Available online at www.sciencedirect.com
ScienceDirect
Geomorphology 96 (2008) 270–297
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central Colorado

Jeffrey A. Coe [a,*], David A. Kinner [b], Jonathan W. Godt [a]

[a] U.S. Geological Survey, Denver Federal Center, MS 966, Denver, Colorado 80225, United States
[b] Geology Program, Department of Geosciences and Natural Resources Management, Western Carolina University, Cullowhee, North Carolina 28723, United States

Received 6 September 2006; received in revised form 8 March 2007; accepted 8 March 2007
Available online 10 May 2007

Abstract

We have monitored initiation conditions for six debris flows between May 2004 and July 2006 in a 0.3 km^2 drainage basin at Chalk Cliffs; a band of hydrothermally-altered quartz monzonite in central Colorado. Debris flows were initiated by water runoff from colluvium and bedrock that entrained sediment from rills and channels with slopes ranging from about 14° to 45°. The availability of channel material is essentially unlimited because of thick channel fill and refilling following debris flows by rock fall and dry ravel processes. Rainfall exceeding $I = 6.61(D)^{-0.77}$, where I is rainfall intensity (mm/h), and D is duration (h), was required for the initiation of debris flows in the drainage basin. The approximate minimum runoff discharge from the surface of bedrock required to initiate debris flows in the channels was 0.15 m^3/s. Colluvium in the basin was unsaturated immediately prior to (antecedent) and during debris flows. Antecedent, volumetric moisture levels in colluvium at depths of 1 cm and 29 cm ranged from 4–9%, and 4–7%, respectively. During debris flows, peak moisture levels in colluvium at depths of 1 cm and 29 cm ranged from 10–20%, and 4–12%, respectively. Channel sediment at a depth of 45 cm was unsaturated before and during debris flows; antecedent moisture ranged from 20–22%, and peak moisture ranged from 24–38%. Although we have no measurements from shallow rill or channel sediment, we infer that it was unsaturated before debris flows, and saturated by surface-water runoff during debris flows.

Our results allow us to make the following general statements with regard to debris flows generated by runoff in semi-arid to arid mountainous regions: 1) high antecedent moisture levels in hillslope and channel sediment are not required for the initiation of debris flows by runoff, 2) locations of entrainment of sediment by successive runoff events can vary within a basin as a function of variations in the thickness of existing channel fill and the rate of replenishment of channel fill by rock fall and dry ravel processes following debris flows, and 3) rainfall and simulated surface-water discharge thresholds can be useful in understanding and predicting debris flows generated by runoff and sediment entrainment.
Published by Elsevier B.V.

Keywords: Debris flow; Flood; Colorado; Erosion; Bedrock; Channel; Entrainment; Bulking; Rainfall; Threshold; Antecedent; Soil moisture; Rock fall; Dry ravel; Surface-water discharge

1. Introduction

Runoff, erosion, and sediment entrainment are important mechanisms for the initiation of debris flows in burned and unburned basins throughout the

* Corresponding author. Tel.: +1 303 273 8606; fax: +1 303 273 8600.
E-mail address: jcoe@usgs.gov (J.A. Coe).

0169-555X/$ - see front matter. Published by Elsevier B.V.
doi:10.1016/j.geomorph.2007.03.017

world (e.g., VanDine, 1985; Wohl and Pearthree, 1991; Takahashi, 1991; Davies et al., 1992; Berti et al., 1999; Cannon, 2001; Hürlimann et al., 2003; Griffiths et al., 2004; David-Novak et al., 2004; Godt and Coe, 2007). The initiation processes, and thus, the hazard implications for runoff-generated debris flows are different from debris flows initiated by the mobilization of landslides (e.g., Iverson et al., 1997; Iverson et al., 2000), and are much less studied and understood (Tongnacca and Bezzola, 1997; Cannon et al., 2003; Berti and Simoni, 2005). In addition to the lack of a physical framework for analyzing these types of debris flows, common problems that inhibit an understanding of initiation conditions include: a lack of rain gages in small basins where debris flows most commonly occur; rain gages that inaccurately measure rainfall from short, intense bursts, common during thunderstorms; little or no knowledge of antecedent rainfall and sediment moisture conditions; and poor constraints on times of occurrence.

To examine initiation conditions and processes for runoff-generated debris flows in unburned areas, we began studying four debris flow basins in central Colorado in May 2004 (Coe et al., 2005). All of the basins are small (<0.5 km^2), steep (25–90° hillslopes), sparsely vegetated, at least partially south facing, and have had recent debris flow activity. In each basin, we have made multiple sets of field observations, monitored initiation-conditions using event-recording rain gages and dielectric soil moisture sensors, and measured and modeled hydrologic characteristics and discharge from colluvium and bedrock in zones where debris flows are initiated.

This paper focuses on one of the four study basins; the basin located at Chalk Cliffs (Figs. 1 and 2). Like many low-order (or “steepland”) basins in the semi-arid, western USA, the Chalk Cliffs basin contains two primary types of hillslope materials: exposed bedrock and sandy colluvium with little soil development. Multiple debris flows have occurred in this basin since May 2004, but none of these flows mobilized from discrete landslide sources (i.e., slides or spreads using the Varnes, 1978 classification). Several water-dominated events (floods) have also occurred in the basin since May, 2004. Although this paper is focused on gaining a better understanding of the debris flows, we also attempt to distinguish debris flows from floods using the previously mentioned data sets.

Our hypothesis is that the frequent initiation of debris flows in the Chalk Cliffs study basin is dependent on the ability of bedrock and/or colluvium to produce surface runoff during rainfall, and the availability of sediment that can be easily entrained by runoff. An additional hypothesis is that the magnitude of debris flows (i.e., travel distance or volume) is positively correlated with rainfall amounts or the elapsed time since the last debris flow, which would control the amount of sediment available for entrainment. In this paper, we examine these hypotheses using the previously mentioned data sets, and follow with a discussion of our results in the context of previous work and the implications for runoff debris flow initiation processes in general.

2. The Chalk Cliffs study area

The Chalk Cliffs are highly fractured and hydrothermally-altered quartz monzonite, which is part of the Eocene–Oligocene Mount Princeton batholith. The cliffs are located in the Sawatch mountain range adjacent to a normal fault which forms the eastern boundary of the range (Miller, 1999). Slip along the normal fault is associated with formation of the Rio Grande Rift and cumulative displacement is estimated at about 3000 m since 23 Ma (Tweto, 1978; Shannon et al., 1987; Kelley, 1991). The most recent fault movement occurred within the last 3 ka (Ostenaa et al., 1981). Several hot springs are located along the normal fault and are apparently the remnants of the hot water system that caused the extensive hydrothermal alteration observed in the area (Sharp, 1970). The name “Chalk Cliffs” is derived from the white color of laumontite and leonhardite (a calcium zeolite variety of laumontite), which are two of the most abundant alteration minerals in the area. Other alteration minerals include chlorite, calcite, illite, epidote, quartz, kaolinite, and fluorite (Sharp, 1970; Emslie, 1991).

The Chalk Cliffs drainage basin that we monitored for this study (Fig. 2) is a tributary of Chalk Creek; an east flowing, formerly glaciated, perennial stream. Coalescing fans (bajadas) line the north and south sides of Chalk Creek, but the bajada at the base of Chalk Cliffs is particularly extensive (Figs. 1A and 2). Deposits from historical debris flow activity are prevalent on this bajada at and near the mouths of many of the small drainage basins in Chalk Cliffs (Figs. 1A and 2). A systematic compilation of historical debris flows in the area does not exist, but several studies have noted the abundance of recent debris flows from basins in the area (Dillon and Grogger, 1982; Mortimer, 1997). Mortimer (1997) found that railroad tracks built on the bajada in 1882 were buried by several meters of sediment from multiple debris flows and floods.

The study basin is small (0.3 km^2) and steep; bedrock slopes range from roughly 40° to vertical, whereas colluvial slopes range from about 25° to 40°. Bedrock is exposed in about 60% of the basin area (Fig. 2).

Colluvium forms an apron downslope from bedrock cliffs and is thickest (roughly 10 m) near the center of the basin. Colluvial areas adjacent to bedrock gulleys are being actively eroded by runoff from the surface of bedrock during rainstorms. Colluvium adjacent to channels has been incised, is oversteepened, and supplies material to the channels by raveling. All channels in the basin, and on the downslope bajada, flow intermittently during rainstorms. The main channel that drains the basin extends about 940 m (measured horizontally) from the mouth of the basin, across the bajada and Chaffee County Road 162 (CCR162), to form a fan in Chalk Creek (Figs. 1A and 2). Where the channel crosses CCR162 (Fig. 2), Chaffee County has widened and lined the channel with concrete. Signs along the road on both sides of the channel warn motorists not to drive through the channel when it is flowing. When debris flows deposit material on the road, the county cleans off the road and hauls away the debris. According to county maintenance records, such cleaning is needed, on average, about once a year (Joe Nelson, 2004, personal communication). A comparison of the Average Recurrence interval (ARI) between debris flows in the study basin (ARI $\leq$ 1 year), with the level in other well known debris flow basins areas in Colorado (e.g., Cascade Creek near Ouray, ARI $\approx$ 5 years, Jochim, 1986; two unnamed basins near Georgetown, ARI $\approx$ 7 years, Coe et al., 2003), indicates that the study basin probably has the highest observed frequency of debris flows in Colorado.

Several recent investigations by Eric Leonard and his students at Colorado College in Colorado Springs, CO indicate that flows from the study basin are water-dominated flows and debris flows (Mortimer, 1997), and that the velocities of debris flows range from about 4 to 13 m/s (Christensen, 2003). Based on these estimates of velocity, the time required for a debris flow to travel from the mouth of the basin to the CCR162 (about 820 m) ranges from about 1 to 3 min.

3. Field and laboratory methods

To examine our hypothesis that debris flows are generated by surface runoff from bedrock and/or colluvium during rainfall, we used a combination of field and laboratory methods to characterize the areal extent and physical properties of surficial geologic materials (colluvium and channel sediment), accurately measure rainfall within the basin, and measure and characterize the hydrologic response of surficial materials to rainfall. We used field observations, geologic mapping, and measurements of grain size and in-situ bulk density to characterize the physical properties of surficial materials. A rain gage was used to monitor rainfall in the basin. Soil moisture sensors and in-situ infiltrometer and permeameter measurements were used to characterize the hydrologic response of surficial materials to rainfall. Field observations following debris flows were used to estimate travel distances and relative magnitudes of the volumes of debris flows (i.e., absolute debris flow volumes were not measured) to evaluate our second hypothesis, that is, that the magnitude of debris flows is correlated with rainfall amounts or the elapsed time since the last debris flow. The timing and magnitude of runoff (i.e., surface-water discharge) from bedrock was simulated using a routing model and is described in Section 4.

3.1. Field observations and geologic mapping

We made field observations in the study basin and on the downslope fan twelve times between May, 2004 and July, 2006. Observations were sometimes made during trips to install or repair instrumentation in the basin, but were often made following notification of a flow by local residents. Observations typically involved determining the extent of the flows, interviewing local residents and authorities to determine the timing of events, following the tracks of flows to the source in the basin to determine characteristics of flow initiation and flow initiation zones, sampling material from flow deposits and source areas, and geologic mapping of bedrock and colluvium. Geologic contacts were identified on aerial photographs in the field, and then transferred from the photographs to a topographic base map using a PG2 photogrammetric plotter (Pillmore, 1989).

