suggests the occurrence of an event in the late 1930s that altered the growth of both trees. The historic record of annual floods along the South Fork of the Shenandoah River at Harriston, Virginia, (Fig. 9), documents large floods in March 1936 (12,600 cfs) and April 1937 (11,700 cfs), suggesting that rainstorms generating high stream flows in Meadow Run might have caused slope instability that resulted in the tilting of the oak and black gum and the subsequent production of reaction wood and sprouts. Landslides could have been initiated by heavy rainfall causing saturation of soils and buildup of pore-water pressure, or from removal of the toe of the slopes associated with lateral migration of stream channels during floods.

Rings of the oak sprout (#1 on Fig. 6a) were examined to determine if changes in width could be used to infer when the sprout became rotated. Ring widths became asymmetric beginning in the early 1970s, and those along the wider radius thereafter exceeded all those along the narrower radius (Fig. 10). The same growth pattern was observed in the black gum sprout, and also in the trunk of a leaning Virginia pine (*Pinus virginiana*). This synchronous production of reaction

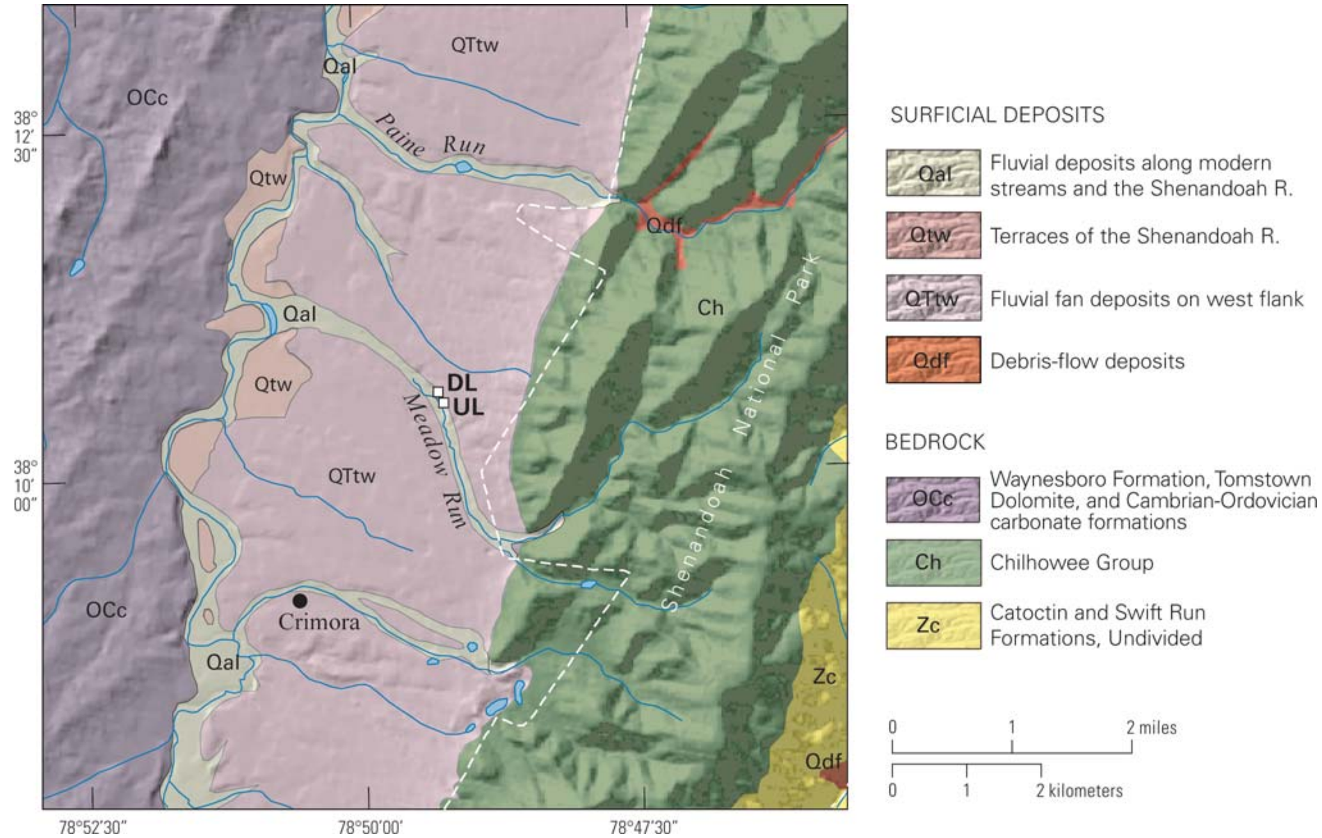

Fig. 2 Geologic map of the Meadow Run region (from Morgan et al. 2003). The drainage basin for Meadow Run originates to the east within the Chilhowee Group (Ch). Further west, the stream cuts through fluvial fan deposits (QTtw) and flows only intermittently westward to the South River

wood by three different species of trees within close proximity suggests a major episode of slope movement on the uppermost scarp of DL, possibly resulting from rainfall and flooding (21,300 cfs) in the wake of Hurricane Agnes in June 1972. No additional evidence of subsequent movement was found in these trees along the uppermost scarp.

The upstream landslide UL (Fig. 6) shows fresh scarp exposures and several blocks of recent movement. The germination of seedlings on disturbed soils and growth-ring responses of previously established trees (N=8 trees) suggest that episodic slope instability occurred in approximately 1993, 1997, and 1999. Species sampled on the UL included sassafras (*Sassafras albidum*), red oak (*Quercus rubra*), red maple (*Acer rubrum*), mountain laurel (*Kalmia latifolia*), and Virginia pine (*Pinus virginiana*). A 50-year old Virginia pine (Fig. 4) formed reaction wood beginning in 1993 followed by a virtual cessation of radial growth after 1997 (Fig. 11). Changes in the rate and quality of growth in this tree seemingly are related to two episodes of slope movement that first tilted the tree and later severely pruned its roots. Reaction wood produced by some study trees, and the proliferation of seedlings of synchronized age classes, suggest that episodic disturbance within localized parts of UL was sufficient to produce new surfaces for plant colonization as well as to tilt the trunks of some larger trees.

