ELSEVIER

Geomorphology 20 (1997) 11–28

GEOMORPHOLOGY

Volumetric analysis and hydrologic characterization of a modern debris flow near Yucca Mountain, Nevada

Jeffrey A. Coe [a,*], Patrick A. Glancy [b], John W. Whitney [a]

[a] *U.S. Geological Survey, Denver Federal Center, Denver, CO 80225, USA*
[b] *U.S. Geological Survey, Carson City, NV 89706, USA*

Received 31 October 1995; revised 19 December 1996; accepted 10 January 1997

Abstract

On July 21 or 22, 1984, debris flows triggered by rainfall occurred on the southern hillslope of Jake Ridge, about 6 km east of the crest of Yucca Mountain, Nevada. Rain gages near Jake Ridge recorded 65 mm and 69 mm on July 21, and 20 mm and 17 mm on July 22. Rates of rainfall intensity ranged up to 73 mm/h on the twenty-first, and 15 mm/h on the twenty-second. Digital elevation models with 2.0 m grid-node spacing, measured from pre-storm and post-storm aerial stereo-photographs, were used to map hillslope erosion and the downslope distribution of debris. Volumetric calculations indicate that about 7040 m^3 of debris was redistributed on the 49,132 m^2 hillslope study area during the two-day storm period. About 4580 m^3 (65%) of the eroded sediment was deposited within the study area and the remaining 35% was deposited outside the study area in a short tributary to Fortymile Wash and in the wash itself. The maximum and mean depths of erosion in the study area were about 1.8 m and 5 cm, respectively. The mean depths of erosion on the upper and middle hillslope were 27 cm and 4 cm, respectively. The mean depth of deposition on the lower hillslope was 16 cm.

Analysis of the values of cumulative precipitation in the context of the precipitation-frequency atlas of the National Oceanic and Atmospheric Administration indicates that precipitation from the main storm on July 21 was more than double that expected, on average, once during a 100-year period. The relations of precipitation intensity/duration, developed from data recorded at a nearby precipitation gage, indicate a storm interval of 500 years or greater. The amount of erosion caused by such a storm is primarily dependent on three variables: storm intensity, development of the drainage network on the hillslope, and the amount of available colluvium. Additionally, the erosive ability of successive storms of equal intensity will decrease because such storms would tend to progressively isolate and reduce the amount of colluvium available. The preservation of Pleistocene deposits on hillslopes of Yucca Mountain, in general, indicates that erosional events that strip 5% of the available hillslope colluvium must be quite rare. We conclude that the recurrence interval of an erosional event comparable to the July, 1984 event is probably much longer than 500 years.

Keywords: photogrammetry; digital elevation models; sediment budget; Yucca Mountain; debris flow; hillslope

1. Introduction

In investigations of modern hillslope erosion, as well as in studies of potential flood and debris-flow

* Corresponding author. Tel.: +1 (303) 273-8606; Fax: +1 (303) 273-8600; E-mail: jcoe@gldvxa.cr.usgs.gov

PII S0169-555X(97)00008-1

hazards, the correlation of individual storm events with the corresponding volumes of sediment eroded by runoff is important. Field measurements of sediment eroded from hillslopes by runoff in arid to semiarid climates are difficult because precipitation events capable of causing erosion are infrequent and often localized. Measurement techniques that have been applied include repeated measurements of painted surface clasts or lines of stakes, and sediment traps on slopes or in channels (Goudie, 1990). Furthermore, measurements of debris eroded during single large storms are uncommon. The above-mentioned traditional techniques of measurement are not well suited for recording large volumes of sediment eroded during sudden events. Typically, after large storms, the volume of eroded sediment is calculated by estimating or surveying the thickness and areal extent of debris deposited at the base of slopes or in channels (Glancy, 1968; Beaty, 1970; Glancy and Harmsen, 1975; Williams and Costa, 1988; Wohl and Pearthree, 1991). The main limitation of conventional surveys is that they do not typically provide information from an entire affected area, but rather provide perimeter and cross-sectional data of only the most disturbed zones.

This report documents modern hillslope erosion and debris flows that occurred on July 21 or 22, 1984, following intense rainfall on the south-facing hillslope of Jake Ridge (Fig. 1). This flat-topped ridge is located about 6 km east of Yucca Mountain, Nevada, the site selected by the U.S. Congress for characterization as a potential repository for high-level nuclear-waste (U.S. Department of Energy, 1988). These debris flows eroded unconsolidated colluvium from the upper hillslope, deepened and widened existing hillslope channels, created new channels on the lower hillslope, and deposited debris up to about 1.2 m thick on a dirt road at the base of the hillslope (Fig. 2). Analytical photogrammetric techniques were used to map and measure the volumes of sediment eroded and deposited by these flows. These measurements of erosion and deposition, made at the hillslope scale for a single event, are rare and are especially relevant in arid to semiarid environments where infrequent debris flows are important geomorphic agents. The volumetric results, combined with a hydrologic analysis of the precipitation event that caused the debris flows, help characterize the potential hazards from debris flows and quantify modern hillslope erosion in the Yucca Mountain area.

2. Setting

2.1. Geology

Yucca Mountain (Fig. 1) consists of several parallel, north–south-trending ridges. These ridges rise abruptly above a piedmont alluvial surface that slopes southward toward the Amargosa River, about 45 km away. Jake Ridge (Fig. 1) is at the southern extremity of a north–south-trending ridge east of Yucca Mountain. Fortymile Wash, a major drainage of about 800 km^2, collects runoff from the east slopes of Yucca Mountain. Local relief is about 500 m between the crest of Yucca Mountain and the channel of Fortymile Wash. The steep-faced ridges of Yucca Mountain result from a dominantly north–south-trending local fault system and the similarly aligned tributary drainage system of Fortymile Wash. Fortymile Wash and its Yucca Mountain tributaries flow ephemerally in response to strong regional or intense local rainstorms.

The Yucca Mountain area is underlain by a thick Tertiary volcanic sequence of silicic ash-flow and air-fall tuffs, rhyolite lava flows, and tuffaceous sedimentary rocks (Frizzell and Shulters, 1990). The hillslopes of Yucca Mountain are underlain by the Paintbrush Tuff (Scott and Bonk, 1984), a moderately transmissive aquifer (Winograd and Thordarson, 1975, p. 10). Jake Ridge is also capped by the Paintbrush Tuff, but, in contrast to Yucca Mountain, is mostly underlain by Tuffaceous Beds of Calico Hills (Christiansen and Lipman, 1965), a relatively nonabsorptive aquifer.

In general, hillslopes in the Yucca Mountain area are a combination of exposed bedrock and bedrock mantled by coarse-grained bouldery colluvium and fine-grained eolian deposits that are generally less than 2.5 m thick. Sparse hillslope vegetation consists primarily of cacti, creosote bush, saltbush, and other associated shrubs; grasses are scarce. Overall, vegetal cover provides little resistance to erosion caused by intense precipitation and the resultant runoff.