3.2. Field instrumentation

We installed two types of instruments in the study basin, a rain gage and four soil moisture probes. The rain gage is a siphoning, tipping bucket rain gage manufactured by Hydrologic Systems and designed to maintain ±2% accuracy at rainfall rates up to 500 mm/h. We installed the gage near the center of the basin on a relatively stable talus surface at an elevation of about 2800 m (R1, Fig. 3). The soil moisture probes are capacitance-based, ECH_20 soil water probes manufactured by Decagon Devices, Inc. The dimensions of the probes are 25 cm × 3 cm × 0.1 cm. The probes measure the apparent dielectric constant of soil within a 2 cm soil zone on both sides of the flat, 25 cm × 3 cm surface and relate the measured constant to volumetric water content through the use of a calibration equation. Bosch (2004) rigorously tested the probes and found that they yielded very accurate estimates of volumetric water content (within ±0.05 cm^3/cm^3) when they were calibrated for specific soils. We developed a calibration equation for our probes using soils sampled from soil pits during installation of the probes, and laboratory techniques outlined by Campbell (2004). The linear calibration equation used for this study is:

$$vw = 0.0007(\mathrm{mV}) - 0.2519 \quad (1)$$

where *vw* is volumetric water content and mV is millivolts measured by the probe with an excitation voltage of 2.5 volts at 10 milliamps for 10 milliseconds.

We installed probes at two locations, on a colluvial mantled hillslope in young colluvium (SM1, SM2, Fig. 3), and in/near the main drainage channel within the basin (SM3, SM4, Fig. 3). On the hillslope, a soil pit was dug and slope-parallel slots for the probes were driven into the upslope wall of the pit using a steel blade with the same dimensions as the probe. The probes were installed in the slots so that the narrow (0.1 cm) edges of the probes were approximately parallel to the slope of the surface. Probes were installed at two slope-normal depths, 1 cm (SM1) and 29 cm (SM2), where depth is measured to the uppermost, narrow edge of the probe. After installation, the pit was filled with the same material that was initially removed. In the channel, a probe was installed as described above at a depth of 45 cm (SM4). Along the edge of the channel, a probe was installed within a debris flow levee at a depth of 1 cm (SM3).

3.3. Field and laboratory tests to characterize colluvium, channel sediment, and debris flow deposits

3.3.1. Grain size analyses

We collected samples for grain size analyses from colluvium in debris flow source areas, (G3, G5, G6, Fig. 3), channel sediments (G2, G4), and fresh debris flow deposits (G1). Samples were analyzed using sieve and hydrometer methods as described in American Society for Testing and Materials (ASTM) standard D-422.

3.3.2. Bulk density

We measured the bulk density of the colluvium in the study basin at three locations (BD1–BD3, Fig. 3) using a Ring-Excavation technique (Grossmann et al., 2001; Grossman and Reinsch, 2002). An aluminum ring of approximately 20 cm in diameter was driven into the colluvial surface. The depth to the ground surface within the ring was measured in about 16 locations using a micrometer and a small shelf placed across the ring. The colluvium inside the ring was then excavated using a spoon and the distance measurements were repeated. The volume of colluvium was then determined using the difference between the two sets of distance measurements and the cross-sectional area of the ring. The porosity and void ratios (ratio of void volume to volume of solid particles) were calculated from the oven dried mass of the colluvium using a specific gravity of 2.65.

3.3.3. Measurements of infiltration

We made mini-disk tension infiltrometer measurements on in-situ colluvium at 5 locations (I1–I5, Fig. 3) to estimate the rate of infiltration of the colluvial surface at a matrix tension head of −6 cm relative to atmospheric. The tension of −6 cm allows measurement of the rate of water infiltration into the colluvium as it approaches saturation, but prior to ponding of water on the surface, thereby simulating anticipated conditions directly before a debris flow. A sample of colluvium was collected nearby each measurement site prior to the test to measure the initial soil moisture, and a sample was collected directly underneath the disk after the test to measure the final soil moisture. The samples were dried over-night at 105 °C to determine the gravimetric soil moisture.

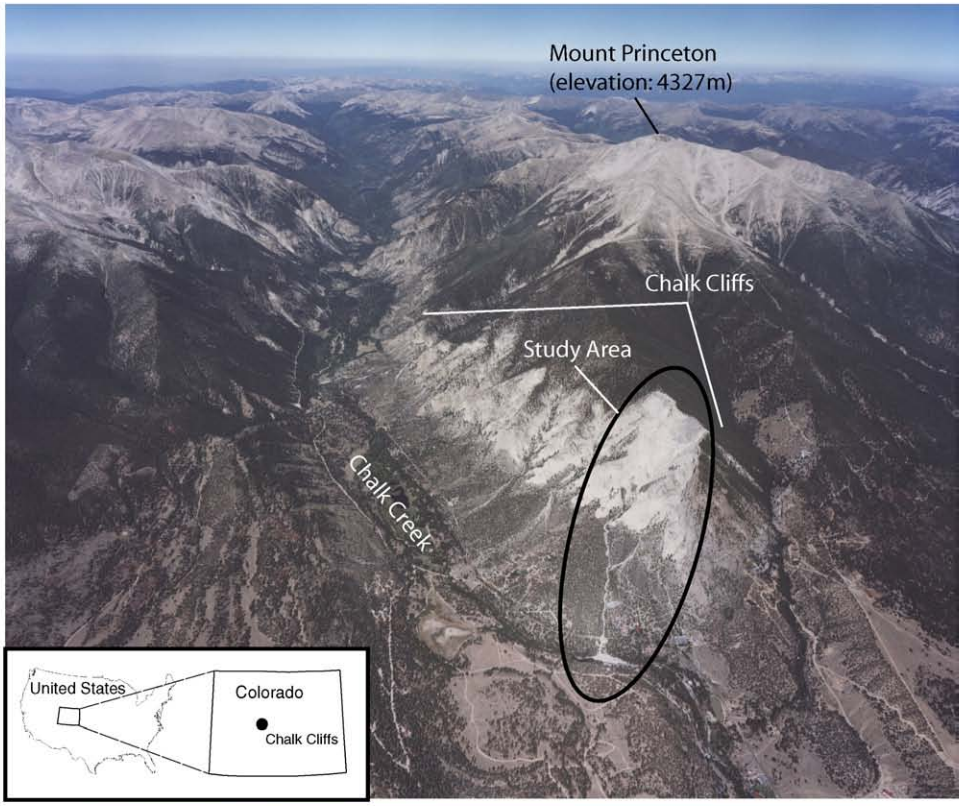
3.3.4. Permeameter measurements

We used a Guelph permeameter (a constant head well permeameter manufactured by Soilmoisture Equipment Corporation, Reynolds and Elrick, 2002) to measure the saturated hydraulic conductivity of colluvium at three locations (Ksg1–Ksg3, Fig. 3) in the study basin. The hydraulic conductivity values obtained using this method are generally assumed to represent a “field-saturated” hydraulic conductivity where the soil is not fully saturated but contains some entrapped air (Elrick and Reynolds, 1992). In general, the saturated conductivity measured in the field using permeameter techniques is assumed to be about half that measured in the laboratory on the same materials using large samples and de-aired water (Bouwer, 1966). To compute the field-saturated hydraulic conductivity of the colluvial material, we used the multiple-head analyses of Reynolds et al. (1985) and the single-head analysis or “Glover” analysis (Zangar, 1953; Amoozegar, 1989). Reynolds and Elrick (2002) provide a detailed discussion of both data reduction methods.

4. Modeling to characterize runoff from bedrock

One of our hypotheses was that runoff-generated on bedrock drives the initiation of debris flows at Chalk Cliffs. Like other studies that have used simple models

A



B

Fig. 1. Photographs showing the Chalk Cliffs study basin. A) Oblique aerial photograph taken in August, 2002. View to the west. Elevation of fan at mouth of study basin in Chalk Creek is about 2500 m. B) Ground based photograph taken on May 27, 2004. View to the northwest. Relief shown is about 420 m.

to test hypotheses (i.e. Piñol et al., 1997; Kinner and Stallard, 2004), this study used a routing model to examine the possible flood hydrographs that were created by various rainstorms producing debris flows and floods. Without observed discharge to verify the modeling, our results were compared to field-observed

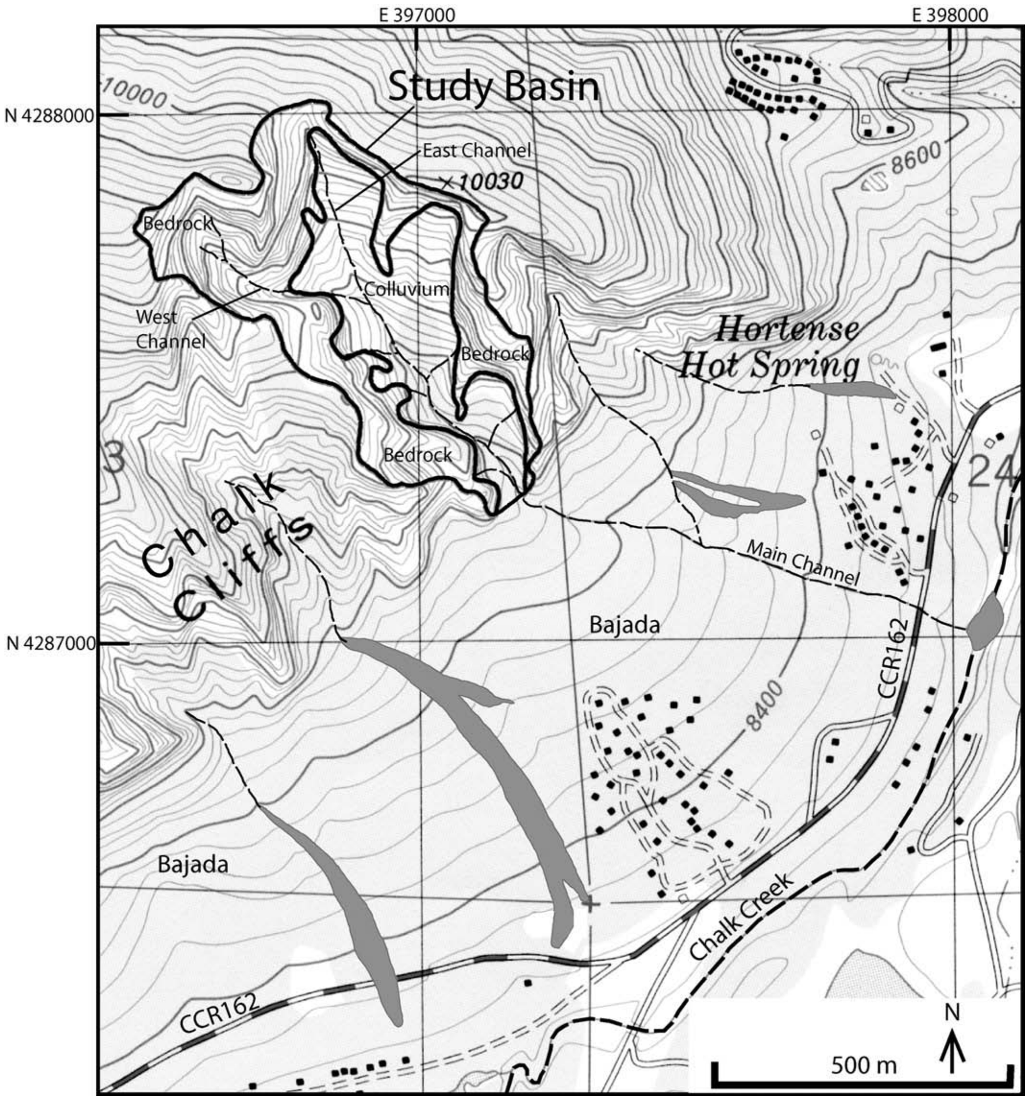


Fig. 2. Map showing the Chalk Cliffs study basin and the areal extent of bedrock and colluvium. Base map from U.S. Geological Survey 1:24,000-scale Mount Antero quadrangle, contour interval, 40 ft (12 m). Coordinates shown are UTM zone 13, units are meters. Darkly shaded areas are historical debris flow deposits.

constraints which provide guidance on the timing and magnitude of runoff.