During the period of record (1924–2003) for the South Fork at Harriston (Fig. 9), recent floods occurred in April 1992 (9840 cfs), March 1993 (7360 cfs), September 1996 (28,900 cfs), and February 1998 (10,000 cfs). In addition to the correlation between the dendrochronologic evidence on the UL and the peak discharge flood record, geomorphic evidence shows numerous paleochannels traversing the Meadow Run floodplain (Fig. 3). These channels have repeatedly avulsed and realigned in many locations during floods, and eroded the base of the slope. Although the exact time of initiation of landslide movement is not directly obtainable from previous dates of flood events and dendrochronologic data, the observed daily beginning of landslide movement during a major flood event of Hurricane Isabel in September of 2003 along Meadow Run supports the general correlation between historic flood periods and landslide events suggested by the dendrochronologic data. More definitive association between previous landslide movement and flood and dendrochronologic events needs to be further confirmed by documented historic observations of landslide movement.

Hurricane Isabel

On September 18–19, 2003, Hurricane Isabel struck the mid-Atlantic coast of the USA, came inland across North Carolina, and then went northwestardly through Virginia along the Blue Ridge Mountains into Maryland and Pennsylvania. The heaviest recorded rainfall reported on the NOAA-NWS IFLOWS network was along the Blue Ridge in central Virginia (Fig. 1). The maximum rainfall reported by the IFLOWS system network was 51.3 cm during 24 h at the Upper Sherando station of Sherando Lake, located 20 km south of Waynesboro, Virginia (Fig. 1). Elsewhere along the central Blue Ridge, up to 27.9 cm of rainfall was recorded by the IFLOWS network. Major flooding occurred in the Sherando region and the larger Back Creek basin. Preliminary reports by the National Park Service indicate no

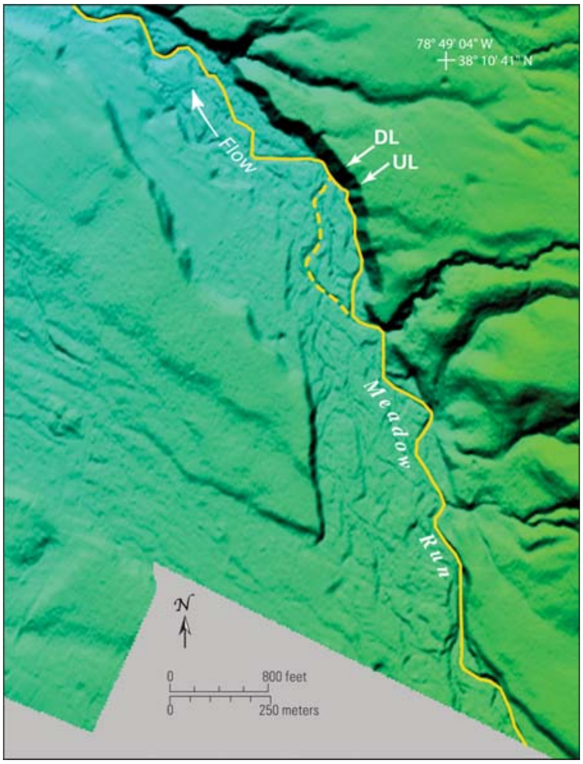

Fig. 3 Meadow Run channel shown on LiDAR image with locations of upper landslide (UL) and downstream landslide (DL). The *solid line* indicates the current mainstream channel flowing to the north–northwest with the *dashed line* indicating the location of an additional active channel during Hurricane Isabel

landslide activity along the Blue Ridge in Shenandoah National Park, located north of Sherando. Imagery in the Sherando-St Mary's River region revealed a very limited number of landslides triggered by Hurricane Isabel, with as few as five relatively small landslides detected in a large area of about 120 km², although no debris flows were detected.

Hurricane Isabel was expected to trigger landslides as it came ashore and passed through mountainous areas; however, the observed landslide impacts were much less severe than anticipated. The speed of Hurricane Isabel as it passed from south to north from North Carolina through Virginia accelerated slightly so that rainfall totals at most locations were less than expected. Rainfall totals of 27.9 cm over 24 h from Hurricane Isabel would not have reached the critical thresholds of rainfall necessary for triggering debris flows previously identified nearby in the Blue Ridge of central Virginia (Wieczorek et al. 2000).

Hurricane Isabel produced 17.4 cm of rain within 24 h at Paine Run (Fig. 1), about 3.5 km to the northeast of Meadow Run. Flooding along the South River was higher than previously recorded since Hurricane Fran in September 1996 (Fig. 9). This heavy rainfall caused flooding along two separate tributary stream channels of Meadow Run whose confluence meet at these two adjacent landslides (Fig. 6). When these two adjacent landslides along Meadow Run were subsequently examined on September 21, a portion of the upstream landslide (UL) had been reactivated (Fig. 12). The direction of stream flow along the tributary of the Meadow Run was directed toward the toe of UL, whereas the other tributary channel was directed toward the toe of the DL near the confluence of these two channels (Fig. 6). During or shortly after Hurricane Isabel, the toe of UL had been removed and a new scarp had formed midway up the slope. The portion of UL reactivated by Hurricane Isabel in relation to the direction of the tributary channel of Meadow Run is shown in Fig. 13. Although

Fig. 4 Upstream landslide (UL) along Meadow Run. Gravel and cobbles at the toe of the landslide were deposited from the stream channel of Meadow Run. Note the deciduous vegetation just above our colleague's head. Photograph taken July 25, 2002. Compare this picture to Fig.12

Fig. 5 Downstream landslide (DL) located along Meadow Run. Dry gravel in foreground was deposited in the stream channel of Meadow Run. Photograph taken April 1, 2003