The south-facing hillslope at Jake Ridge is man-

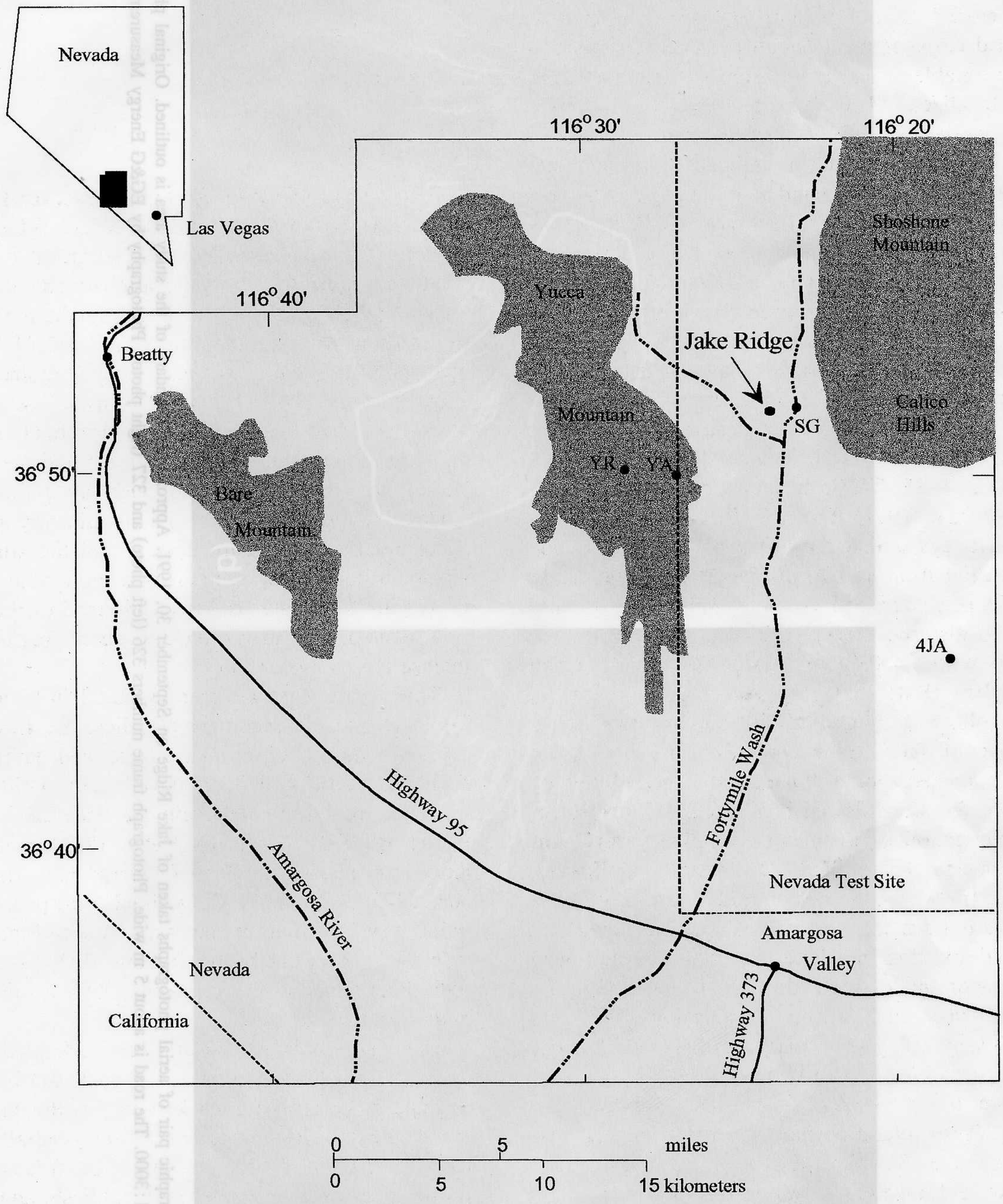

Fig. 1. Index map showing Yucca Mountain and Jake Ridge. Shaded areas are dominant mountains. Non-shaded area is predominantly piedmont. *SG* is a stream gage in Fortymile Wash, elevation about 1120 m. *YR* and *YA* were tipping-bucket rain gages operated by Sandia National Laboratories. YA and YR are no longer in operation. YR was at the crest of Yucca Mountain, elevation about 1469 m. YA was at the east base of Yucca Mountain, elevation about 1143 m. *4JA* is a weighing-bucket rain gage operated by the National Weather Service, elevation about 1049 m.

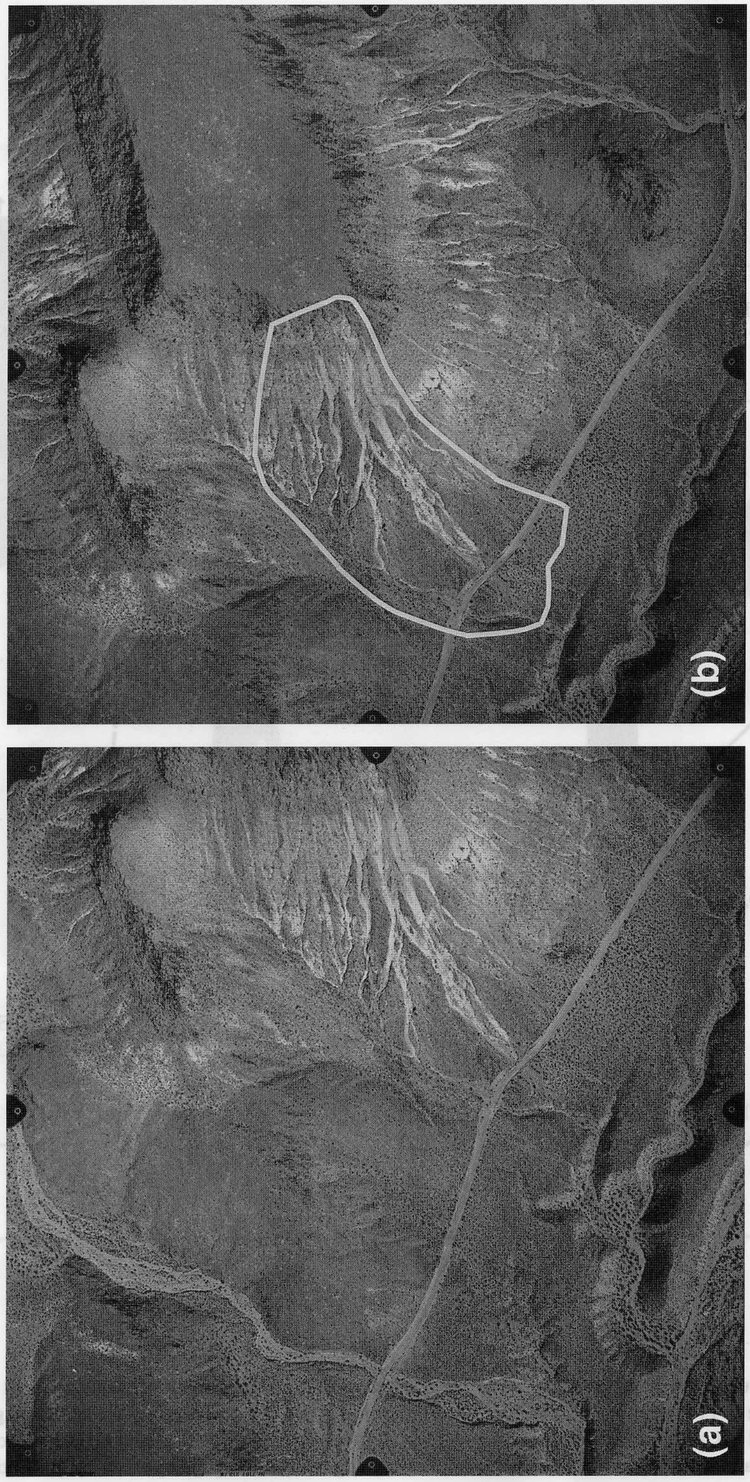

Fig 2. Stereographic pair of aerial photographs taken of Jake Ridge on September 30, 1991. Approximate boundary of the study area is outlined. Original photo scale approximately 1:3000. The road is about 5 m wide. Photograph frame numbers 326 (left photo) and 327 (right photo). Photography by EG&G Energy Measurements, Inc.

tled by less than 2 m of bouldery colluvium and has a slope gradient that ranges from about 32° just below the caprock to less than 4° at the base of the slope (Fig. 2). The hillslope drains to a minor and relatively short tributary of Fortymile Wash. The top-surface of Jake Ridge, a dip-slope on resistant caprock, grades slightly (about 4°) to the southeast and is covered by a thin (less than 30 cm) mantle of cobbly colluvium.

Cation-ratio and CL-36 age estimates of varnished, relict, colluvial-boulder, hillslope deposits in the Yucca Mountain area range from about 150 thousand years (ka) to 1.2 million years (Ma) (Whitney and Harrington, 1993). Long-term average rates of slope degradation, marginal to these dated deposits, range from 0.2 to 7 mm/ka (Harrington and Whitney, 1991; Coe et al., 1993). On the basis of area and thickness estimates of Late Pleistocene and Holocene surficial deposits on the east side of Yucca Mountain, S.C. Lundstrom, et al., written commun. (1996) suggest minimum degradation rates for hillslope colluvium that range from 25 to 28 mm/ka for the last 25 ka.

2.2. Climate

The Yucca Mountain area is in a transitional climatic zone between the mid-latitude southern Great Basin desert, and the low-latitude northern Mojave desert (Houghton et al., 1975). It has a dry semiarid continental climate with cool to cold winters and hot to very hot summers. For the years 1988–1989 mean-monthly temperatures ranged from 3.9°C in January to 28.9°C in July (Whitney and Harrington, 1993). Extreme temperatures during the same time period were −3.9°C in January and 40.6°C in July. Mean annual precipitation at and near Yucca Mountain ranges from about 125 to 150 mm (Quiring, 1983). Precipitation records from thirteen U.S. Weather Service stations (Water Years 1965–1981) indicate that about 70% of annual precipitation falls during the cool season (October–April) and the remainder during the warm season (May–September; Quiring, 1983).