We used a routing model that accompanies the program RiverTools (Rivix, 2001), called TOPOFLOW, to simulate the timing and magnitude of runoff created on bedrock. Simulated runoff was examined at the mouth of the west channel (Fig. 3), a 4th order bedrock channel, before it entered the sediment-laden main channel (Fig. 3, near G3 and G5), a 5th order channel that drains to Chalk Creek. We chose this point for simulating runoff because the upslope drainage area is almost entirely bedrock (Fig. 3) and the downslope area is loose sediment. The main channel downslope from the simulation point consistently contains sediment that can be entrained by runoff, unlike the west channel, which intermittently contains sediment. We assigned stream orders based on field observations that orders 1 and 2 were small rills and gulleys on bedrock cliffs and hillslopes, and order 3 was the first level of well-developed bedrock channels that merge to form the 4th order channels shown in Fig. 3.

TOPOFLOW models overland flow by mass balance using Manning's equation applied to a mesh of grid cells. The equations used for routing in TOPOFLOW

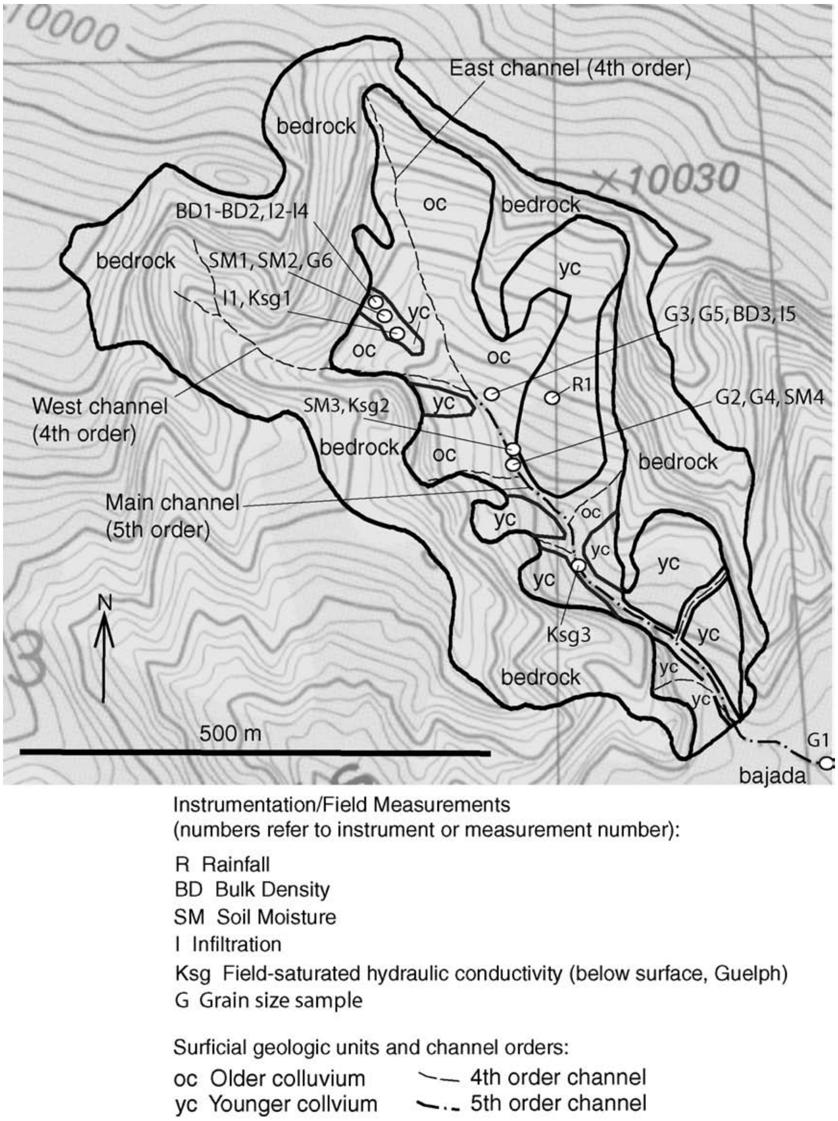


Fig. 3. Map showing geology and instrumentation in the Chalk Cliffs study basin. Base map from U.S. Geological Survey 1:24,000-scale Mount Antero quadrangle, contour interval, 40 ft. (12 m).

begin with the overland flow out of a pixel (Q_{out}; units of m^3/s):

$$Q_{\mathrm{out}} = wd\frac{R^{0.66}S^{0.5}}{n} \tag{2}$$

where w is the average width of the channel bed (m); d is the depth of flow (m); R is hydraulic radius (m) defined as A_{c}/P, the cross-sectional area divided by the wetted perimeter; S is the bed slope; and n is Manning's coefficient. Because of the extremely steep topography in the study basin, kinematic routing (fixed slope and no momentum terms) is assumed.

The volume (V; units m^3) of water in a grid cell with coordinates $x=i$, $y=j$ is updated each time step (t) through the following mass balance statement:

$$V_{ijt} = V_{ij(t-1)} + dt((Pda) - Q_{\mathrm{out}} + Q_{\mathrm{in}}) \tag{3}$$

where dt is a time step, P is rainfall rate (m/dt), and da is the grid-cell area (100 m^2 in this study). Q_{in} is derived from surrounding cells that flow into cell $x=i$, $y=j$. These cells are determined by the one-dimensional flow (D-8) flow grid (Jenson and Domingue, 1988). Using the D-8 algorithm, flow is directed to one of the adjacent cells with the greatest slope, and flow over flat areas (multiple cells with the same elevation) is resolved with the

Fig. 4. Recent rock fall and dry ravel deposits in an unnamed 4th order channel northwest of Ksg3. Snow is about 40 days old. Photograph taken February 28, 2006. View to the northwest. See circled rock hammer for scale.

imposed gradients plus algorithm (Garbrecht and Martz, 1997; Rivix, 2001). Given a resolved flow grid, Q_{in} is therefore defined:

$$Q_{\mathrm{in}} = \int_{c=1}^{8} x_{\mathrm{c}} Q_{\mathrm{outc}} \tag{4}$$

where c are adjacent cell numbers 1–8 and x_{c} is a binary vector that is either 1 (flows into the cell) or 0 (does not flow into the cell).

TOPOFLOW inputs are a time series of observed rates of rainfall, a catchment slope grid and flow grid derived from a USGS 10-m DEM, and three stream-order varying parameters: Manning's n ($\mathrm{m}^{-0.33}$ s), channel width (m), and channel side slope (m/m). Calculation of stream order begins at the catchment boundary and, thus, includes bedrock hillslope (orders 1 and most of 2) and bedrock channels (orders 3 and 4).

The procedure we used for defining Manning's n groups for first to fourth order channels is as follows. The n value for a non-vegetated, relatively smooth overland flow surface is 0.01 to 0.02 (Emmett, 1978) and rock channels are generally assigned a value of 0.025 to 0.035 (Chow, 1959), so the value $n=0.025$ is assigned to first and second order flowpaths. For steep bedrock channels, like those of third and fourth order, critical flow is often assumed in estimating discharge (Moody and Martin, 2001), requiring that velocity (v) is defined:

$$v = \sqrt{gd} \tag{5}$$

where g is gravitational acceleration, 9.8 $\mathrm{m/s^2}$. To fit the critical flow assumption within the structure of TOPO-FLOW, critical flow was assumed for different depths of

Fig. 5. Rock fall, dry ravel, and channel sediments in 5th order, main channel near SM3 and Ksg2 (see Fig. 3 for location). View to south. Width of field of view at foreground is about 4 m. Photograph taken February 28, 2006.

flow (0.1 m and 0.5 m) given the average slope for different scale channels (3rd order S=1.78; 4th order S=0.55). Given the critical flow velocity, the slope and an estimated depth, the equivalent Manning coefficient can be calculated. The coefficient values for 3rd and 4th order channels were set to 0.90 and 0.16, respectively.

We also defined channel dimensions by order. Hillslope cells (orders 1 and 2) have flowpath widths of 10 m or the cell width. Because planar flow for hillslope cells was assumed, channel banks were assumed to have angles of 0 (i.e., no banks). Widths of bedrock channels were estimated based on field observations. Bedrock channels are roughly 2 m wide in the area being simulated, so a 2-m channel width was assumed for third and fourth order channels. Additionally, many of the channels have steep or vertical banks so we assumed a bank angle of 90°.

TOPOFLOW has several outputs at each cross-section, including depth of flow and discharge. Simulated velocity was also monitored to make sure that the flow estimates were reasonable.

5. Results

5.1. Geologic mapping and physical properties of geologic materials

Geologic mapping (Fig. 3) revealed five geologic units within the study basin; bedrock; young loose colluvium on and near (generally at depths less than 0.5 m) the surface (yc, Fig. 3); underlying, older compacted colluvium that has been exposed by erosion and raveling triggered by channel incision (oc, Fig. 3); channel sediment from debris flows or floods; and recent colluvial fill in channels. Channel sediment and colluvial fill are not shown because of limitations of map scale for Fig. 3. Mapping also showed that the 4th and 5th order channels within the basin (those shown on Fig. 3) all begin within bedrock or at the bedrock/oc contact. The bedrock cliffs were the original source for all four surficial geologic units in the basin.