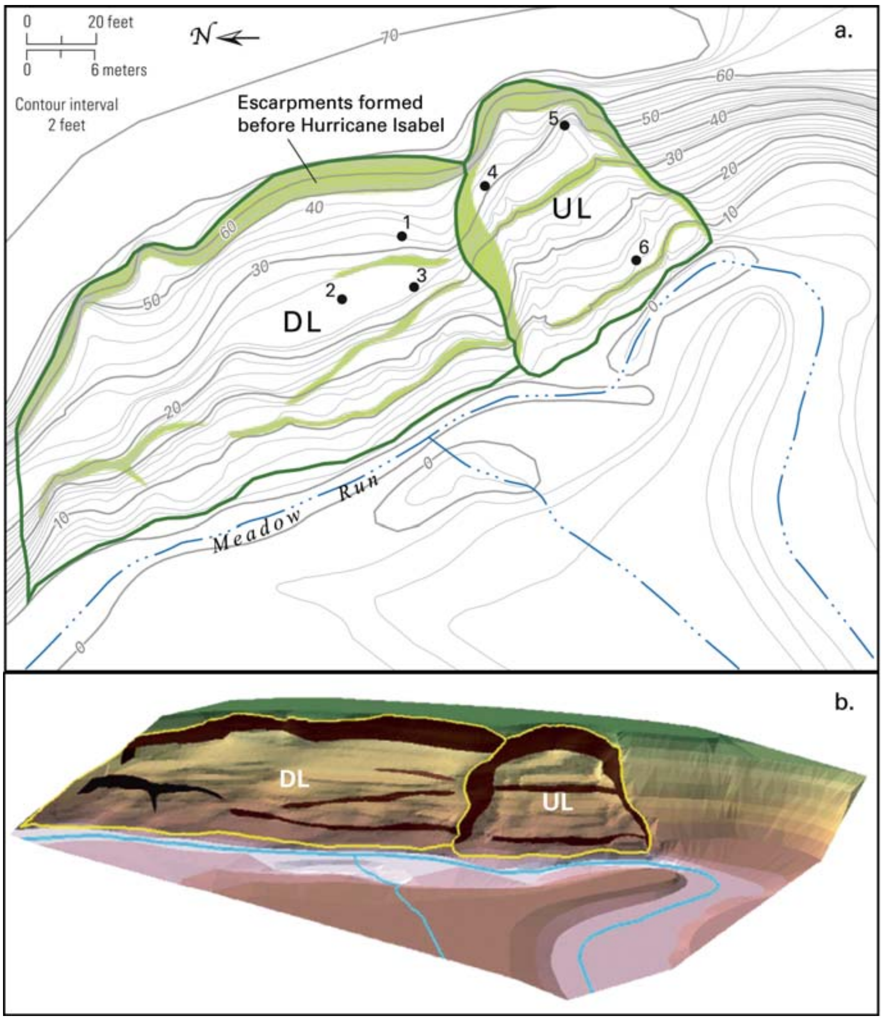

Fig. 6 Illustrations showing two adjacent landslides, UL and DL, along the northeastern side of Meadow Run. **a** Contour lines were prepared from field survey conducted in March 2003. The numbers (1–6) represent locations of trees sampled for dendrochronology: 1– tilted white oak with sprout, 2– tilted black gum with sprout, 3– leaning Virginia pine, 4– sassafras and red oak, 5 – red oak, sassafras, and mountain laurel, and 6 – cedar, sassafras, and leaning 50-year old Virginia pine, **b** Three-dimensional image of UL (*right side*) and DL (*left side*) prepared from 2-foot topographic contours shown in Fig. 4a. The main and secondary scarps are shown as shaded parts (*brown*) of the landslides, and the outline boundary of the landslides outlined in *yellow*. The diagram features the two channels of Meadow Run impacting the toes of UL and DL

Fig. 7 Saprolite exposed near base of channel below alluvium along northwestern lateral scarp of (UL) landslide

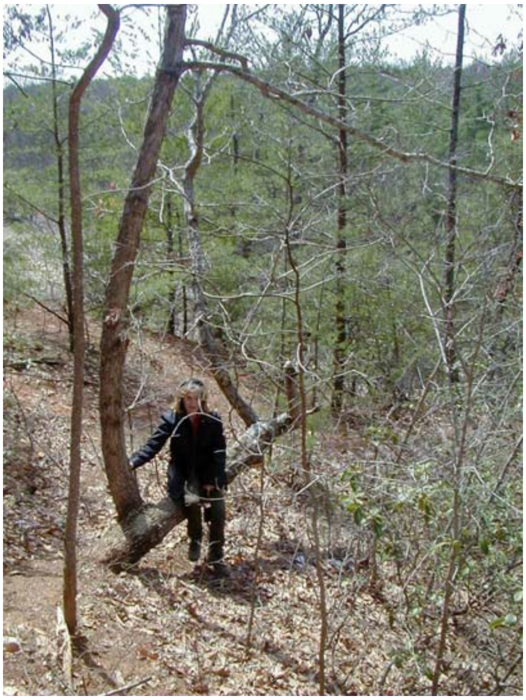

Fig. 8 Tilted trunk and basal sprout of a white oak growing along the head of the upper scarp of DL. The tree was tilted in the late 1930s and the basal sprout started to grow no later than 1940. Note that the sprout was subsequently rotated and also tilted, although it has now resumed a more vertical orientation. Photograph taken April 1, 2003

there was no reactivation of DL during Hurricane Isabel, the orientation of the other tributary channel did suggest that high flows in the past could have triggered DL when the main stem Meadow Run channel followed this tributary channel as recognized on 1937 aerial photography (Peebles and Eaton 2004).

Following Hurricane Isabel, the main scarp was documented on September 20, located halfway upslope within UL. The initial movement was likely a toe failure and runout (Bromhead and Ibsen 2004) triggered by the large and rapid stream impact. The sliding appeared to be confined to weak soil materials (Table 1), although some stronger saprolite failures were observed at a few locations along the flanks of the slide (Fig. 7). A portion of the toe of the landslide, including soil, trees, and previously documented fallen tree trunks had been removed by the erosive flooding along Meadow Run. Some fragments or blocks of the slightly cohesive red clayey sand originating from the toe were noted up to about half a km downstream of UL along the main downstream channel of Meadow Run.

Rates of landslide movement

As observed periodically following Hurricane Isabel, the reactivated UL continued to move downslope, and the zone of instability expanded in the upslope direction during the next several months. New cracks formed and in some areas these cracks became minor escarpments, which generally indicated an upslope retrogressive form of slope movement (Fig. 14).