Severe convective summer storms are believed to be the dominant cause of debris flows and flash floods in small drainages of the Yucca Mountain area. For several days each summer, a monsoonal flow of atmospheric moisture commonly occurs in southern Nevada; some years it is recurrent and more prolonged. This monsoonal flow often provides an abundant supply of atmospheric moisture needed to form severe summer convective storms. Many of these convective storms are limited to small areas; some have unusually intense rainfall and, when reasonably isolated from surrounding rainstorms, are defined as 'local storms' (Hansen and Schwartz, 1981). Precipitation from these storms can increase and intensify when convection occurs in conjunction with frontal convergence and orographic uplifting. These thunderstorms can occasionally yield rainfall in excess of about 50 mm (the expected seasonal amount) in less than an hour and are capable of mobilizing debris flows.

2.3. Precipitation during 1984

Precipitation patterns were unusual throughout southern Nevada during the 1984 Water Year (October 1983–September 1984). Precipitation averaged about 1.3 times normal during the early cool season (October–December) but less than 10% of normal during the late cool season (January–April) and early warm season (May–June). July and August were extremely wet; overall rainfall was on the order of 600% of normal (U.S. National Weather Service, unpubl. Nevada Test Site data). The 1984 annual precipitation total, however, was about 130% of normal; 1984 was a wet year but not unusually wet.

The uncommonly wet summer resulted from unusually strong monsoonal conditions that persisted between late July and early September. These monsoonal conditions were not related to the strong El Niño southern oscillation of 1982–1983 (Bergman, 1984; Ropelewski, 1985). The conditions seem to have been the result of high-atmospheric pressure over the eastern United States and a persistent low-pressure atmospheric trough off the Californian coast. The combined effect of this dual pressure system promoted and maintained a southerly atmospheric flow that persistently injected abundant moisture into the atmosphere of the southern Great Basin and prompted numerous severe thunderstorms and flash floods in southern Nevada (for example, see Lins et al., 1985, events 85 and 97, pp. 20, 21).

July rainfall at Yucca Mountain and Jake Ridge, prior to July 19, was minimal (U.S. National Weather Service, unpubl. data). Two rain gages, one at the east base of Yucca Mountain, about 5.4 km southwest of Jake Ridge (gage YA, Fig. 1), and the other (gage YR, Fig. 1) near the crest of Yucca Mountain 7.5 km southwest of Jake Ridge, registered 0.25 mm and 4.8 mm, respectively, on July 19 (Hugh Church, Sandia National Laboratory, written commun., 1985). Neither these rain gages, nor National Weather Service rain gage 4JA (Fig. 1), about 14 km southeast of Jake Ridge, registered any precipitation on July 20. The minimal precipitation in early–middle July suggests that local hillslope colluvium was dry or nearly dry prior to the July 21 storm.

3. The July 21 and 22, 1984 storms

The storms that caused the July 21 or 22, 1984, debris flows at Jake Ridge were severe localized

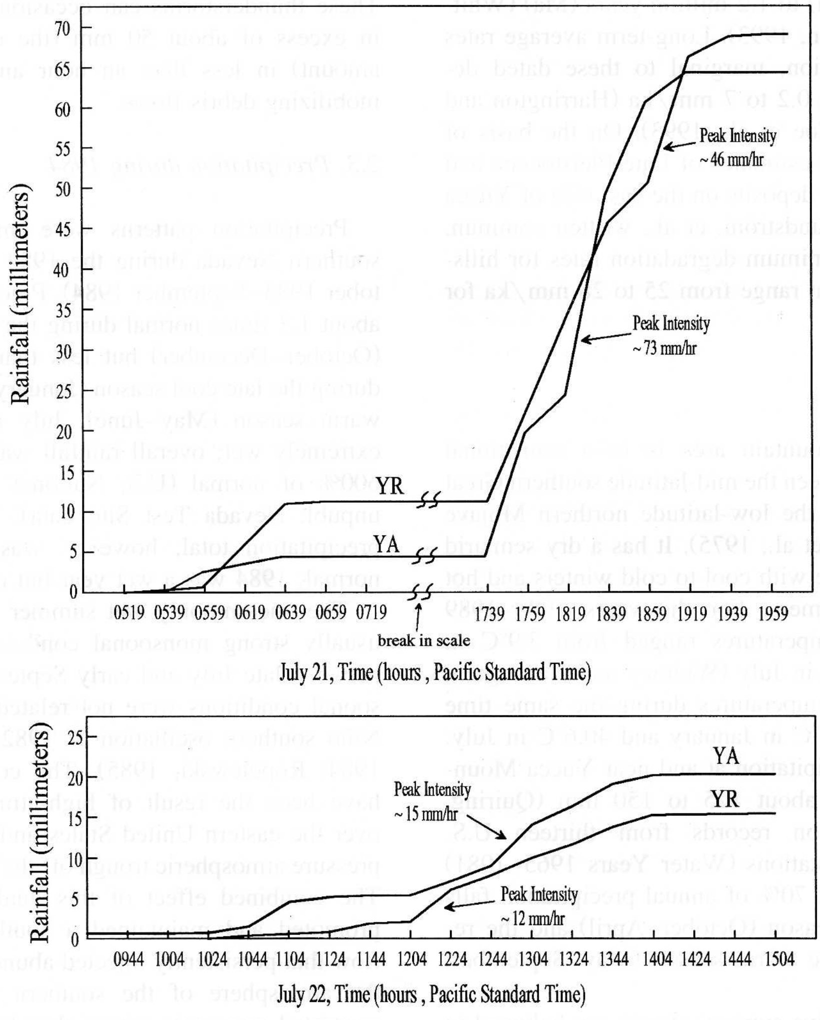

Fig. 3. Cumulative rainfall records for July 21 and 22, 1984, storm events at rain gages YA and YR (Fig. 1). Total accumulation at rain gage YR was 69.3 mm on July 21 and 16.5 mm on July 22 (0.8 mm of rain fell between 15:04 and 16:59 h on July 22 that is not shown on the graph). Total accumulation at rain gage YA was 64.4 mm on July 21 and 20.4 mm on July 22 (0.5 mm fell between 06:24 and 06:44 h on July 22 that is not shown on the graph).

convective storms that occurred during the early part of the monsoonal storm period in summer. Daily satellite images from mid-June through August 1984 show that this storm system was part of a regional atmospheric flow system that brought moisture over a large area of the southern Great Basin, as described earlier.

Rainfall at Yucca Mountain began during the early morning hours of July 21 (Fig. 3) when about 4 mm of rain fell at the eastern base of the mountain between 05:44 and 06:44 h (Pacific Standard Time). About 11 mm fell at the crest (gage YR) between 05:19 and 07:19 h. The next ten hours were dry. Heavy rainfall commenced during the late afternoon (about 17:39 h) and continued until about 19:59 h. Rainfall intensities reached 73 mm/h at gage YA and 46 mm/h at gage YR. Cumulative precipitation totals for the late-afternoon storm were about 60 mm and 58 mm at the YA and YR gages, respectively. Heavy rainfall was apparently restricted to a small area because gage 4JA, about 15 km east-southeast of the Yucca Mountain gages, recorded only about 8 mm of rain during the entire day (U.S. National Weather Service Nuclear Support Office, written commun., 1984).

Rainfall began on July 22 during the early morning (06:24–06:44 h) at gage YA and during mid-morning (10:19–10:39 h) at gage YR (Fig. 3). Rain continued until the mid-afternoon (14:24 h) at gage YA and until late-afternoon (16:59 h) at gage YR. Cumulative rainfall amounts and maximum intensities for the day were, respectively, 20 mm and 15 mm/h at gage YA, and 17 mm and 12 mm/h at gage YR.

Some of the runoff from the storms was recorded by a stream gage in Fortymile Wash (SG, Fig. 1) about 1.2 km east and slightly upstream from Jake Ridge (Pabst et al., 1993). Flow began at this gage on July 21 at about 19:00 h, peaked at 21 m^3/s within about 1.5 h, and then began to rapidly recede. The flow receded to less than 1 m^3/s by 22:00 h (total flow time of about 3 h), indicating that this storm was quite local (total drainage basin area upstream from gage SG is about 650 km^2). A smaller runoff pulse of about 15 m^3/s followed at about 22:30 h. The precise location, timing, and magnitude of the rainfall that caused the second runoff pulse at the stream gage is uncertain. The second pulse may have been the result of a different storm cell, or from the same storm cell as it moved further upstream along Fortymile Wash; in either case, the runoff-pulse arrival could have been delayed by its greater distance of origin from the gage. A third streamflow pulse began on July 22 about 11:30 h and peaked at about 1 m^3/s at 13:00 h; this flow continued for 13 h, ending about 00:30 h on July 23.

4. Field observations

Jake Ridge was observed at least once a month from 1983 to 1991. Fresh debris-flow scars and deposits were discovered at Jake Ridge on August 16, 1984. Precipitation records from gages YA and YR revealed that rainfall on July 21 and 22 was the sole candidate for initiating the debris flows. During the 1983–1991 period, the only storms that caused notable deposition on the dirt road at the base of the hillslope were the July 21 and 22 storms.