Bedrock forms steep cliffs in the basin, but has been highly altered by hydrothermal activity and contains abundant mineralized veins and barren fractures. The combination of weakened ground mass and abundant discontinuities makes the bedrock highly susceptible to rock fall. Rock falls were observed during every trip to the basin and ranged from rates of 5 to 20 falls per hour. The timing and frequency of rock falls appeared to be at least partially controlled by thermal expansion associated with exposure to sunlight. We observed this process one winter morning in February 2006. We arrived in the basin before direct sunlight reached the exposed bedrock slopes in the upper basin and did not observe any rock-fall activity. Immediately after direct sunlight hit the bedrock slopes, however, rock falls began to occur at a rate of about 20 per hour. When these falling rocks impacted colluvial slopes,

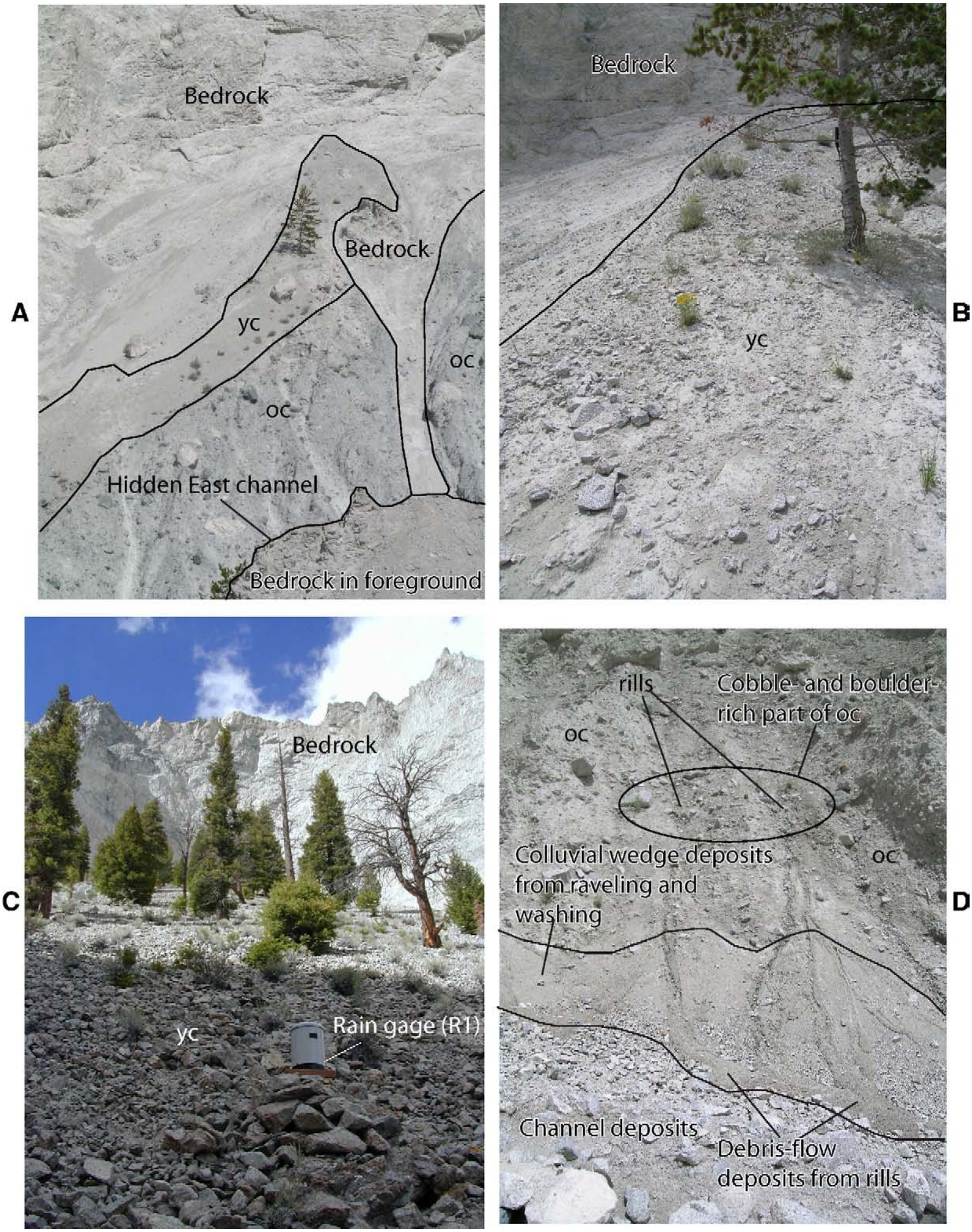


Fig. 6. Colluvium in the study basin. A) Bedrock cliff, older colluvium (oc), and young colluvium (yc) near the head of the basin. View to the northwest. Relief shown is about 120 m. Evergreen tree is also visible in B. B) Sandy yc and bedrock. Width of field of view at foreground is about 3 m. View to the northwest. C) Coarse yc (talus) at rain gage R1 (see Fig. 3 for location). View to the northeast. D) oc with rills near instrumentation SM3, Ksg2. Width of field of view at foreground is about 4 m. View to the east.

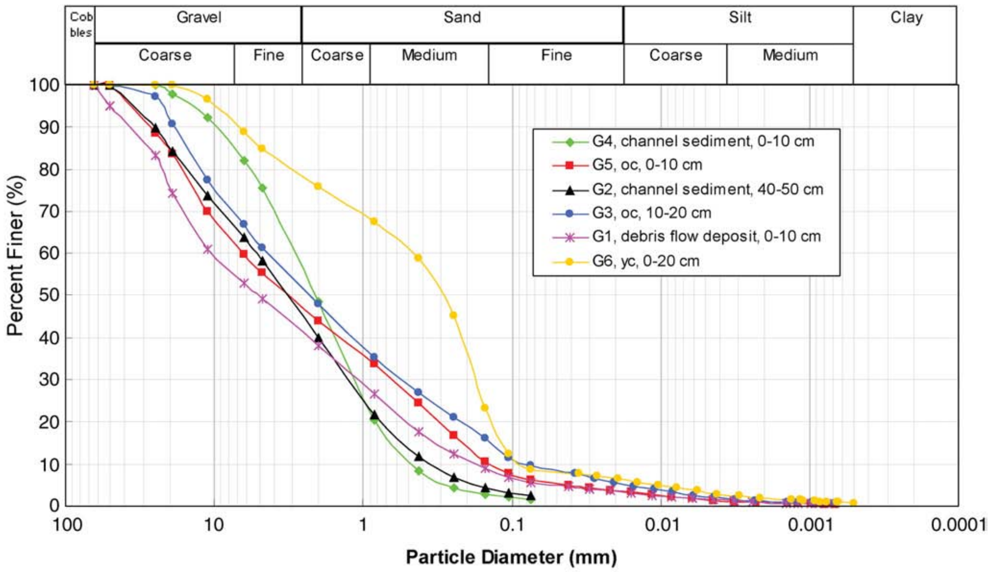


Fig. 7. Results from grain size analyses.

they caused dry sediment to ravel (Gabet, 2003) to downslope positions in channels.

The 4th order channels have exposed bedrock at the surface, or at a shallow (<0.5 m) depth. The amount of sediment in the 4th order channels is a function of the elapsed time since the last flow. When sediment is present, we estimate (from field observations) that about 10% of the sediment has been previously moved by debris flows or floods, and that about 90% is colluvial fill deposited by rock fall and dry ravel processes. Our observations of rock fall and dry ravel deposits on top of one month old snow during the winter of 2005/2006 (Fig. 4), and after debris flows that flush out the channels, indicate that the channels quickly fill through the formation and expansion of colluvial wedges along the channel banks (Figs. 4 and 5).

A major break in slope occurs where the 4th order channels feed into the 5th order channel. The average slope of the 4th order channels is about 40°, whereas the average slope of the 5th order channel is 14° in the basin, and 9° on the bajada. During the monitoring period, the 5th order channel in the basin was continuously lined by thick (generally > 3 m) rock fall, dry ravel, debris flow, and flood deposits (Fig. 5). Our observations following debris flows (described in the next section) indicate that the 5th order channel is the sediment source for the initiation of debris flows when the 4th order channels are depleted of sediment.

Young colluvium (yc) tends to fall into two categories, either talus, or a poorly sorted mix of sand-, gravel, and cobble-sized sediment (Fig. 6). Both categories of yc are loose and uncompacted. The underlying, older colluvium (oc) is a poorly sorted mix of sediment ranging in size from silt to boulders (Fig. 6). Results from grain size analysis indicate that the matrix of both types of colluvium is similar, that is, a sediment dominated by gravel and sand, with less than 6% silt and clay (Fig. 7). Older colluvium (oc) has a higher density than younger colluvium (yc) probably because it was buried (i.e., compacted from overlying colluvium and/or snow and ice during Pleistocene glaciation) prior to exposure. Bulk density results (Table 1) confirm this field observation and show that oc has a higher bulk density (1.46 g/cm^3), and lower porosity (0.45) and void ratio (0.81) compared to yc, which has bulk densities that range from 1.10 to 1.21, porosities from 0.58 to 0.54, and void ratios from 1.19 to 1.41. Uncertainties

Table 1
Dry bulk density, porosity, and void ratio of colluvium in the study basin (see Fig. 3 for site locations)

Site name and description	Dry bulk density (g/cm^3)	Porosity	Void ratio
BD1 — colluvial surface (yc) near SM1 and SM2	1.10	0.58	1.41
BD2 — colluvial surface (yc) near I2	1.21	0.54	1.19
BD3 — raveling colluvium (oc) near I5	1.46	0.45	0.81

associated with measured volumes and assumed specific gravities of sediment samples suggest that errors in bulk density, porosity, void ratio values given in Table 1 are about ±20%.

Material in channels is either sediment that has been previously mobilized by debris flows or floods, or fresh colluvial fill. Both types of sediment are loose and unconsolidated (Figs. 4 and 5). Channel sediment has similar grain size characteristics to colluvium, except that it contains a lower percentage silt and clay (<2%, versus <6% for colluvium, Fig. 7). A visual comparison of channel materials (Figs. 4 and 5), with both types of colluvium (Fig. 6), strongly suggests that the channel sediment has lower bulk density and higher porosity values than colluvium. We estimate that channel materials have a minimum porosity of about 0.5.

5.2. Field observations following debris flows and floods

Field observations and interviews with local residents and county authorities indicate that at least six debris flows and two floods occurred in the study basin between May 2004 and July 2006 (Table 2). Although we did not directly observe any of these flows, we were able to classify them as predominantly debris flows or floods based on the type of deposits that we observed soon after they occurred.