The cracks and escarpments separated the moving mass into several general individual blocks (Fig. 15). Measurements of displacement were made along scarps and within the blocks with flag points installed as stakes within parts of the separate blocks (Fig. 16). The rates of movement of three main blocks varied over the period starting from Hurricane Isabel (September 18–19) until the end of January

Table 1 Soil properties

Sample	Peak shear strength (friction angle/cohesion)	Liquid limit	Plastic limit	PI	% Clay (<.004 mm)	% Gravel (>.476 mm)
MR-1	37.2/14.8	41	22	19	6.2	0
MR-2	–	40	18	22	5.7	0
MR-3	–	41	20	21	5.7	0
MR-4	29.0/19.9	40	23	17	5.7	0
MR-5	39.3/15.6	29	18	11	3.5	11.2

Location of samples taken on Meadow Run landslide shown in Fig 15. Geotechnical testing performed by Jonathan McKenna, USGS, Denver, Colorado

Friction angle units are degrees, cohesion units are kPa, liquid limit and plastic limit units are water content

PI represents Plasticity Index (Liquid Limit–Plastic Limit)

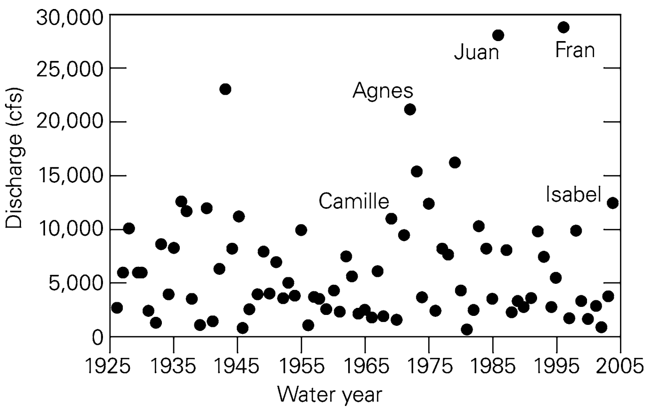

Fig. 9 Annual peak discharge of the South River at Harriston, Virginia, located 4.8 km northwest of the study area (Fig. 1). A water year runs from October 1 through September 30. Hurricanes identified within this region caused some of the highest river discharges. Discharge data from 1952 to 1968 were not recorded for this station, and are approximated from the Middle River gaging station at Grottoes, located ~12 km north of Harriston. Long-term records between the two gaging stations show that the median value of Middle River discharge at Grottoes is 1.3 times greater than flows recorded at Harriston; therefore, this relationship was used to approximate the missing discharge values

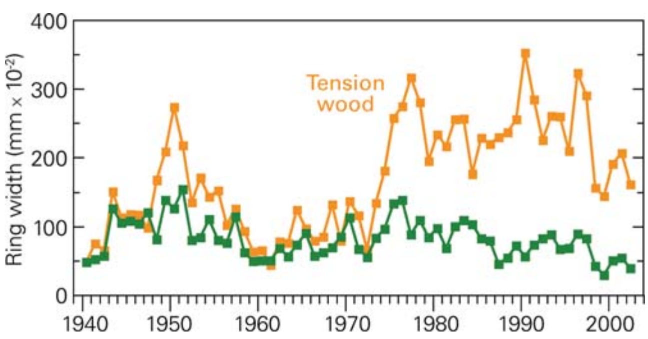

Fig. 10 Widths of rings of the white oak sprout along the axis of lean. Wider rings (tension wood) formed along the upslope side of the sprout when it was rotated and tipped in the early 1970s, presumably in response to heavy rainfall and flooding associated with Hurricane Agnes in June 1972

13, 2004, when movement of all blocks within UL had ceased. The rates of movement of the three main blocks are shown in terms of m per week (Fig. 17). The block on the lower part of the slope on the downstream side (Lower Slope Downstream Side) (Fig. 15) had moved 1.3 m within the first 4 days (rate of 2.3 m/week) immediately following Hurricane Isabel. Subsequently, the rate of movement decreased to 0.9 m/week from September 23 through October 7, when it temporarily ceased moving.

In the upper part of UL, the initiation of retrogressive movement above the main scarp was recognized by October 7, as tension cracks started to develop upslope. An intact block with a tree on the top upstream side (Top Tree Block), began to show slight movement of 5 cm between October 18 and October 28, following 1.93 cm of rainfall on October 14 (Fig. 17). During the next 4 weeks, this block continued to move at a slow steady rate of 0.064 m/week after a storm of 2.87 cm of precipitation on November 5–6, and another storm of 4.75 cm of precipitation on November 12–16. During the period from November 18 to 25, with no additional precipitation, this same block moved another 80 cm. Two winter storms in early December each brought 10.2–12.7 cm of snow and ice. Additional movement was observed after subsequent freeze–thaw processes. The block continued moving over the next 3 weeks at a steady rate of about 0.35 m/week until December 30, after which movement had ceased.

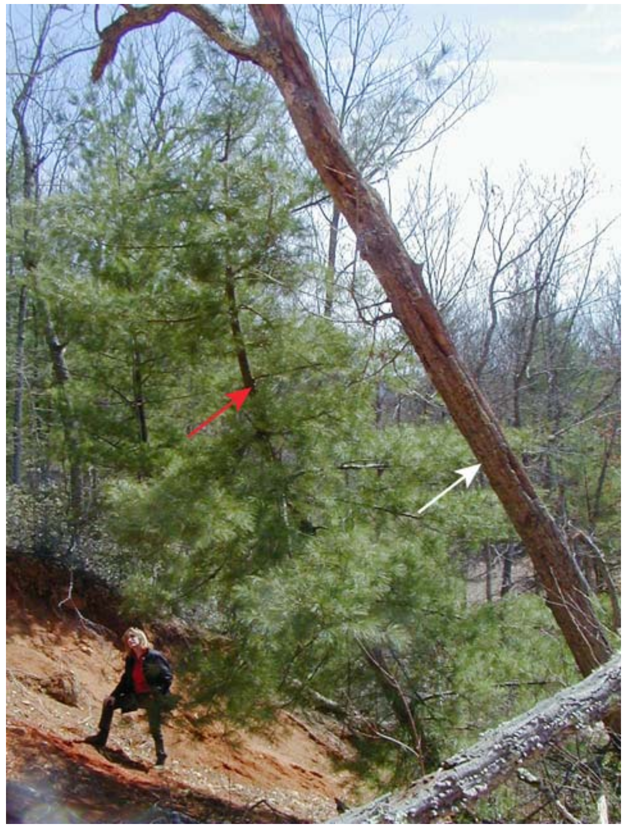

Fig. 11 Tilted Virginia pine (*red arrow*) shows evidence of recent movement (1993) of upstream landslide (UL). Tilted chestnut oak (*white arrow*) of unknown age also resides on same disturbed slump block as the Virginia Pine. Photograph taken April 1, 2003