No evidence of other large-scale debris flows or mass movements related to the July 21 and 22 storms at Yucca Mountain was found in the summer of 1984. Abundant evidence of water-dominated sediment transport, however, was observed in many ephemeral stream channels. Furthermore, subsequent (1992–1994) field work and review of aerial photographs of the Yucca Mountain area suggested that at least one debris flow occurred (during the July, 1984 storms) on the east-facing hillslope of Joey Ridge, about 1 km west of Jake Ridge.

Post-storm field observations on the top of Jake Ridge revealed no evidence of intense runoff over the thinly mantled surface (Fig. 2). The source area for much of the eroded debris at Jake Ridge was between 25 and 80 m below the top of the ridge. Water and debris widened and deepened existing channels on the upper and middle slope and cut new channels predominantly on the middle slope. Bouldery levees were deposited along channel margins on the middle and lower hillslope. The levees and bouldery lobe deposits contain a fine-grained matrix that indicates that the main flows were debris flows, rather than Newtonian, or water-dominated flows (Costa, 1984).

Three primary zones of deposition include: (1) a

Fig. 4. Photograph of deposits at the base of the main and southern channels. View is to southeast from about half-way up the slope. The main lobe on the road is about 30 m wide and 75 m long at the widest and longest points. Fortymile Wash is visible in the distance. Additional lobes occur on the road to the left and in the tributary to Fortymile Wash. See pickup truck for scale. Photograph taken 8/16/84.

debris lobe located outside the study area about halfway down the large tributary channel that feeds into Fortymile Wash; (2) a debris lobe on the road at the base of the main hillslope channel (Fig. 4); and (3) an elongated area of debris deposits along the southernmost, east–west-trending channel that drains the hillslope (Fig. 4). Debris in the tributary depositional lobe is poorly sorted and contains boulders (up to 0.5 m in diameter) from the Jake Ridge hillslope as well as from the Fortymile Wash alluvial terrace. The terrace gravels are cut by the tributary channel downstream from the base of the Jake Ridge hillslope. The lobe occurs as a fan where the tributary widens. The main depositional lobe on the road is poorly sorted and contains a fine-grained matrix. It was deposited where the hillslope flattens to less than 4°. Debris deposits on the road and along the east–west tributary contain boulders up to about 1 m in diameter. At the intersection of the tributary and Fortymile Wash, no debris larger than cobble size was observed.

5. Photogrammetric methods

5.1. General background

Photogrammetric measurements made from multiple sets of stereo photographs taken during successive time increments (multi-temporal) provide an ideal means of recording topographic change caused by mass movement processes, including debris flows (Brunsden, 1993). Additional geomorphological applications are by Brunsden and Jones (1976), Chandler and Moore (1989), and Baum and Fleming (1991).

Digital elevation models (DEMs) are often derived directly from photogrammetric measurements. DEMs have been used for geomorphologic applications (Band, 1986; Tribe, 1991; Dietrich et al., 1992, 1993; Lundstrom et al., 1993), but the grid-node spacing is typically not adequate for large-scale studies of small individual landforms.

Volumetric analyses using photogrammetrically derived elevation measurements are common in civil engineering, cut-and-fill problems, and stock-pile inventory applications (for example, Massa, 1958; Huberty and Anderson, 1990), but have just begun to be used for geomorphological applications (for example, Mills, 1992; Coe et al., 1993; Chandler and Brunsden, 1995). Typically, such volumetric analyses involve the calculation of elevation differences between successive sets of cross-section or DEM measurements, and then numerically integrating these differences to calculate volumes of material lost or gained. We have used this approach, with DEMs of 2 m grid-node spacing, to examine topographic changes at Jake Ridge.

5.2. Pre- and post-storm stereo photographs

DEMs were measured from pre-storm (1982, 1 : 8000 scale; Fig. 5) and post-storm (1991, 1 : 3000 scale; Fig. 2) stereographic pairs. Both stereo pairs have conventional 60% overlap. Flying heights were about 1280 m and 660 m above a mean height of the terrain of about 1220 m for the 1982 and 1991 pairs, respectively. The 1991 photographs were acquired using a Wild aerial camera (serial number 7167) with a focal length of 213.78 mm. The 1982 photographs were acquired using a Fairchild aerial camera with a focal length of 151.56 mm. The 1982 pair was taken using black and white film, whereas the 1991 pair was taken using color film. Even though the 1982 and 1991 photographs were taken at different times of the year (May and September, respectively), seasonality and solar azimuth have not impacted our study because shadows are not present in either set of stereo pairs.

5.3. Theoretical considerations regarding achievable accuracies of elevations measured from pre- and post-storm photographs

Photogrammetric textbooks often state that heights of points measured from stereo photographs can be obtained with a precision ranging from 0.6/10,000 (Kraus, 1993) to 1/10,000 (Wolf, 1983) of the flying height. Accuracies of spot heights quoted in the literature range from 0.25 to 1.5 parts per 10,000 of the flying height (Fryer et al., 1994). On the basis of testing done using conventional photogrammetric mapping configurations, Fryer et al. (1994) suggest that a precision of 1/10,000 of the flying height is the best that can be expected for the standard deviations of spot heights. If 1/10,000 is used here, flying heights of 660 and 1280 m would yield vertical precisions of 0.066 and 0.128 m, respectively. Following the law of propagation of errors, the vertical accuracy of an elevation-difference value derived from elevation measurements from the two sets of photography would be 0.14 m.

5.4. Orientation of stereo pairs and actual accuracies achieved

The 1982 and 1991 stereo pairs were oriented to a common ground coordinate system in a Kern [1] DSR15 analytical stereo plotter (Chapius and van den Berg, 1988). Orientation consisted of two main procedures, interior orientation and exterior orientation (Slama et al., 1980; Ghosh, 1988). During interior orientation, fiducial marks on the photographs were digitized and residual errors were computed between the measured photo coordinates and the known fiducial coordinates by using a least squares fit. Residuals from the least squares fit (using an affine transformation) were less than 10 μm for all 4 photographs.

Exterior orientations consisted of registering (using a least squares fit) the stereo pairs to ground-control points. The 1982 pair, which contained a previously established set of ten easting, northing, and elevation (xyz) ground-control points (Fig. 5; Wu, 1995) was oriented in the plotter first. Once oriented, the 1982 stereo pair served as a baseline source of ground-control points for the 1991 stereo pair. Sixteen points that were photo-identifiable in both the 1982 and 1991 photography were recorded and transferred to the 1991 stereo pair. The 16 points were evenly distributed throughout the 1991 stereo pair in non-disturbed areas surrounding the debris-flow scars and deposits. These points were used as ground-control points for the exterior orientation of the 1991 stereo pair. Overall standard deviations of residuals resulting from the least squares fit of the exterior orientation of the 1991 stereo pair were 0.14 m in the x, y, and z directions. The individual x, y, and z sets of 16 residuals were approximately normally distributed about a mean of zero. Thus, using this orientation procedure, the 1982 and 1991 photographs were registered to each other to within an overall x, y, and z standard deviation of 0.14 m. Because the 16 control points were evenly distributed and include much redundancy (only three points are needed to orient a stereo model) we conclude that: (1) errors associated with subsequent DEM measurements were random (systematic errors are negligible); and (2) the computed 1σ value of 0.14 m is a reasonable estimate of the horizontal and vertical accuracy of the elevation-difference DEM (described later in this section) derived from the measured DEMs. Additionally, it should be noted that the 1σ value of 0.14 m matches the 1σ value derived from theoretical considerations described in the last section.

[1] Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

Fig. 5. Stereographic pair of aerial photographs taken of Jake Ridge on May 24, 1982. Original photo scale approximately 1:8000. Photograph frame numbers 249 (left photo) and 250 (right photo). Annotated points are previously established ground-control points referred to in the text.

5.5. Generation of digital elevation models

Each DEM, which consisted of an xyz grid with 2.0 m xy-node spacing, was measured from within a 49,132 m^2 study area (Fig. 2) in each stereo pair. The analytical plotter and associated grid-measurement software were used to measure elevations at 12,283 identical xy-grid-node locations. Because elevation data were measured on a regularly spaced xy grid, no grid interpolation was necessary to create the DEMs. IDRISI Geographic Information System software (Eastman, 1992) generated thematic maps from the DEMs.

To calculate volumetric changes caused by the debris flows, an elevation-difference DEM was created by subtracting the 1982 DEM from the 1991 DEM. The elevation-difference DEM was used to generate an elevation-difference map of the study area (Fig. 6). On the basis of the relative amounts of deposition and erosion shown on this map, the study area was divided into upper, middle, and lower hillslope zones (Fig. 6). The upper-hillslope zone is dominated by erosion. The middle zone is dominated by channel widening and deepening and deposition. The lower zone is dominated by deposition.