Of the six debris flows, three of the flows traveled to Chalk Creek and deposited fans in the creek, and the other three either stayed in the basin, or stopped in the channel on the bajada near the mouth of the basin. We visited the study area within several days following two

Table 2
Flows during the monitoring period

Date	Time (Mountain Daylight Time, MDT)	Source of timing information	Dominant type of flow	Comments
July 24, 2004	Approximately 21:30	Bob Warren, US Forest Service employee who lives in Chalk Canyon	Debris flow	Debris flow(s) traveled the length of the 5th order channel, crossed CR 162, and deposited a small fan in Chalk Creek
August 18, 2004	Approximately 18:30	Joe Nelson, head of Chaffee County Road Maintenance Group	Debris flow	Debris flow(s) traveled the length of the 5th order channel, crossed CR 162, and deposited a large fan in Chalk Creek. Field observations indicated that the volume of this flow was roughly an order of magnitude larger than the July 24, 2004 flow.
September 25, 2004	Roughly 20:30, but poorly defined.	Eric Dahlberg, manager of Silver Cliff Ranch adjacent to the channel.	Possible debris flow	Possible debris flow(s), but CR 162 is apparently not affected and timing is poorly constrained.
September 22, 2005	Approximately 16:30	Eric Dahlberg, manager of Silver Cliff Ranch adjacent to the channel.	Debris flow	Debris flow(s) travels about halfway down the 5th order channel and stops upslope of CR 162.
October 18 or October 19, 2005	Late on the 18th or early on the 19th	Eric Dahlberg, manager of Silver Cliff Ranch adjacent to the channel.	Water-dominated flow (flood)	Field observations of deposits indicated that the flow was water-dominated. Flood traveled the length of the 5th order channel, crossed CR 162, and progressed to Chalk Creek, but no fan was deposited. Small debris flow tracks and deposits were observed on colluvium in the basin, but not in the primary channel.
May 22, 2006	Between 20:30 and 21:30	No eyewitness information, timing constrained based on dates of field observations and available storms	Debris flow	Debris flow restricted to 4th order channels at head of the basin.
July 8, 2006	Approximately 14:00	Travis Collins, Chaffee County Road Maintenance Group	Debris flow	Debris flow(s) traveled the length of the 5th order channel, crossed CR 162, and deposited a moderate-sized fan in Chalk Creek. Field observations indicated that the volume of this flow was smaller than the August 18, 2004 flow, but larger than the July 24, 2004 flow.
July 26 or 27, 2006	July 26th or July 27th	Observations from July 28 and information from local resident	Water-dominated flow (flood)	Flood traveled the length of the 5th order channel, crossed CR 162, and progressed to Chalk Creek, but no fan is deposited. Small debris flow tracks and deposits were observed on colluvium in the basin, but not in the 5th order channel.

of these flows (the July 24, 2004 and May 22, 2006 flows, Table 2), and walked from Chalk Creek to the source areas of the debris flows near the head of the study basin (Fig. 2). The July 24 flow traveled to Chalk Creek whereas the May 22 flow only traveled to the junction of the west and east 4th order channels near the head of the basin (see Fig. 3). Debris flow deposits in Chalk Creek from the July 24 flow were fan shaped and partially blocked the flow of the creek. The deposits were matrix supported, poorly sorted, and contained abundant clasts up to 0.3 m in diameter. In the channel on the bajada, we observed debris flow levees, debris flow runup zones around channel bends, and multiple, often overlapping, lobate deposits (Fig. 8). The deposits were similar to those on the fan in the creek, both were poorly sorted and matrix supported, and contained clasts up to about 0.3 m in diameter. No evidence was observed that the debris flows incised and entrained sediment along the thalweg of the previously existing channel on the bajada.

In the basin, sediment was mobilized during debris flows along the length of the 4th order channels where abundant loose debris existed from recent rock falls and dry ravel of colluvial deposits (Fig. 9), as well as along the 5th order channel near the junctions with the 4th order channels (Fig. 10). Some minor rilling and associated, small debris flow deposits were observed on exposed older colluvial deposits (oc, e.g., Fig. 6D), but none were observed on younger deposits (yc). We found no evidence for slides that mobilized into debris flows in any of the source areas, although we did observe some small slides in colluvial wedge deposits that had been undercut by erosion along the flanks of channels. The debris flows initiating on oc were very small, with individual volumes of flow much less than 1 m^3 (Fig. 6D). The heads of the rills above the deposits tended to be within or immediately downslope from cobble- and boulder-rich patches of colluvium. The lack of slides at the head of the rills indicates that the debris flows initiate through sediment entrainment in the rills themselves (Fig. 6D). On bedrock exposed at the heads of 4th order channels, we found evidence for overland flow of water, sediment entrainment, and transformation into debris flows in the form of preserved levees flanking rills and gulleys on sideslopes that were thinly (1–2 cm) mantled by fresh dry ravel deposits (e.g., Fig. 9B). A sequence of photographs of the western 4th order channel taken throughout the monitoring period (Fig. 11) show that debris flows occurred as a series of pulses (some of which are still preserved in place in the photographs) that entrained sediment and scoured the channel to bedrock, and that the channel quickly refilled following the debris flows. In the 5th order channel, the truncation of fresh debris flow deposits by well-sorted

Fig. 8. Debris flow deposits in 4 m-wide main channel on bajada. Photograph taken July 25, 2004. View to south. Note post-debris flow incision in center of channel.

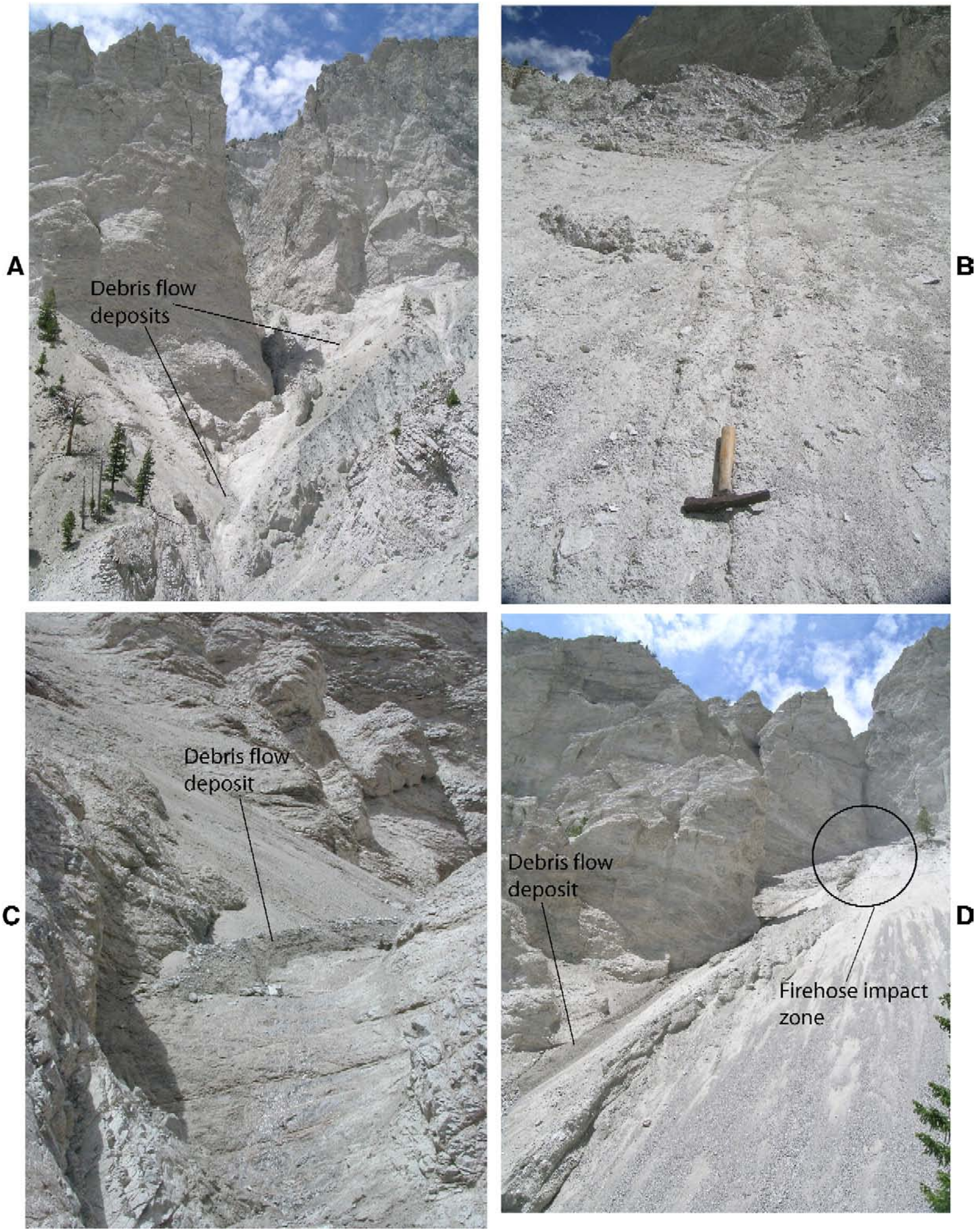


Fig. 9. Debris flow source areas in 4th order channels. See Fig. 3 for locations. A) Bedrock catchment area at the head of the west channel. Lower portion of photograph is also shown in Fig. 11. Relief shown is about 300 m. View to the northwest. Photograph taken on July 28, 2006. B) Rill with debris flow levees on thinly mantled bedrock at head of east channel. View to north. See hammer for scale. Photograph taken on May 26, 2006. C) Freshly scoured portion of west channel with debris flow levee. Also shown in Fig. 11. View to northwest. Channel in foreground is about 2 m wide. Photograph taken on July 25, 2004, one day after a debris flow. D) Channel to southwest of SM4. Relief shown is about 120 m. View to southwest. Photograph taken on July 28, 2006.

Fig. 10. Debris flow source area in 5th order channel between BD3 and mouth of west channel (see Fig. 3 for location). Width of channel in foreground is about 3 m. Photograph taken on July 25, 2004.

sandy deposits indicates that some water-dominated, recessional flow occurred immediately after each debris flow (e.g., Fig. 8).

We also made field observations within several days after the two floods of October 19, 2005 and July 27, 2006. At Chalk Creek, and in the 5th order channel on the bajada, the floods were characterized by the redistribution and sorting of sediment that was previously deposited by debris flows (Fig. 12). Also in the channel, incision and truncation of existing debris flow deposits was observed. In the basin, we observed evidence for water-dominated flow and debris flows, although we still classified the overall events as floods because the debris flow deposits were relatively minor. In 5th order channels in the basin, water-dominated flows incised the channel and undercut and eroded away colluvial wedge deposits along the channel flanks. A variety of deposits were observed in the 4th order channels in the basin. Debris flow deposits were observed in the upper-most portions of some channels, and minor rilling and small debris flow deposits were observed on oc. Unlike the three debris flows that we previously described, the debris flow deposits associated with the floods were only present in the upper portions of the 4th channels (e.g., Fig. 9D), and were not present in the 5th order channel.

5.3. Rainfall

Rainfall that triggered debris flows and floods in the basin (Fig. 13) occurred between late spring (May) and early fall (October) each year. No debris flows or floods were triggered by snowmelt. In typical years, about 50% of the average annual precipitation (345 mm, Fig. 13A) in the basin falls between May and September, with July, August, and September tending to have the most intense storms.

Eyewitness reports indicate that flow events tended to be triggered by rainstorms with durations of much less than 1 h. Because of these observations, and because our intent was to develop a rainfall threshold for triggering flows, we divided the rainfall record (Fig. 13A) into individual periods of high-intensity rainfall, which we call storm "bursts" (Fig. 13B). We define a burst as a segment of a storm that has less than 10 min gaps between rain gage bucket tips. If the gap between bucket tips is greater than 10 min, then a new burst is defined. Thus, by our definition, storm bursts have intensities greater than 1.52 mm/h, which would be the intensity calculated from 1 bucket tip every 10 min. Results from this exercise (Fig. 13B) reveal that the rainfall threshold for triggering the observed debris flows is:

$$I_{\mathrm{B}} = 6.61(D_{\mathrm{B}})^{-0.77} \tag{6}$$

where burst intensity, I_{B}, is in mm/h and burst duration, D_{B}, is in hours. Several of the bursts triggered debris flows in 4th order channels (October 19, 2005 and July 27, 2006), and triggered floods in the 5th order channel. These two bursts are distinguished from the other bursts by long (2.4 h, October, 19, 2005) and short (0.3 h, July 27, 2006) durations. Although the bursts triggering floods can be distinguished from the bursts triggering debris flows by duration times, the actual channel response is a function of the generated runoff (i.e., discharge) and the availability of sediment in channels. Both of these topics will be explored in a later section.