During this same period of snow and ice in December, the Lower Slope Upstream Side reactivated at a moderate movement rate (Varnes 1978) of 1.60 m/week for 2 weeks between November 30 and December 13, before slowing down greatly and ceasing movement by January 13, 2004. By this date, additional fresh tension cracks were observed upslope of the Top Tree Block, reaching the uppermost dormant scarp of UL (Fig. 14). However, these small tension cracks quickly filled with loose regolith and no displacement was subsequently observed over the entire landslide between January 13 and March 19, 2004.

Landslide morphology

The displacement of UL following Hurricane Isabel showed little evidence of rotation of the earth blocks or of vegetation as they moved downslope. Although the rupture surface could not be observed or detected beneath the ground surface and its depth is unknown, it is likely to be relatively shallow, perhaps only several meters deep, based on the relative short height of the active scarps and the thickness of the individual blocks. Because the slope angle below the main scarp became steeper, e.g., the downstream part of UL had modified from about 28° to a steeper slope angle of 39°, there was no

Fig. 12 Upstream landslide (UL) reactivated by Sept. 18–19, 2004 Hurricane Isabel. The new scarp of the reactivated landslide formed midway upslope (*arrows*). Stream flow of Meadow Run remains near toe of landslide. Photograph taken September 21, 2003

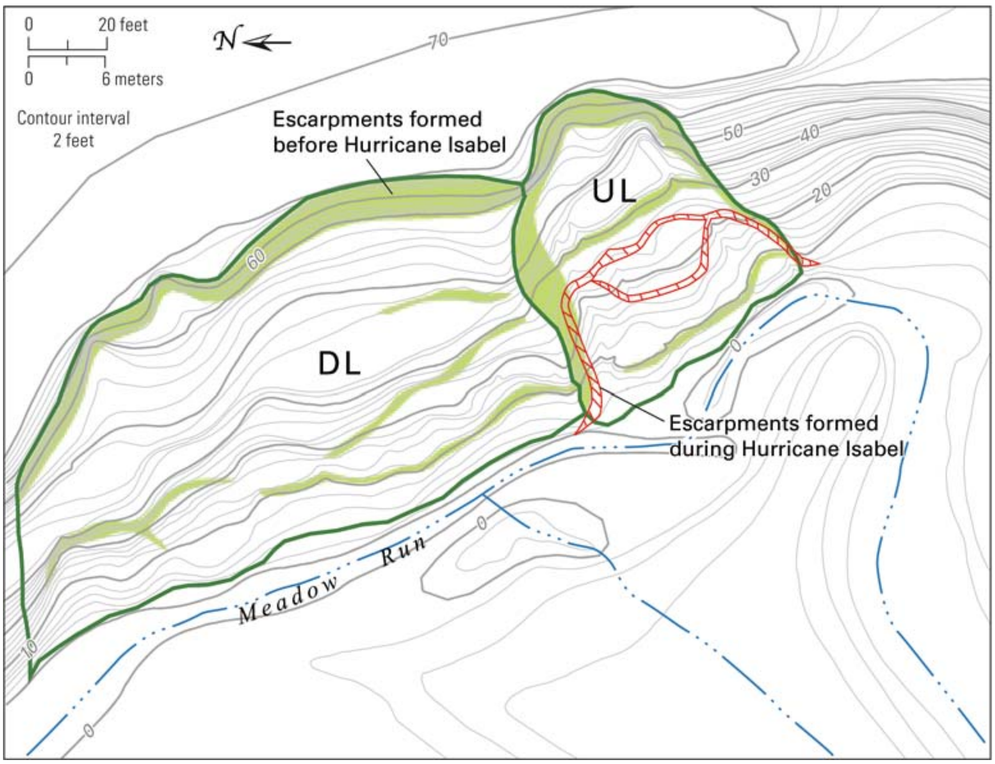

Fig. 13 Illustration depicting reactivation of UL from Hurricane Isabel. Contour lines are constructed from survey data that predate Hurricane Isabel and subsequent instability and movement of the slope. *Red lines* represent escarpments formed during Hurricane Isabel on September 21, 2003

indication that rotation had made the lower part of the slope flatter near the toe (Fig. 18). This increase in the degree of slope along the lower part of UL was likely the cause for the development of upslope instability that lasted for the several months following Hurricane Isabel. Although previous movement of UL before Hurricane Isabel suggests rotational slumping from evidence of rotation of trees, the recent landslide movement is more planar, resembling an earth slide. Presence of stronger material at slightly greater depth, e.g., saprolite observed along the flanks of UL, could be limiting the depth of the rupture surface beneath the center of UL, or may have a lower