A slope map (Fig. 7) was generated from the 1982 DEM to evaluate the position of individual hillslope zones on the basis of slope gradient. Slope values at each grid node were determined by calculating the maximum slope around the node from elevations at neighboring nodes in the x and y directions. On the slope map, the boundary between the upper and middle zone corresponds to about a 12° slope gradient, whereas the boundary between the middle and lower zones corresponds to about a 4° slope gradient (Fig. 7).

Several possible sources of error (in addition to the random-photogrammetric-measurement error already mentioned) are inherent in the elevation-difference DEM and map. The first is caused by the inherent assumption that the pre-storm, and post-storm, sediment densities have not changed. In reality, this is probably not true. For example, a few of the deposits consist of boulder-sized clasts and lack the fine-grained matrix present in the original bouldery colluvium. This would therefore tend to skew elevation-difference values in a positive direction. Additionally, any deposition of fine sand by eolian processes between 1982 and 1991 could skew the elevation-difference values in a positive direction.

Another factor that would similarly skew the results is that some areas on the hillslope were first cut by erosion and then refilled by deposition. Where refilling occurred, the elevation-difference value would not account for the actual amount of erosion that had taken place. Because refilling undoubtedly occurred, volumes described throughout the remainder of the paper are considered net volumes.

6. Volumetric analysis

Net volumes for each hillslope zone shown in Fig. 6 were calculated as follows:

$$V = \frac{A}{n} \sum_{i=1}^{n} \Delta z_i \tag{1}$$

where V is volume, A is area, n is the number of 2×2 m cells, and Δz_i is the elevation-difference value of the ith cell (1991 elevation–1982 elevation). Statistical assumptions inherent in Eq. (1) and in the analysis overall are that the $\Delta z_i (i = 1,2, \cdots ,n)$ of the n cells are independent but not identically distributed random variables with different means and same standard deviations, $\sigma_{\Delta z_i} = \sigma_{\Delta z}$. In order to estimate errors for the calculated volumes, Eq. (1) is further developed as follows:

$$V = A \tfrac{1}{n} \sum_{i=1}^{n} \Delta z_i \tag{2}$$

which can be rewritten as:

$$V = A \cdot \overline{\Delta z} \tag{3}$$

where $\overline{\Delta z}$ is the sample mean Δz value. The standard deviation of V, σ_v, derived from Eq. (3) is given by:

$$\sigma_v = A \cdot \sigma_{\overline{\Delta z}} \tag{4}$$

where $\sigma_{\overline{\Delta z}}$ is the standard error of $\overline{\Delta z}$. Substituting in Eq. (4) according to the equation for standard error of the mean $\left[\sigma_{\overline{\Delta z}} = \left(\sigma_{\Delta z} / \sqrt{n} \right) \right]$ yields:

$$\sigma_v = \frac{A}{\sqrt{n}} \sigma_{\Delta z} \tag{5}$$

Eq. (5) was used to calculate the 2σ errors for the calculated volumes. The previously established 1σ value (0.14 m) of the elevation-difference DEM was used for $\sigma_{\Delta z}$ in this equation.

Inherent in this volumetric analysis process was the assumption (established by field observations) that erosion and deposition from other storms between 1982 and 1991 were negligible relative to that caused by the 1984 debris flows. Additionally, because a single Δz_i value was used to calculate the volume change at each 4 m^2 cell, the volumes

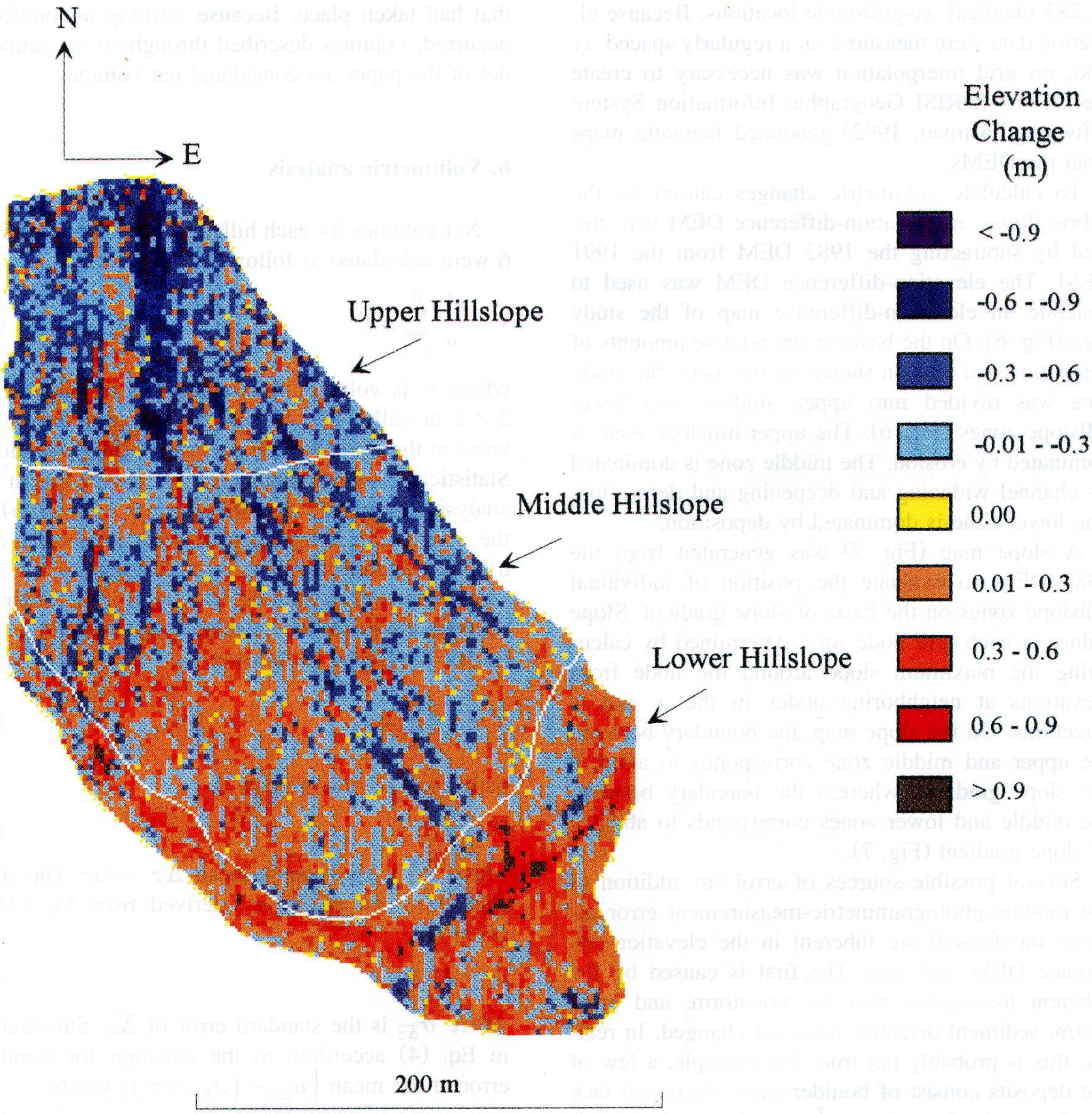

Fig. 6. Plan view elevation-difference map of Jake Ridge hillslope. Hillslope zones shown are defined in the text. Red and blue areas experienced positive and negative elevation change, respectively. Yellow areas showed no elevation change. Topographic relief from the base of the hillslope to the top of the ridge is approximately 130 m. Northeast–southwest-trending deposits in the southeast corner of the map are the sides of a dirt road (see Figs. 2 and 5) that are visible because of road grading between 1982 and 1991.

reported should be considered estimates. In some cases (e.g., a Δz_i value from an undisturbed lip of a deeply eroded channel slightly less than 2 m wide) this estimate would differ greatly from the true volume change. Smaller grid-node spacing and the measurement of breaklines would yield more accurate volume estimates, although the value of such improved estimates has to be weighed in terms of the additional effort required to make the more refined measurements.