Also, no easily distinguishable difference exists between bursts that triggered debris flows with long travel distances (July 24, 2004, August 18, 2004, and July 8, 2006) and those that triggered debris flows with short travel distances (September 25, 2004; September 22, 2005; and May 22, 2006). The only commonality between bursts that triggered debris flows with long travel distances is that the duration is between 0.55 and 0.65 h. Bursts with shorter and longer durations resulted in debris flows with shorter travel distances. Again, these differences may be more accurately explained by

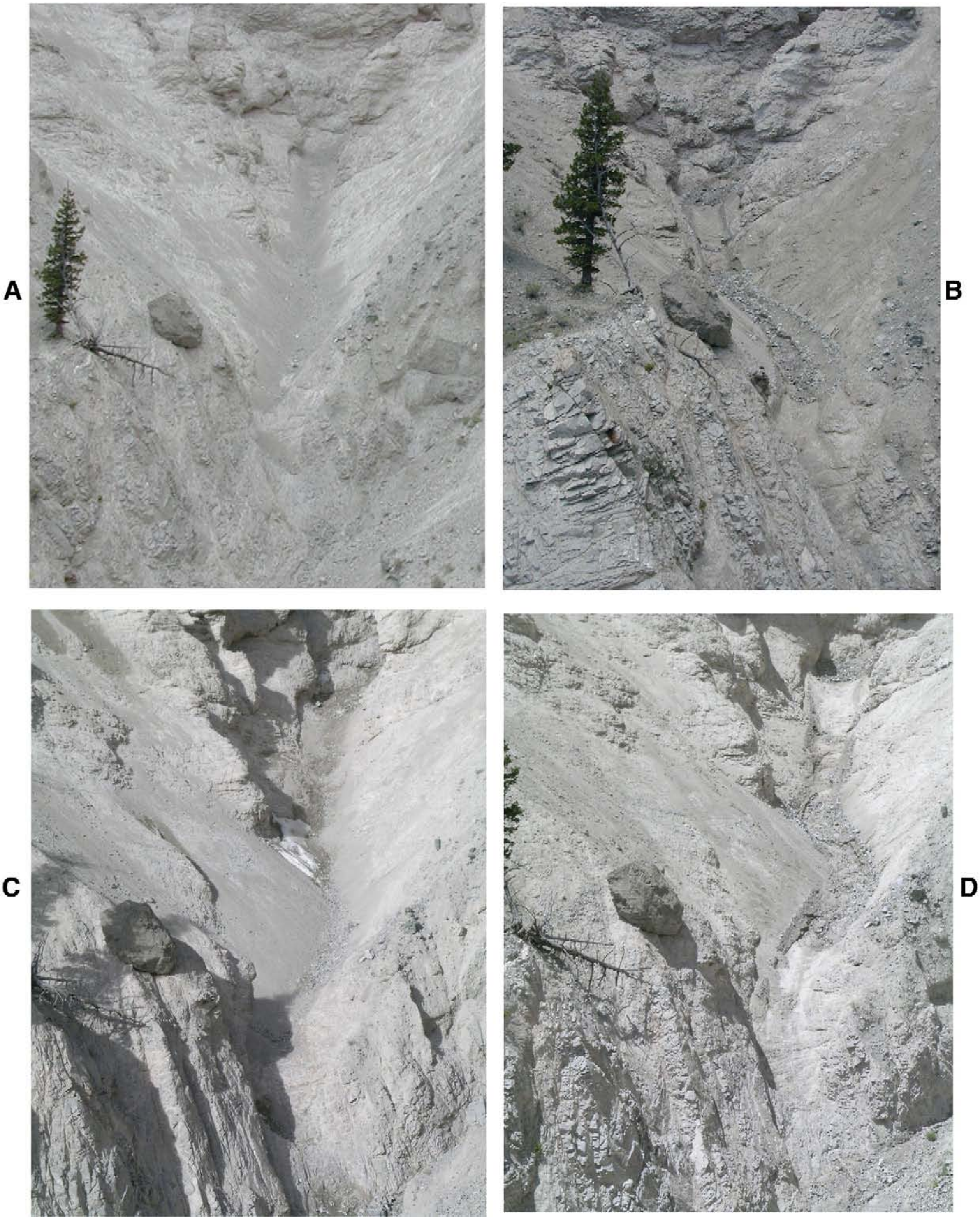


Fig. 11. Photographs showing alternating fill by rock falls and dry ravel, and scour by debris flows in west channel during the monitoring period. Boulder on left side of photos is about 4 m long. A) May 27, 2004. B) July 25, 2004. C) February 28, 2006. D) July 28, 2006.

Fig. 12. Photographs showing flood deposits in main channel on bajada (see Figs. 2 and 3 for location). View is upstream to the northwest. Width of fresh deposits in foreground is about 2 m. Photograph taken on October 21, 2005.

differences in generated runoff and the availability of sediment in channels.

5.4. Soil moisture

Records of soil moisture are available for three debris flows and two floods between May 2005 and August 2006 (Fig. 14A). Expanded records for individual flows are shown in Fig. 14B to F. Moisture on the hillslope, in the channel levee, and at depth in the 5th order channel, immediately prior to triggering rainstorms (antecedent moisture), was always less than 22% moisture by volume (Fig. 14). The lowest porosity measured for colluvium in the study area was 0.45 (45%) (Table 1); therefore, sediment was always unsaturated at the beginning of rainstorms that triggered flows. At depths of 1 cm on the hillslope and in the levee, antecedent moisture ranged between 4 and 9% (Fig. 14). At a depth of 29 cm on the hillslope, antecedent moisture ranged between 4 and 7% (Fig. 14). Although few data are available from the 5th order channel, antecedent moisture at a depth of 45 cm ranged from about 20–22% (Fig. 14B and C), the highest antecedent moisture levels of any of the monitored sites.

Peak moisture levels during flows were also low (Fig. 14B–F), with peak shallow (1 cm) moisture ranging from about 10–20%, hillslope moisture at 29 cm ranging from 4 to 12%, and channel moisture at 45 cm ranging from 24 to 38%. As with antecedent moisture, all of the peak moisture levels indicate unsaturated conditions at monitoring sites during flows. Interestingly, the hillslope moisture sensor at 29 cm (SM2, Fig. 3) did not show an increase in moisture during three of the five flows (Fig. 14B, D, and F), and showed a moisture increase of only a few percent within a day following the other two flows (Fig. 14C and E).

Distinguishing debris flows from floods is difficult based on the soil moisture records alone. The moisture levels are very similar for both types of flows, except that the limited records (two events) of channel moisture at 45 cm suggest that deep channel materials are wetter during floods than during debris flows (compare Fig. 14C to B).

Unfortunately, because of practical limitations (i.e., possible destruction of sensors by flows) we do not have any moisture measurements from shallow channel materials. Field observations of shallow channel materials, however, suggest that antecedent moisture levels were similar to those in colluvium (i.e., sensors SM1 and SM2). In 4th order channels, where shallow materials were consistently mobilized by runoff, moisture levels during floods and debris flows were likely at or near saturation. Moisture levels of shallow sediment in the 5th order channel during floods and debris flows are unknown. Additionally, local areas of shallow, older hillslope colluvium (oc, Fig. 3) where rilling occurred during flows, was also likely saturated, but only very near the surface.

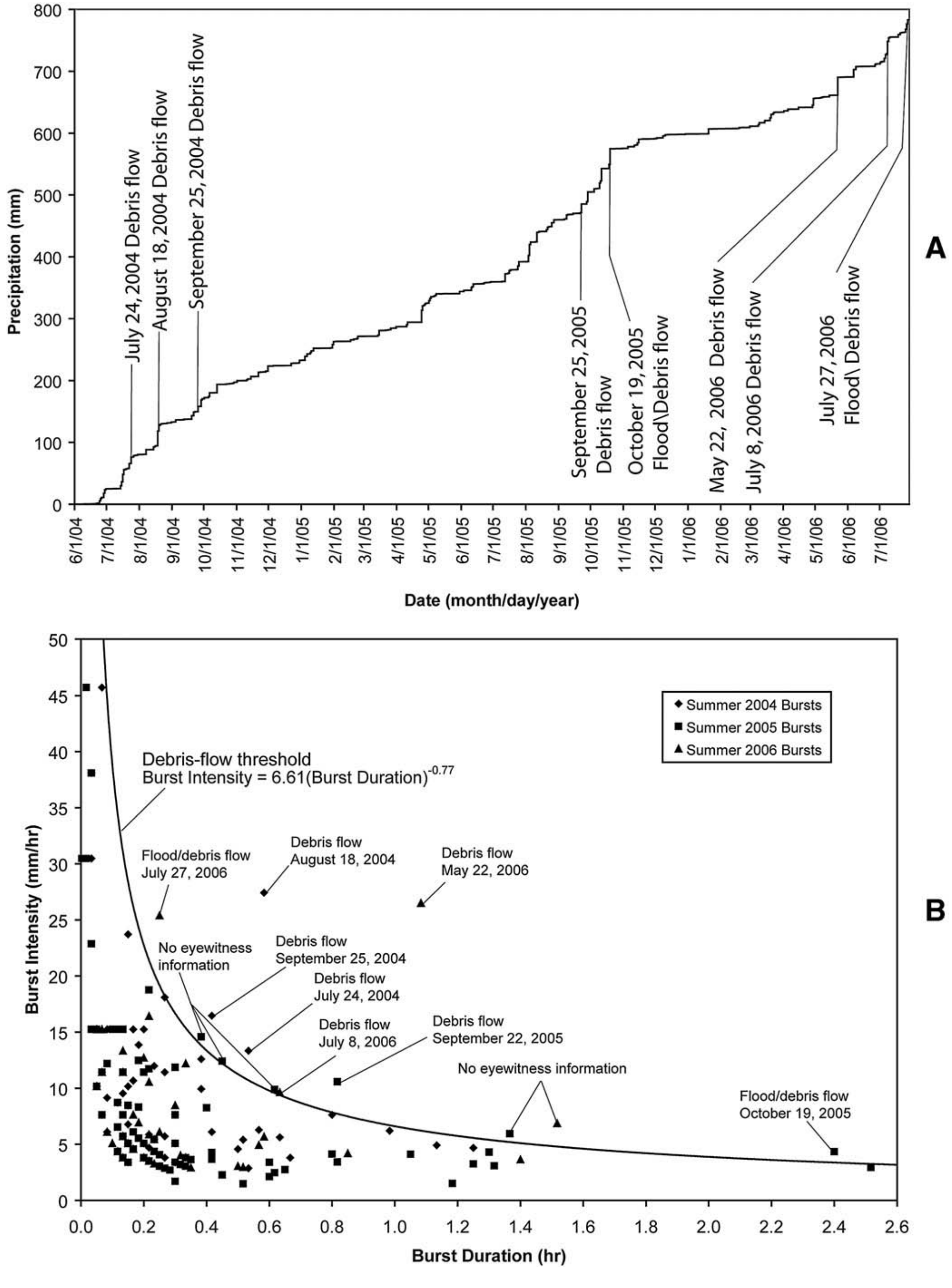


Fig. 13. Diagrams showing rainfall during the monitoring period collected at rain gage R1 (see Fig. 3 for gage location). A) Cumulative rainfall from starting date of May 27, 2004. B) Rainfall bursts and debris flow threshold.