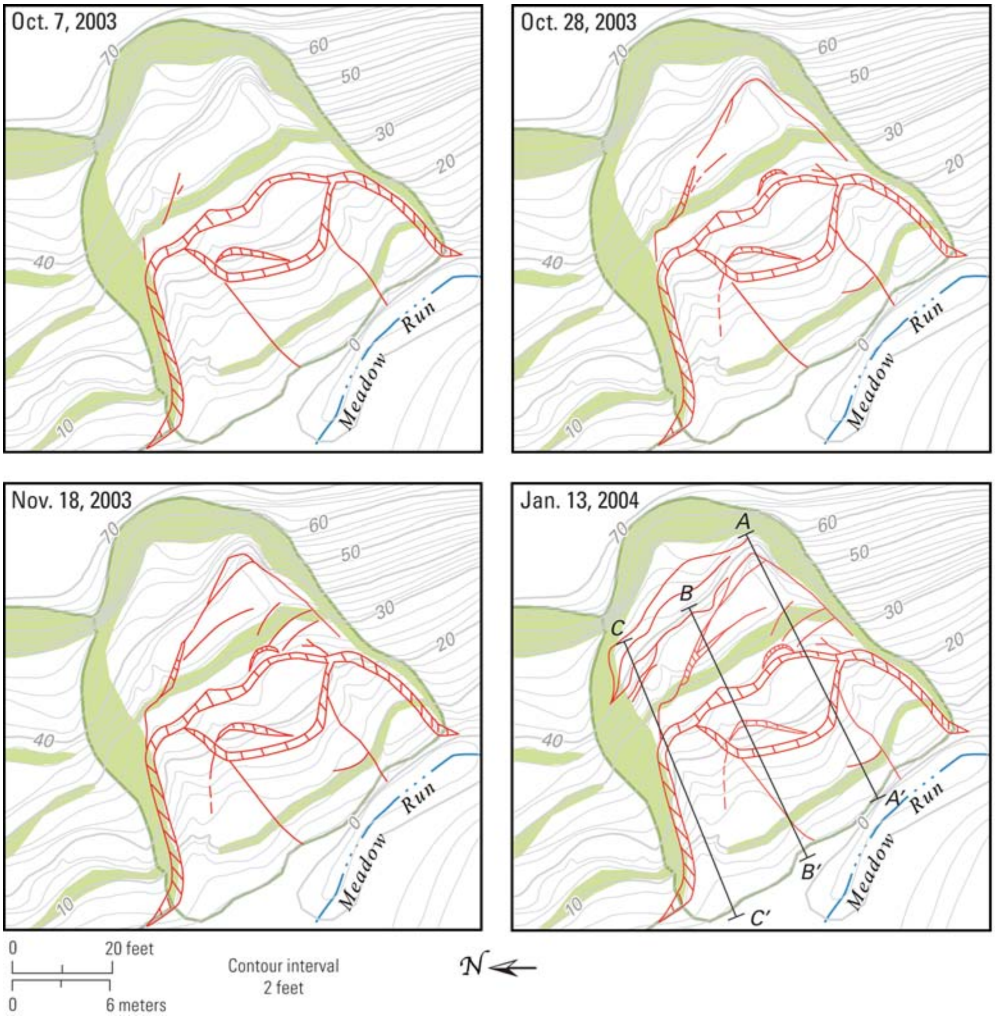

Fig. 14 Retrogressive landslide movement of UL after initial movement during Hurricane Isabel (9/21/03). Landslide features (*red*) changes represented on October 7, 2003, October 28, 2003, November 16, 2003, and January 13, 2004. Profile locations (A-A′, B-B′, and C-C′) are shown on the January 13, 2004 image

permeability, thereby facilitating high pore pressures and subsequent loss of shear strength of the basal regolith units.

The changes in the alignment between the upper tributary of Meadow Run and the toe of UL from Hurricane Isabel are difficult to recognize. Following Hurricane Isabel, more material from the toe was removed from the center and downstream part of UL than from the upstream section (Fig. 18). Using cross sections of UL from the March 2003 (pre-Hurricane Isabel) topographic map and resurveying along the same profiles in March 2004 (Fig. 18), the volume of removed landslide material was estimated at approximately 900 m^3. From immediately after Hurricane Isabel to the time that the retrogressive activity of UL had ceased expanding the size of the reactivated landslide, the length of the active landslide had about doubled from about 17 to 32 m (parallel to the slope) from the toe along the stream to the bottom of upper unaffected scarp. With a width of about 24 m and assuming a median thickness of about 2 m (perpendicular to the slope) to the rupture surface (Fig. 18), the remaining landslide volume on the slope would be estimated to be about 1500 m^3. The width, depth, direction, and velocity of the tributary of Meadow Run that impacted the toe of UL during the flood stage of Hurricane Isabel were not observed or measured. Likewise, whether the initial movement of UL was gradual or sudden is unknown. If the movement of UL was sudden, it could have resulted in a temporary blockage of

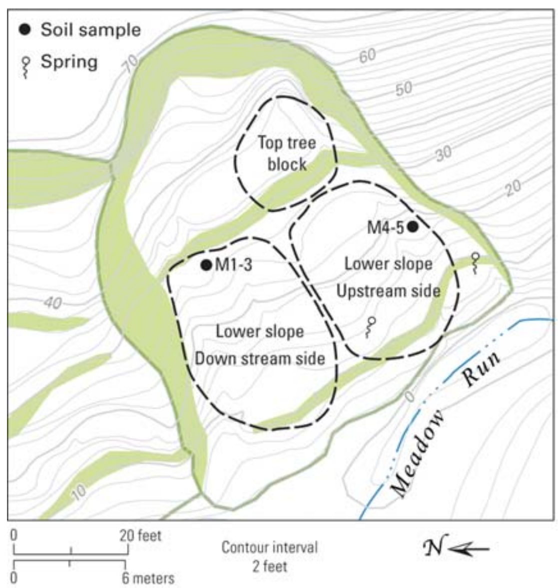

Fig. 15 Characterization of separate blocks within UL reactivated by Hurricane Isabel. Location of observed springs and soil samples (M1-3 and M4-5) are identified

Fig. 16 Four days after Hurricane Isabel, displacement of about 1.3 m was measured on a block (Lower Slope Downstream Side) below the scarp (*white arrow*). Red flag points had been installed 2 days earlier during which time multiple tension cracks had developed. Photograph taken September 23, 2003

Meadow Run. The minimal erosion of the upstream toe segment of Line A–A′ (Fig. 18) compared to Lines 1 and 3 (Fig. 18) suggest that the stream-flow impact was slightly greater at the midstream to downstream part of UL. Higher stream velocity or possible more resistant strength of material, e.g., saprolite, could have controlled the location of erosion along the toe of the slide.