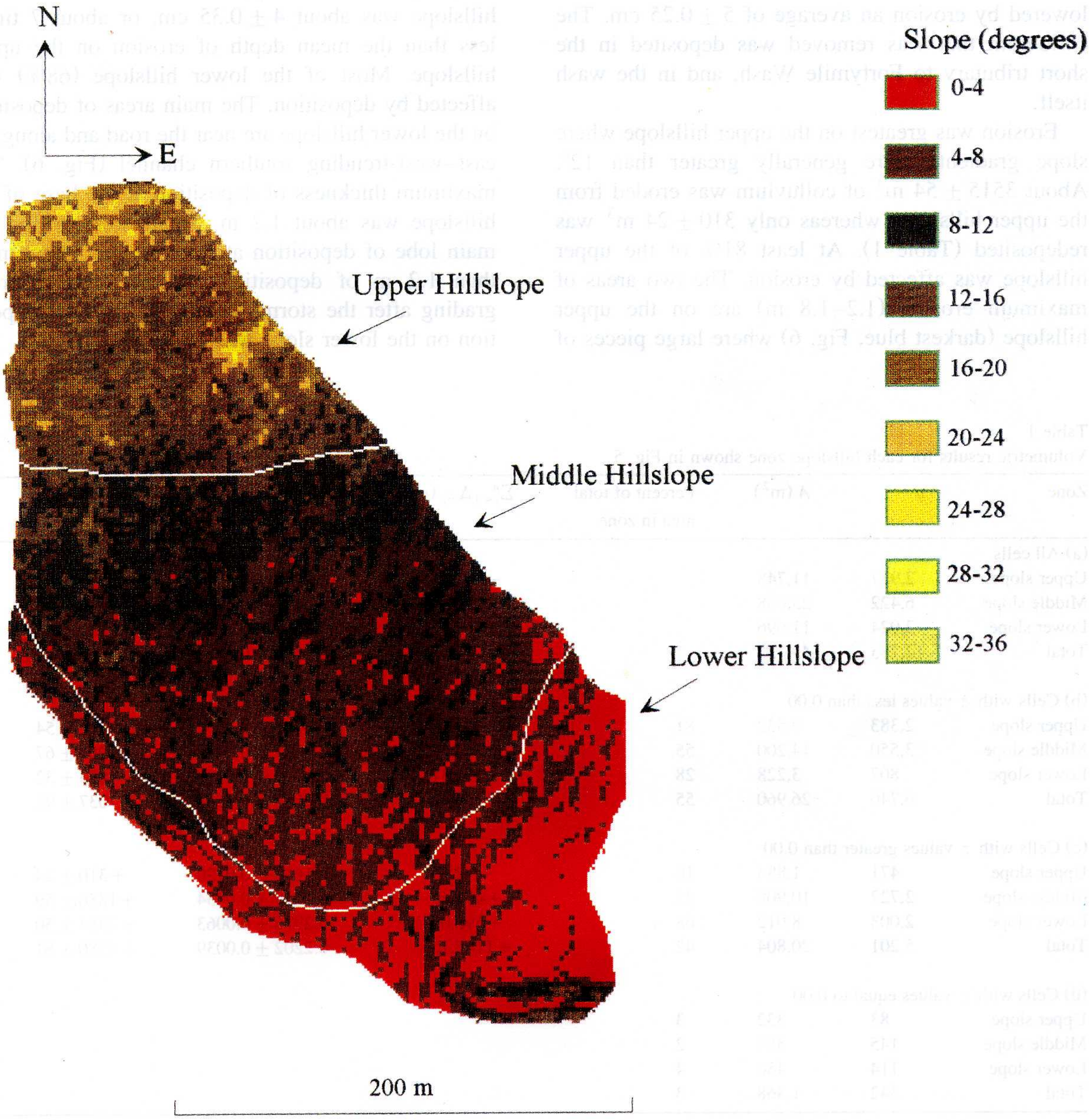

Fig. 7. Plan view slope map of Jake Ridge hillslope derived from 1982 digital elevation model. Hillslope zones shown are defined in the text.

7. Results

About 7037 ± 92 m^3 of colluvium was redistributed within the 49,132 m^2 Jake Ridge study area by the debris flows (Table 1). About 2457 ± 120 m^3 (35%) of this colluvium was removed from the study area and about 4580 ± 81 m^3 (65%) was deposited within the area. Thus, the overall study area was lowered by erosion an average of 5 ± 0.25 cm. The colluvium that was removed was deposited in the short tributary to Fortymile Wash, and in the wash itself.

Erosion was greatest on the upper hillslope where slope gradients were generally greater than 12°. About 3515 ± 54 m^3 of colluvium was eroded from the upper hillslope, whereas only 310 ± 24 m^3 was redeposited (Table 1). At least 81% of the upper hillslope was affected by erosion. The two areas of maximum erosion (1.2–1.8 m) are on the upper hillslope (darkest blue, Fig. 6) where large pieces of bedrock were removed. The mean depth of erosion on the upper hillslope was 27 ± 0.52 cm. The middle hillslope, where slope gradients generally ranged from 4 to 12°, was more equally affected by erosion and deposition. About 55% of the middle hillslope was affected by erosion and 43% by deposition. The elevation of the other 2% of the area remained unchanged. The mean depth of erosion on the middle hillslope was about 4 ± 0.35 cm, or about 7 times less than the mean depth of erosion on the upper hillslope. Most of the lower hillslope (68%) was affected by deposition. The main areas of deposition on the lower hillslope are near the road and along the east–west-trending southern channel (Fig. 6). The maximum thickness of deposition at the base of the hillslope was about 1.2 m. Small areas within the main lobe of deposition at the road that show more than 1.2 m of deposition are the result of road grading after the storm. The mean depth of deposition on the lower slope was 16 ± 0.52 cm.

Table 1
Volumetric results for each hillslope zone shown in Fig. 5

Zone	n	A (m^2)	Percent of total area in zone	$\Sigma_{i=1}^{n} \Delta z_i$ (m)	$\overline{\Delta z} \pm 2\sigma_{\overline{\Delta z}}$ (m)	$V \pm 2\sigma_v$ (m^3)
(a) All cells						
Upper slope	2,937	11,748		−801.21	-0.2728 ± 0.0052	-3205 ± 61
Middle slope	6,422	25,688		−270.89	-0.0422 ± 0.0035	-1084 ± 90
Lower slope	2,924	11,696		457.77	0.1566 ± 0.0052	$+1832 \pm 61$
Total	12,283	49,132		−614.33	-0.0500 ± 0.0025	-2457 ± 120
(b) Cells with z values less than 0.00						
Upper slope	2,383	9,532	81	−878.76	-0.3688 ± 0.0057	-3515 ± 54
Middle slope	3,550	14,200	55	−742.37	-0.2091 ± 0.0047	-2969 ± 67
Lower slope	807	3,228	28	−138.31	0.1710 ± 0.0099	-553 ± 32
Total	6,740	26,960	55	−1759.44	-0.2610 ± 0.0034	-7037 ± 92
(c) Cells with z values greater than 0.00						
Upper slope	471	1,884	16	+77.55	0.1650 ± 0.0130	$+310 \pm 24$
Middle slope	2,727	10,908	43	+471.47	0.1729 ± 0.0054	$+1886 \pm 59$
Lower slope	2,003	8,012	68	+596.08	0.2976 ± 0.0063	$+2384 \pm 50$
Total	5,201	20,804	42	+1145.10	0.2202 ± 0.0039	$+4580 \pm 81$
(d) Cells with z values equal to 0.00						
Upper slope	83	332	3			
Middle slope	145	580	2			
Lower slope	114	456	4			
Total	342	1,368	3			

n = number of cells; A = area; Δz_i = elevation-difference value of the ith cell (1991 elevation–1982 elevation); $\overline{\Delta z}$ = sample mean Δz value; $\sigma_{\overline{\Delta z}}$ = standard error of $\overline{\Delta z}$; V = volume; σ_v = standard deviation of V.

8. Discussion

8.1. Debris flow initiation

Several initiation mechanisms were probably responsible for the debris flows. Some water may have percolated down through the cobble mantle on the hilltop into the underlying fractured caprock and then exited the fractures at the cliff face at the top of the relatively impermeable Calico Hills bedrock unit. Several triangular stripped areas increase in size downslope from fractures in and just below the face. These light colored areas at the cliff face are visible in the 1991 photographs (Fig. 2). This suggests that at least some debris movement was initiated by streams of water flowing from the caprock and applying a 'fire hose' effect (Johnson and Rodine, 1984) to the hillslope colluvium. The relatively low permeability of the underlying bedrock, probably combined with an already saturated colluvial mantle, would have prohibited this water from dispersing into the slope, and enhanced shallow mass movement failures or 'soil slips' (Campbell, 1975; Ellen and Fleming, 1987). With the inclusion of additional water, these initial soil slips would have flowed downslope in channels on the upper hillslope. The presence of levees indicates fairly rapid flows.

The creation of several new channels and the deepening of existing channels on the middle and lower hillslopes suggests that at least some erosion took place by channel scour before and after the debris flows. Additionally, inspection of interchannel areas (Fig. 2) on the elevation-difference map (Fig. 6) suggests that some minor erosion and deposition took place by overland flow.