5.5. Hydrologic characterization of colluvium and channel sediment

Results from Guelph and Mini Disk field measurements indicate that hydraulic conductivity (*Ks*) and infiltration (*I*) increases as progressing from older colluvium (oc), to younger colluvium (yc), to channel sediment (Table 3 and Fig. 15). Guelph measurements indicate that field-saturated *Ks* ranges from 58 to 101 mm/h for yc and 504 to 864 mm/h for channel and levee sediments (Table 3). Values for yc are about two times greater than the highest rainfall intensity that triggered debris flows

(27.4 mm/h, August 18, 2004, Fig. 13B), whereas values for channel sediments are about 18 to 31 times higher. We did not make Guelph measurements in older colluvium (oc) because abundant pebbles and cobbles made it very difficult to auger a bore hole with geometrically stable sides (a requirement for Guelph measurements). Instead, we relied on Mini Disk measurements for estimates of infiltration at the surface of oc.

Results from the Mini disk measurements show that oc has a lower rate of infiltration than yc (Fig. 15). The rate of infiltration measured for the matrix of oc is about 26 mm/h, which is close to the maximum rainfall intensities that triggered debris flows (~ 27 mm/h), whereas the rates for yc are greater than 43 mm/h (Fig. 15). Small variations (several percent) in initial soil moisture at each site may have partially contributed to the observed rate differences; but overall, the results suggest that differences exist in the hydrologic properties of two types of colluvium.

5.6. Modeled runoff response

Modeled runoff at the mouth of the 4th order, west channel (Fig. 3), provides an indication of how rainfall translates into peak-flow discharge. The estimated peak discharges of surface-water indicate the potential for runoff to entrain sediment once it encounters loose sediment. To better understand the effect that variable sediment supply had on the generation of debris flows, we plotted modeled peak-flow discharge against the time since last flow (Fig. 16). One of our hypotheses was that the magnitude of debris flows (i.e., travel distance, volume) would be positively correlated with the elapsed time since the last flow. Results shown on Fig. 16 indicate that this hypothesis is incorrect, because two of the largest debris flows (August 18, 2004; July 8, 2006, Table 2) occurred after some of the shortest elapsed times (Fig. 16). Fig. 16 also suggests that debris flows occur at an approximate minimum peak discharge threshold of 0.15 m^3/s.

Fig. 16 does a reasonably good job of distinguishing floods from debris flows. Both floods occurred with elapsed times (i.e., time since previous debris flow) of less than 30 days since the last flow. One debris flow (August 18, 2004) also occurred with an elapsed time of less than 30 days (24 days), but this debris flow resulted from the storm with the highest intensity (27 mm/h, Fig. 13B) and the highest modeled peak discharge (~ 0.62 m^3/s, Fig. 16). These observations suggest that floods are most likely when elapsed times are less than 30 days, but that debris flows are also possible with short elapsed times if the rainfall burst intensity is well above the rainfall threshold. Interestingly, the two rainfall bursts that resulted in floods had very different durations. One storm had a very short duration (0.3 h, Fig. 13B) and one had a long duration (2.4 h, Fig. 13B), but the modeled peak discharge response was very similar (Fig. 16).

6. Discussion — debris flow initiation

A summary of initiation conditions for debris flows in the study basin is given in Table 4. These results indicate that debris flows are triggered by short duration, moderate to high intensity rainfall (see threshold in Fig. 13) that results in overland flow from unsaturated, consolidated older colluvium, and steep bedrock cliffs. Interestingly, the rainfall threshold for Chalk Cliffs is very similar to thresholds developed by Cannon et al. (2008-this volume) for areas recently burned by wildfires in Colorado. The Cannon thresholds, however, only apply for one year after a fire (i.e., until vegetation becomes reestablished on burned slopes), whereas the Chalk Cliffs threshold is for long-term conditions. During the monitoring period, an average of two debris flows occurred per year in the study basin. Because short recurrence rainstorms trigger debris flows at Chalk Cliffs on a regular basis, the site as an ideal natural laboratory to study debris flows generated from runoff.

Debris flows on older colluvium (oc) initiate through sediment entrainment in rills. The rate of infiltration measured for the matrix of oc (see I5, Fig. 15) is roughly 26 mm/h. This suggests that most bursts of rainfall would not result in runoff from the oc matrix, but that concentrated runoff from cobbly/bouldery patches could easily exceed the infiltration capacity of the matrix and create rills. Moisture levels in colluvium immediately before and during debris flows were low; between 4 and 20% by volume. Debris flows initiating from colluvium contribute sediment to the 4th and 5th order channels where it can be entrained by large debris flows, but these volumes are very small compared to the amount of sediment that is entrained from the 4th and 5th order channels by runoff from bedrock.

Whether or not debris flows are initiated in the 4th order channels (Figs. 9 and 11) appears to depend on the availability of sediment in the channel. Field observations indicate that the channels fill rapidly from rock fall and dry ravel. Two successive debris flows occurred in 2004 within 24 days of one another, although the second of these debris flows probably formed from entrainment of sediment from the 5th order channel, rather than from the 4th order channel. All of the 4th order channels have heads within or immediately adjacent to bedrock. Runoff from bedrock is water-rich and sediment poor and when runoff reaches sediment lined-channels, sediment is entrained in the flow and debris flows are generated. Field observations of debris flow levees near the heads of the 4th order channels indicate that sediment entrainment occurs quickly and that debris flows are formed within the first several meters of water flowing over the sediment.

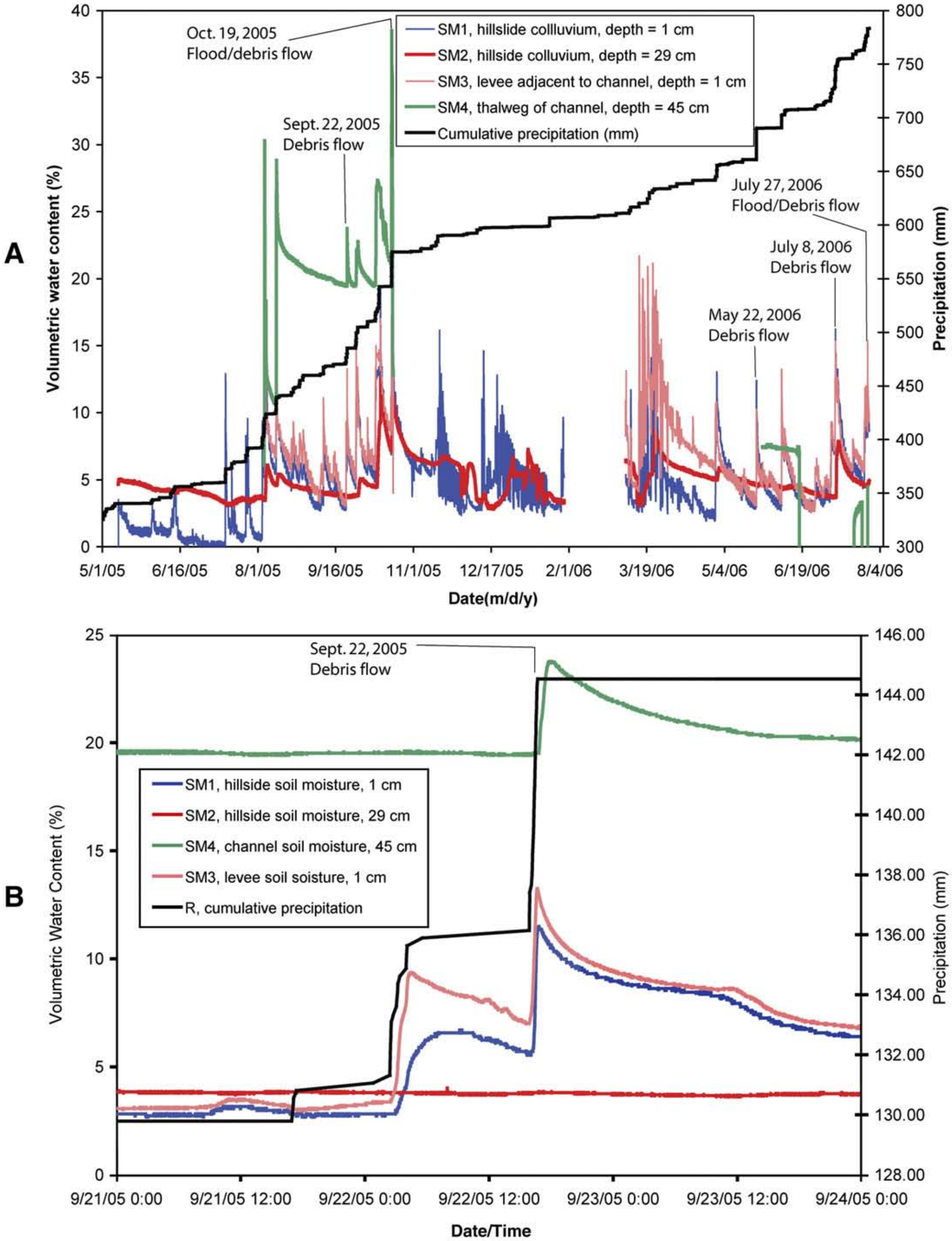


Fig. 14. Soil moisture data during the monitoring period. See Fig. 3 for instrument locations. A) All available data. Note that SM4 is only a partial record because of problems maintaining the sensor because of channel erosion and rodents. Large fluctuations in shallow moisture between November and April are from freezing and thawing of shallow colluvium. Sensor SM1 was partially exposed to air between June 15 and August 14, 2005. B–F) Data from individual flow events.