In the months following Hurricane Isabel, two water springs with low rates of seepage were observed in the lower parts of UL (Fig. 15). Antecedent moisture conditions from the wet spring and summer (2003) may have facilitated water spring activity. These springs located at elevations about 4 m above the base of the stream channel suggest that a perched groundwater table exists in the lower part of UL, and is influenced by infiltration of rainfall rather than by stream flow from Meadow Run. These springs very possibly affected the stability of the landslide after Hurricane Isabel. Their locations are coincident with parts of the UL where the blocks of soil had become sufficiently crumbled and moistened, thereby greatly reducing their strength. In some instances the material was remobilized and flowed downhill, producing small-scale earth flows.

Discussion

Although some types of landslides, e.g., debris flows, occur at decadal frequency during heavy storms and hurricanes in steep parts of the Blue Ridge Mountains of central Virginia (Wieczorek et al. 2000), earth slumps or slides initiating on alluvial fans may occur as frequently. The relief of bluffs within the alluvial fan created by stream incision of Meadow Run is higher than most observed regionally and accounts for potential destabilization. Although the flow along Meadow Run is intermittent, the high flows during flood stages not only cause flow on different and multiple stream channels which have the capacity to migrate and avulse, but as suggested by dendrochrono-

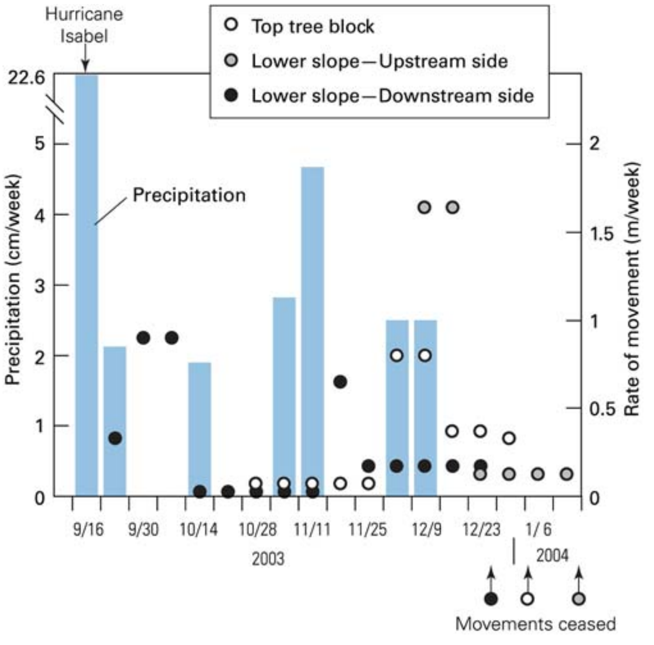

Fig. 17 Graph showing rates of landslide movement (m/week) versus precipitation (cm/week) for three main blocks of UL for the period September 19, 2003 through January 13, 2004

logic dating of two adjacent landslides, is a frequent trigger for slope instability.

The observations of continuing instability of the two adjacent landslides and association with climatic events following Hurricane Isabel suggests that multiple triggering events occurred within the last century. From 1937 to 2003, including the Hurricane Isabel event, there

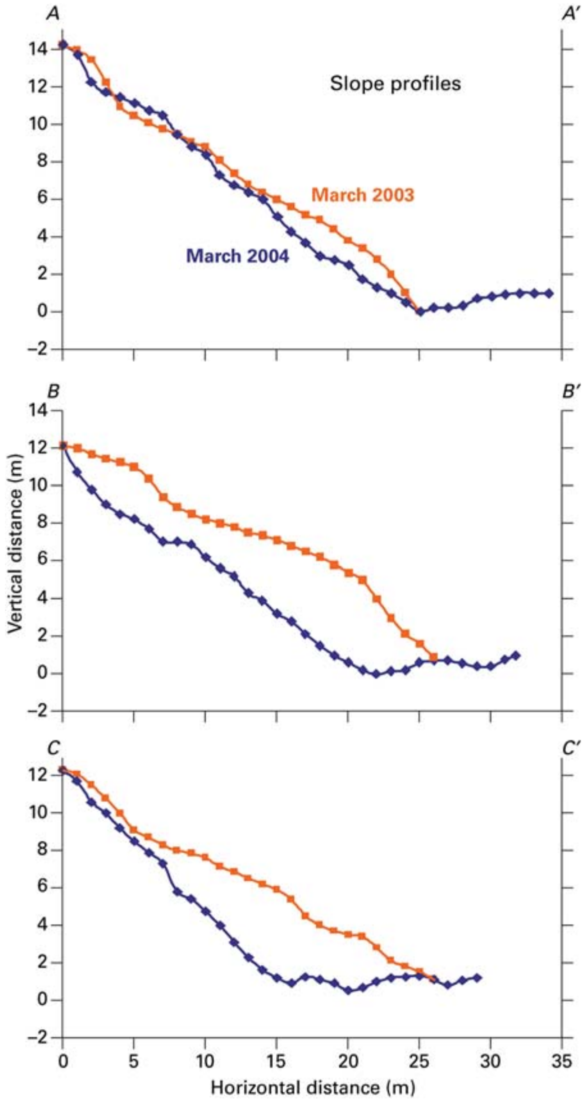

Fig. 18 Cross sections of upstream landslide (UL) before (March 2003—*red line*) and after landslide movement ceased (March 2004—*blue line*) from above the scarp activated in Hurricane Isabel to Meadow Run stream channel. The toe of UL on the downstream side was removed about 7–8 m (*horizontal*) by the flooding of Meadow Run during Hurricane Isabel. Line A-A′ is located at furthest upstream (*south*) section of UL, Line B-B′ is the center section, and Line C-C′ is at downstream (*north*) section of UL

have been six storm-landslide events identified at this specific location on Meadow Run (1937, 1972, 1993, 1997, 1999, and 2003) a relatively high landslide recurrence rate for central Virginia. Whereas stream bank erosion was judged the preliminary trigger following Hurricane Isabel, subsequent retrogressive landslide movement was extended by infiltration of precipitation. This process increased pore water pressure during several moderate storms, and later snow and ice affected freeze and thawing within the landslide mass.