8.2. Percentage of available hillslope colluvium eroded by the July storm

About 2457 m^3 of sediment was removed from the south-facing hillslope of Jake Ridge. The entire south-facing hillslope study area is 49,132 m^2. Field observations indicate that non-channelized areas of the south-facing hillslope are generally mantled by 0–2 m of colluvium. If a mean value of 1 m is assumed for the amount of unconsolidated colluvium cover, approximately 49,000 m^3 of debris would have existed on the south-facing hillslope prior to the July 1984 storms. Therefore, about 5% of the available colluvium was removed from the hillslope during the two-day storm.

8.3. Storm recurrence interval

Precipitation gaging sites in the southern Great Basin are widely scattered and have not been in operation for long periods of time (generally less than 50 years). Estimating the recurrence interval of a storm comparable to that of July 21 and 22, 1984 is difficult. Additionally, the accumulation and intensity of rainfall at Jake Ridge, about 5.4 km northeast of rain gages YA and YR, is unknown. It is unlikely, however, that the maximum rainfall during the storms occurred at gages YA and YR. The established record of debris flows in the vicinity of these gages (Glancy, 1994) and the absence of flows during the 1984 storms reinforces the likelihood that rainfall amounts and intensities were greater at Jake Ridge than those recorded at gages YA and YR.

The most intensive period of rainfall recorded at gages YA and YR occurred during a 2-h period on the evening of July 21 (Fig. 3). The magnitude of such a 2-h storm with a probable 100-year recurrence interval was calculated as about 29 mm, using methods prescribed in the Precipitation-Frequency Atlas of the western United States (Miller et al., 1973). Thus, the 2-h totals of 60 and 58 mm recorded by gages YA and YR, respectively, are about twice those expected with a 1% probability of occurrence in any given year. A probable maximum precipitation amount calculated for a 2-h duration storm in the arid southwestern U.S. is about 307 mm (Hansen et al., 1977), or about five times greater than that recorded by the Yucca Mountain rain gages on July 21.

The average intensity of the 2-h storm on July 21 was about 30 mm/h. The expected intensity for a 2-h storm with a 100-year return period at a precipitation station (Cane Springs, Nevada) located about 30 km southeast of, and at the same elevation as Jake Ridge, ranges from about 14 to 19 mm/h (French, 1983). The expected intensity for a 2-h storm with a 500-year return period at this same station ranges from about 18 to 25 mm/h. Thus, the intensity of the July 21 storm was greater than that expected for a storm with a 500-year return period at the nearby Cane Spring station.

8.4. Erosion recurrence interval

If storms equal in magnitude to the July 21 storm return to Jake Ridge with some regularity, the upper hillslope will become progressively stripped of colluvium and the hillslope channels will become more deeply incised. Also, the areas of interchannel colluvium on the middle and lower slopes will become more isolated from the erosive effects of hillslope runoff. Eventually, the upper hillslope will be stripped to bedrock, and would no longer be a source of potential debris flows. Assuming that little or no new hillslope colluvium is created by weathering between storms, this model of hillslope evolution suggests that the amount of hillslope erosion by sequential storms of the same intensity will decrease.

If we momentarily assume that the Jake Ridge hillslope does not evolve with each progressive storm, but continues to erode 5% of the available colluvium during each 1984 magnitude storm, then we can demonstrate that the recurrence of erosion comparable to that in 1984 must be greater than 500 years. For example, if storms of similar magnitude and intensity as the July 1984 storm were to revisit Jake Ridge every 500 years, and the hillslope was eroded by similar debris flows, then most of the pre-July 1984 colluvium (about 49,000 m^3) would be stripped in about 10,000 years. The preservation of Pleistocene deposits on Yucca Mountain hillslopes in general (see Faulds et al., 1994; and four surficial deposit maps by Lundstrom and Taylor, 1997; Lundstrom et al., 1997a,b,c) seems to indicate that erosional events that strip 5% of available hillslope colluvium must be quite rare. At Jake Ridge, a large portion of hillslope colluvium appears to have been stable for at least tens of thousands of years, as evidenced by accumulations of rock varnish on the surface of colluvial boulders.

The amount of hillslope erosion for a given storm is primarily dependent on three variables: the intensity of the storm, the maturity of the drainage network on the hillslope, and the amount of colluvium available. If successive storms of similar size were capable of the same volume of erosion, very few Pleistocene deposits would be preserved on hillslopes of Yucca Mountain. Although the recurrence interval of storms of the same intensity as the July 21, 1984 storm appears to be on the order of 500 years or greater, the recurrence of an erosional event comparable to the July, 1984 event is probably much longer.

9. Summary

A photogrammetric method has been used to volumetrically calculate net erosion and sediment redistribution on an individual hillslope. About 2457 m^3 (5%) of the available colluvium was removed from the Jake Ridge study area during a two-day period of convective rainstorms. The mean depth of erosion for the overall study area was about 5 cm. The maximum depth of localized erosion and deposition was about 1.8 m and 1.2 m, respectively. Nearby rain gages recorded up to 69 mm of rain at intensities that reached 73 mm/h. Analysis of cumulative precipitation from the main storm on July 21 indicates that it was more than double that expected to occur once, on average, in 100 years. Precipitation intensity/duration relations indicate that the recurrence interval of this storm is on the order of 500 years. We suggest that the amount of hillslope erosion caused by the 1984 storm has a significantly longer recurrence interval than the precipitation event because the amount of erosion is dependent on the intensity of the storm, on the amount of colluvium on the slope, and the maturity of the drainage network.

The photogrammetric method provides an efficient means to obtain spatial data from an entire area of interest, as compared to boundary and cross-sectional data often obtained by traditional field surveys. The photogrammetric approach is dependent, however, on the availability, scale, and resolution of pre-event stereographic photographs. The accuracy of the method is principally controlled by the scale of the pre-event photographs because post-event photography can be flown at any desired scale. We strongly urge investigators with an interest in using photogrammetric techniques to acquire large-scale aerial photographs of areas of potential interest. The accuracy of elevations measured from photographs in this study was about 1/10,000 of the flying height used to acquire the photography.

Acknowledgements

We gratefully acknowledge Keld Dueholm and Bob Crovelli for their helpful suggestions in formulating the volumetric analysis. Dan Cayan and Dale Ambos provided important meteorological reference material. We thank Scott Lundstrom, Dennis Grasso, Dave Moore, Thomas Bjerstedt, Mary-Margaret Coates, and three anonymous reviewers, for their critical reviews of the work. Sherman Wu and Elaine Ezra provided pre-flow and post-flow photography, respectively. Bob Fleming, Adel Zohdy, Anne McCafferty, Joe Hevesi, and Loren Crow had helpful suggestions during various stages of the project. We appreciate the support of all of these people, but make it clear that any remaining errors are our own. This study was supported by the U.S. Department of Energy Yucca Mountain Project.

References

Band, L.E., 1986. Topographic partition of watersheds with digital elevation models. Water Resour. Res. 22, 15–24.

Baum, R.L., Fleming, R.W., 1991. Use of longitudinal strain in identifying driving and resisting elements of landslides. Geol. Soc. Am. Bull. 103, 1121–1132.

Beaty, C.B., 1970. Age and estimated rate of accumulation of an alluvial fan, White Mountains, California, USA. Am. J. Sci. 268, 50–77.

Bergman, K.H., 1984. The climate of autumn 1983—featuring the conclusion of a major El Nino event. Mon. Weather Rev. 112, 1141–1456.

Brunsden, D., 1993. Mass movement, the research frontier and beyond—A geomorphological approach. Geomorphology 7, 85–128.

Brunsden, D., Jones, D.K.C., 1976. The evolution of landslide slopes in Dorset. Philos. Trans. R. Soc. London A283, 605–631.

Campbell, R.H., 1975. Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California. U.S. Geol. Surv. Prof. Pap. 851, 51 pp.

Chandler, J.H., Brunsden, D., 1995. Steady state behaviour of the Black Ven mudslide: the application of archival analytical photogrammetry to studies of landform change. Earth Surf. Process. Landforms 20, 255–275.

Chandler, J.H., Moore, R., 1989. Analytical photogrammetry—a method for monitoring slope instability. Q. J. Eng. Geol. 22, 97–110.

Chapius, A., van den Berg, J., 1988. The new Kern DSR series of first order analytical stereo plotters. Int. Soc. Photogramm. Remote Sensing, 16th Int. Congr., Comm. II, Kyoto, 8 pp.

Christiansen, R.L., Lipman, P.W., 1965. Geologic map of the Topopah Spring Northwest quadrangle, Nye County, Nevada. U.S. Geological Survey Geologic Quadrangle Map GQ-444, scale 1:24,000.

Coe, J.A., Whitney, J.W., Harrington, C.D., 1993. Photogrammetric analysis of Quaternary hillslope erosion at Yucca Mountain, Nevada. Geol. Soc. Am. Abstr. Progr. 25, 22.