Although stream flow during Hurricane Isabel on the South River was not as great as during several other recent storms, e.g., Hurricanes Agnes, Juan, and Fran (Fig. 9), the direction and impact of stream flow on Meadow Run was sufficient to reactivate UL. Of additional interest is that landslide movement of UL continued well beyond the time of Hurricane Isabel. This suggests that using dendrochronolgy for dating the time of landslide activation can be stretched temporally because not all impacts on vegetation occur simultaneously. This technique may prove useful for dating past slope movement events in other remote areas that see minimal human travel, where slope failures may go undetected.

The reactivation of UL in 2003 in a translational rather than rotational form could be due to the additional strength of subsurface materials. The recent movements of UL in 1993, 1997, and 1999, removed additional surficial material. The likely presence of stronger material at a slightly beneath the surface, e.g., several meters, is evidenced by the presence of saprolite along the low flanks of the UL and could be limiting the deeper rotational movement.

If future severe stream-flow events adopt the predominant route of the northern tributary of Meadow Run, the potential reactivation of the DL is more likely than continued reactivation of UL, which has shown frequent dendrochronologic evidence of recent movement since 1993. Possible reactivation of DL would correspond to the previously photographically identified period (1937–1957) when the stream tributary direction of Meadow Run directly impacted DL.

Conclusions

Examining the dendrochronlogy of many trees on a dormant landslide along Meadow Run in the eastern Shenandoah Valley, Virginia has shown that since 1937 landslide movement has occurred at least six times during periods of local flood events. At this same site a recent landslide movement triggered by Hurricane Isabel in September of 2003 indicated that stream bank erosion at the base of the dormant landslide was the principal triggering event. The monitored continuing retrogressive landslide movement for several months following the initial activation from the hurricane suggested that modification of tree rings altered by landsliding may represent not only the initial movement, but more lengthy periods of continuing landslide movement.

Acknowledgements

The preparation of this report was significantly assisted by David Jones and Boros Barrios, who prepared and improved the figures. We also acknowledge Harry Hibbitts and Sargent Bray of James Madison University who conducted a field survey in March 2003 to prepare the original topographic map of two landslides along Meadow Run. Jonathan McKenna aided us by conducting the geotechnical laboratory tests of the soil samples. The Grove family graciously granted us permission to access the field site. Frank Deviney of the University of Virginia provided the useful rainfall data. Ben Morgan and Cliff Hupp are acknowledged for the review of the initial version of the paper, and subsequently James Griffiths, Maia Ibsen, and an anonymous reviewer greatly aided our revisions of the submitted journal text.

References

Bromhead EN, Ibsen M-L (2004) Bedding-controlled coastal landslides in Southeast Britain between Axmouth and the Thames Estuary. Landslides 1:131–141

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (eds) Landslides: investigations and mitigation, special report 247. Transportation Research Board, Washington, DC, pp 36–75

Eaton LS, Morgan BA, Kochel RC, Howard AD (2003) Quaternary deposits and landscape evolution of the central Blue Ridge of Virginia. Geomorphology 56:139–154

Hupp CR (1988) Plant ecological aspects of flood geomorphology and paleofloods history. In: Baker VR, Kochel RC, Patton PC (eds) Flood geomorphology. Wiley, New York, pp 335–356

Kochel CR (1987) Holocene debris flows in central Virginia. In: Costa JE, Wieczorek GF (eds) Debris flows, avalanches: process, recognition, and mitigation. Geol Soc Am Rev Eng Geol 7:139–155

Morgan BA, Wieczorek GF, Campbell RH (1999) Map of rainfall, debris flows, and flood effects of the June 27, 1995, storm in Madison County, Virginia. US Geol Surv Misc Invest Ser Map I-2623A, 1:24000

Morgan BA, Eaton LS, Wieczorek GF (2003) Pleistocene and Holocene colluvial fans and terraces in the Blue Ridge region of Shenandoah National Park. US Geol Surv Open-File Rep 03-410, plate 1:100000. (http://pubs.usgs.gov/of/2003/of03-410/)

Peebles EK, Eaton LS (2004) The past, present, and future locations of the stream of Meadow Run, Blue Ridge mountains, Virginia.Geological Society of America, NE-SW Section Meeting, March 26–29, 2004, Abstracts with Programs, 36(2): 114

Sigafoos RS (1964) Botanical evidence of floods and flood-plain deposition. US Geol Surv Prof Pap 485A

Varnes DJ (1978) Slope movement types and processes. In: Schuster RL, Krizek RJ (eds) Landslides analysis and control. National Academy of Sciences, pp 12–33

Wieczorek GF, Morgan BA, Campbell RH (2000) Debris-flow hazards in the Blue Ridge of central Virginia. Environ Eng Geosci VI(1):3–23

Wieczorek GF, Mossa GS, Morgan BA (2004) Regional debris-flow distribution and preliminary risk assessment from severe-storm events in the Appalachian Blue Ridge Province, USA: Landslides, vol 1. Springer-Verlag, Berlin Heidelberg New York, pp 53–59

Williams GP, Guy HP (1973) Erosional and depositional aspects of Hurricane Camille in Virginia, 1969. US Geol Surv Prof Pap 804

Yanosky TM (1983) Evidence of floods on the Potomac River from anatomical abnormalities in the wood of flood-plain trees. US Geol Surv Prof Pap 1296

Yanosky TM, Jarrett RD (2002) Dendrochronologic evidence for the frequency and magnitude of paleofloods. In: House PK, Webb RH, Baker VR, Levish DR (eds) Ancient floods, modern hazards: Principles and Applications of Paleoflood Hydrology. Water Sci Appl 5:77–89

G. F. Wieczorek (✉)
U.S. Geological Survey,
Menlo Park, CA 94025
e-mail: gwieczor@usgs.gov
Tel.: +650-329-5251
Fax: +650-329-5203

L. S. Eaton · E. J. Turner
James Madison University,
Harrisonburg, VA 22807

T. M. Yanosky
National Center, U.S. Geological Survey,
Reston, VA 20192

Present address:
E. J. Turner
2121 Canyon Boulevard #405, Boulder, CO 80302