Costa, J.E., 1984. Physical geomorphology of debris flows. In: Costa, J.E., Fleisher, P.J. (Eds.), Developments and Applications of Geomorphology. Springer, Berlin, pp. 268–317.

Dietrich, W.E., Wilson, C.J., Montgomery, D.R., McKean, J., Bauer, R., 1992. Erosion thresholds and land surface morphology. Geology 20, 675–679.

Dietrich, W.E., Wilson, C.J., Montgomery, D.R., McKean, J., 1993. Analysis of erosion thresholds, channel networks, and landscape morphology, using a digital terrain model. J. Geol. 101, 259–278.

Eastman, J.R., 1992. IDRISI GIS Technical Reference Guide. Clark University Graduate School of Geography, Worcester, Mass., 213 pp.

Ellen, S.D., Fleming, R.W., 1987. Mobilization of debris flows from soil slips, San Francisco Bay region, California. In: J.E. Costa and G. Wieczorek (Editors), Flows/Avalanches—Process, Recognition, and Mitigation. Geol. Soc. Am., Rev. Eng. Geol. 7, 31–40.

Faulds, J.E., Bell, J.W., Feuerbach, D.L., Ramelli, A.R., 1994. Geologic map of the Crater Flat area, Nevada. Nev. Bur. Mines Geol. Map 101, scale 1:24,000.

French, R.H., 1983. A preliminary analysis of precipitation in southern Nevada. Desert Research Institute, Univ. Nev. Syst. Rep., DOE/NV/10162-10, 39 pp.

Frizzell, V.A., Shulters, J., 1990. Geologic map of the Nevada Test Site, southern Nevada. U.S. Geol. Surv. Misc. Invest. Ser. Map I-2046, scale 1:100,000.

Fryer, J.G., Chandler, J.H., Cooper, M.A.R., 1994. On the accuracy of heighting from aerial photographs and maps: implications to process modellers. Earth Surf. Process. Landforms 19, 577–583.

Ghosh, S.K., 1988. Analytical Photogrammetry, 2nd ed. Pergamon Press, New York, 308 pp.

Glancy, P.A., 1968. A mudflow in the Second Creek drainage, Lake Tahoe Basin, Nevada, and its relation to sedimentation and urbanization. U.S. Geol. Surv. Prof. Pap. 650-C, C195–C200.

Glancy, P.A., 1994. Evidence of prehistoric flooding and the potential for future flooding at Coyote Wash, Yucca Mountain, Nevada. U.S. Geol. Surv. Open-File Rep. 92-458, 31 pp.

Glancy, P.A., Harmsen, L., 1975. A hydrologic assessment of the September 14, 1974, flood in El Dorado Canyon, Nevada. U.S. Geol. Surv. Prof. Pap. 930, 28 pp.

Goudie, A.S., 1990. Geomorphological Techniques, 2nd ed. Unwin Hyman, London, 570 pp.

Hansen, M.E., Schwartz, F.K., 1981. Meteorology of important rainstorms in the Colorado River and Great Basin drainages. U.S. Dep. Army Hydrometeorol. Rep. 50, 167 pp.

Hansen, M.E., Schwartz, F.K., Riedel, J.T., 1977. Probable maximum precipitation estimates, Colorado River and Great Basin drainages. U.S. Dep. Commerce, and U.S. Dep. Army Hydrometeorol. Rep. 49, 161 pp.

Harrington, C.D., Whitney, J.W., 1991. Quaternary erosion rates on hillslopes in the Yucca Mountain region, Nevada. Geol. Soc. Am. Abstr. Progr. 23, A118.

Houghton, J.G., Sakamoto, C.M., Gifford, R.O., 1975. Nevada's weather and climate. Nev. Bur. Mines Geol., Spec. Publ. 2, 78 pp.

Huberty, B., Anderson, C., 1990. Coal pile inventory using 35-mm oblique terrestrial photogrammetry. Photogramm. Eng. Remote Sensing 56, 1169–1171.

Johnson, A.M., Rodine, J.R., 1984. Debris flows. In: Brunsden, D., Prior, D.B. (Eds.), Slope Instability. Wiley, Chichester, pp. 257–361.

Kraus, K., 1993. Photogrammetry, 4th ed. Dummler, Bonn.

Lins, H.F., Kammerer, J.C., Chase, E.B., 1985. Overview of Water Year 1984 hydrologic conditions and water-related events. In: National Water Summary 1984—Hydrologic Events Selected Water-Quality Trends and Ground Water Resources. U.S. Geol. Surv. Water Supply Pap. 2275, 8–21.

Lundstrom, S.C., Taylor, E.M., 1997. Preliminary surficial deposits map of the southern half of the Topopah Spring NW 7.5-minute quadrangle, Nye County, Nevada. U.S. Geol. Surv. Open-File Rep., 95-132, scale 1 : 12,000, in press.

Lundstrom, S.C., McCafferty, A.E., Coe, J.A., 1993. Photogrammetric analysis of 1984–89 surface altitude change of the partially debris-covered Eliot Glacier, Mount Hood, Oregon, U.S.A. Ann. Glaciol. 17, 167–170.

Lundstrom, S.C., Wesling, J.R., Taylor, E.M., Paces, J.B., 1997a. Preliminary surficial deposits map of the northeast corner of the Busted Butte 7.5-minute quadrangle, Nye County, Nevada. U.S. Geol. Surv. Open-File Rep., 94-341, scale 1 : 12,000, in press.

Lundstrom, S.C., Mahan, S.A., Paces, J.B., 1997b. Preliminary surficial deposits map of the northwest quarter of the Busted Butte 7.5-minute quadrangle, Nye County, Nevada. U.S. Geol. Surv. Open-File Rep., 95-133, scale 1 : 12,000, in press.

Lundstrom, S.C., Whitney, J.W., Paces, J.B., Mahan, S.A., Ludwig, K.R., 1997c. Preliminary surficial deposits map of the southern half of the Busted Butte 7.5-minute quadrangle, Nye County, Nevada. U.S. Geol. Surv. Open-File Rep., 95-311, scale 1 : 12,000, in press.

Massa, W.S., 1958. Inventory of large coal piles. Photogramm. Eng. 24, 77–81.

Miller, J.F., Frederick, R.H., Tracey, R.J., 1973. Precipitation-frequency atlas of the western United States, NOAA Atlas 2, Volume VII—Nevada. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Silver Spring, Md., 43 pp.

Mills, H.H., 1992. Post-eruption erosion and deposition in the 1980 crater of Mount St. Helens, Washington, determined from digital maps. Earth Surf. Process. Landforms 17, 739–754.

Pabst, M.E., Beck, D.A., Glancy, P.A., Johnson, J.A., 1993. Streamflow and selected precipitation data for Yucca Mountain and vicinity, Nye County, Nevada, Water Years 1983–85. U.S. Geol. Surv. Open-File Rep. 93-438, 66 pp.

Quiring, R.F., 1983. Precipitation climatology of the Nevada Test Site. U.S. Weather Service, Nuclear Support Office Publication WSNSO 351-88, 34 pp.

Ropelewski, C.F., 1985. Seasonal climate summary—the global climate June–August 1984—a return to 'normal' in the tropics. Mon. Weather Rev. 113, 664–679.

Scott, R.B., Bonk, J., 1984. Preliminary geologic map of Yucca Mountain, Nye County, Nevada with geologic sections. U.S. Geol. Surv. Open-File Rep., 84-494.

Slama, C.C., Theurer, C., Henriksen, S.W., 1980. Manual of Photogrammetry. American Society of Photogrammetry and Remote Sensing, Bethesda, Md., 1056 pp.

Tribe, A., 1991. Automated recognition of valley heads from digital elevation models. Earth Surf. Process. Landf. 16, 33–49.

U.S. Department of Energy, 1988. Site Characterization Plan, Yucca Mountain Site. Nevada Research and Development, Nevada. U.S. Department of Energy, DOE/RW-0199, Washington, D.C.

Whitney, J.W., Harrington, C.D., 1993. Relict colluvial boulder deposits—indicators of climatic change and long-term slope stability in the Yucca Mountain region, southern Nevada. Geol. Soc. Am. Bull. 105, 1008–1018.

Williams, G.P., Costa, J.E., 1988. Geomorphic measurements after a flood. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, New York, pp. 65–77.

Winograd, I.J., Thordarson, W., 1975. Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada–California, with special reference to the Nevada Test Site. U.S. Geol. Surv. Prof. Pap. 712-C, 126 pp.

Wohl, E.E., Pearthree, P.P., 1991. Debris flows as geomorphic agents in the Huachuca Mountains of southeastern Arizona. Geomorphology 4, 273–292.

Wolf, P.R., 1983. Elements of Photogrammetry. McGraw Hill, New York.

Wu, S., 1995. Unpublished ground-control point data. U.S. Geological Survey, Flagstaff, Ariz.