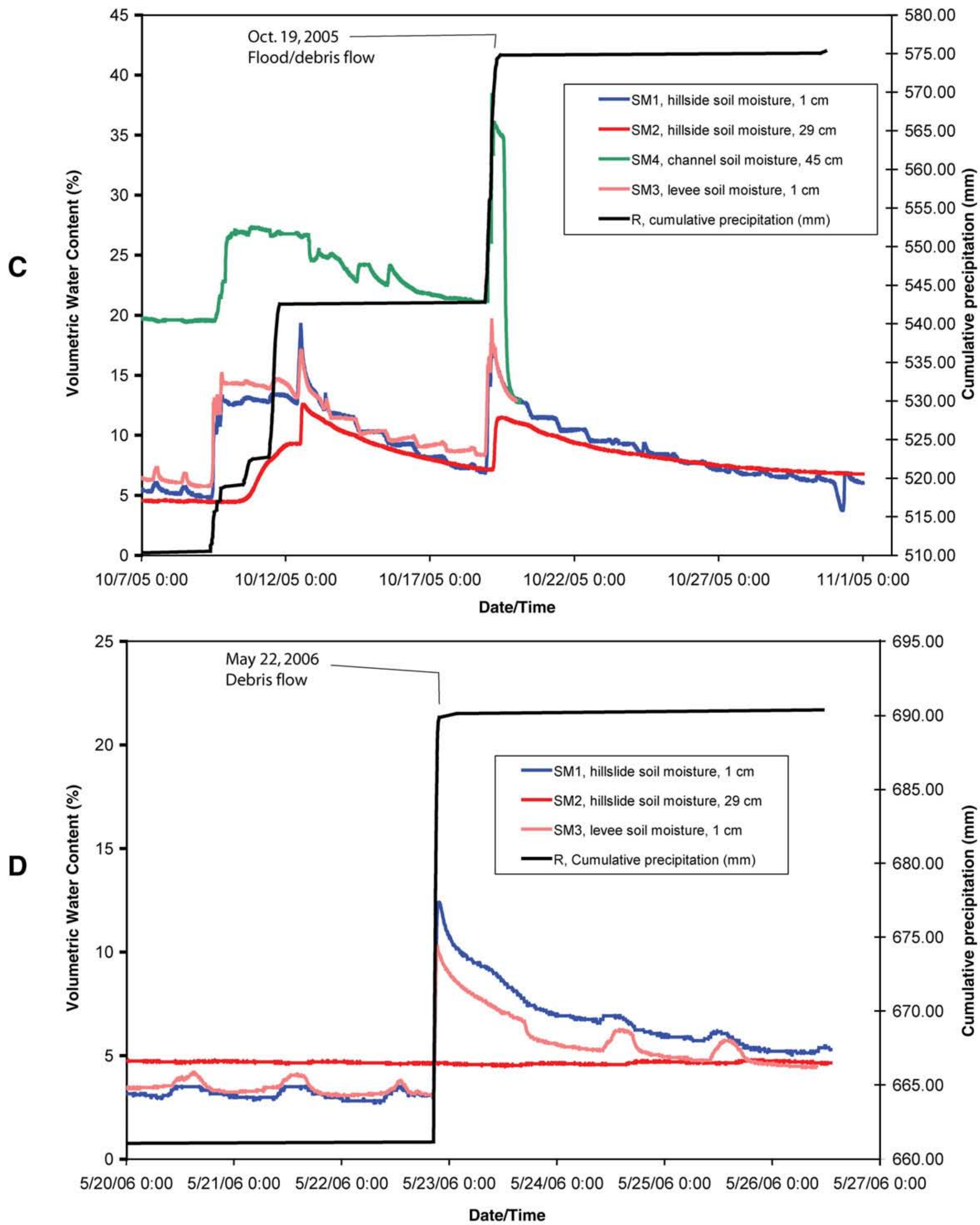
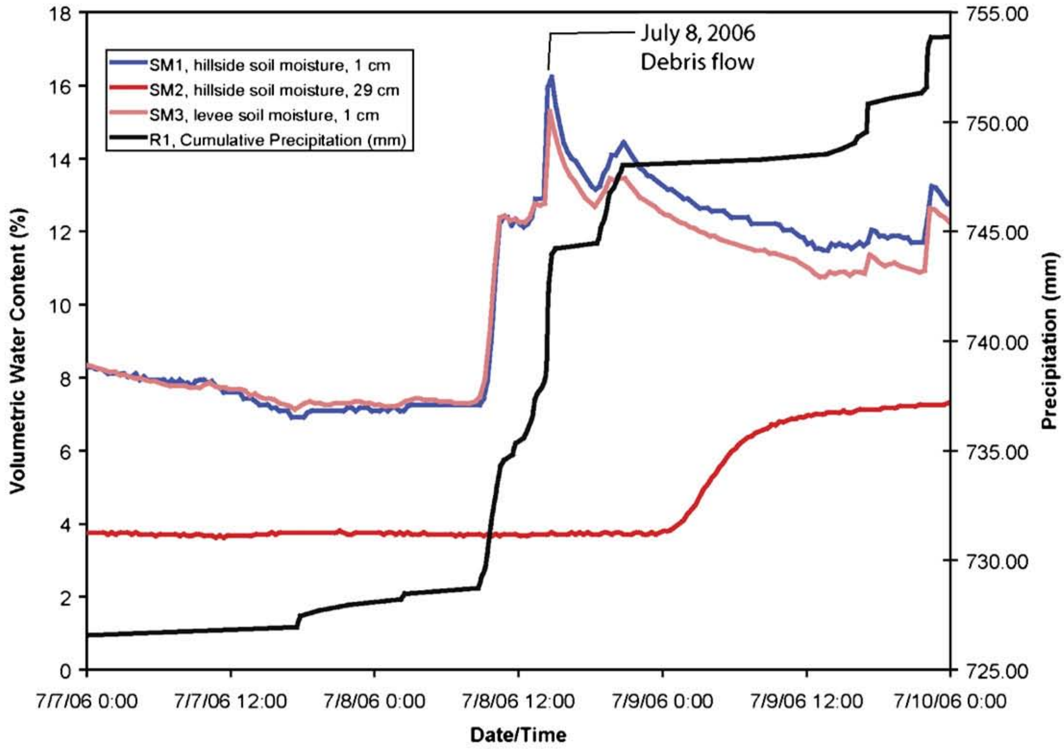


Fig. 14 (*continued*).

Hungr et al. (2005) suggest that two main mechanisms are responsible for sediment entrainment in channels; bed destabilization and erosion, and failure of stream banks undercut by erosion. Both types occur in the study basin. As stated previously, two types of 4th order channels occur in our study area, those that begin at the bedrock/colluvial contact (Fig. 9D), and those that begin on bedrock (Fig. 9A). The entrainment process is different for each type of channel. For channels that begin at the bedrock/colluvial contact, entrainment

E



F

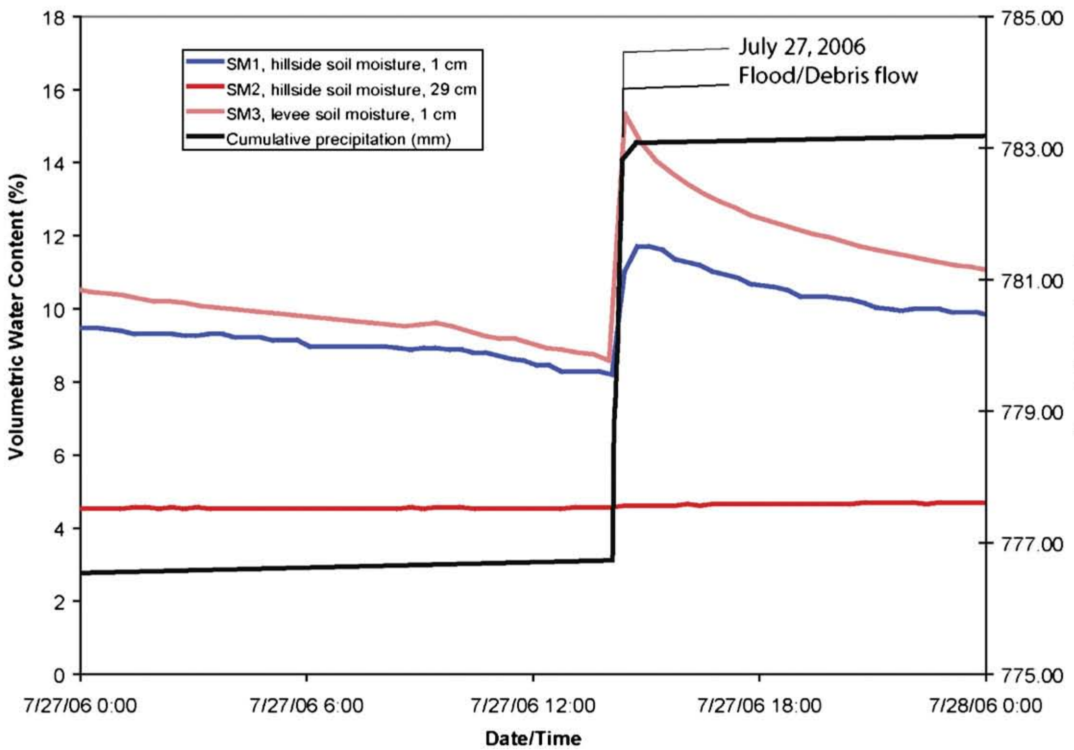


Fig. 14 (*continued*).

Table 3
Field-saturated hydraulic conductivity determined from Guelph permeameter measurements in colluvium in the study basin (see Fig. 3 for site locations)

Site name, description	Depth (cm)	Ks (cm/s)	Ks (mm/h)	Type of solution
Ksg1, yc near SM1 and SM2.	19	1.6×10^{-3}	58	Multi-head
Ksg1, yc near SM1 and SM2	19	2.8×10^{-3}	101	Single-head
Ksg2, channel and levee sediments	13	1.4×10^{-2}	504	Single-head
Ksg2, channel and levee sediments	30	2.4×10^{-2}	864	Multi-head
Ksg2, channel and levee sediments	30	1.5×10^{-2}	540	Single-head
Ksg3, recently deposited channel sediments	12	1.9×10^{-2}	684	Single-head

occurs during a "firehose effect" where water-rich runoff from gulleys in bedrock cliffs pours on downslope colluvium. The firehose effect has been described in many previous studies (e.g., Fryxell and Horberg, 1943; Johnson and Rodine, 1984; Coe et al., 1997; Glancy and Bell, 2000; Larsen et al., 2006; Godt and Coe, 2007), although the actual mechanics of the process are poorly understood. Our new insights into this process are that high antecedent moisture levels are not required for the initiation of debris flows and that the location of the entrainment sites can change as a function of the conditions of sediment supply (see discussion of 5th order channels later in this section). Furthermore, entrainment occurs nearly instantaneously upon impact, as we have observed debris flow levees immediately adjacent to impact points (Fig. 9D).

For channels that begin within bedrock, entrainment appears to occur through the progressive increase in sediment concentration of runoff along the thalwegs of the channels (Figs. 9 and 11). Previous work indicates that the level of moisture in soils and sediments is important in controlling soil cohesion (Fredlund et al., 1978; Matsushi and Matsukura, 2006) and the efficiency of erosion by overland flow (Huang et al., 2001). Although we do not have soil moisture data from the thin sediments in any of our studied 4th order channels, we know from numerous field observations that moisture levels of sediments in the channels are similar to moisture levels in colluvium, which are always unsaturated prior to debris flows. Therefore, high antecedent moisture levels in sediment in the 4th order channels are not a prerequisite for the initiation of debris flows at Chalk Cliffs. After rainfall and runoff begins, however, sediment along the thalwegs of the 4th order channels undoubtedly becomes quickly saturated. Once this sediment is moving as a debris flow, further sediment is added to the flow by bank failures of colluvial wedge deposits (dry ravel and rockfall deposits). Once debris flows are moving, observations of deposits in the channels (e.g., Fig. 11) indicate that they occur as pulses or waves, rather than as single, massive debris flows.

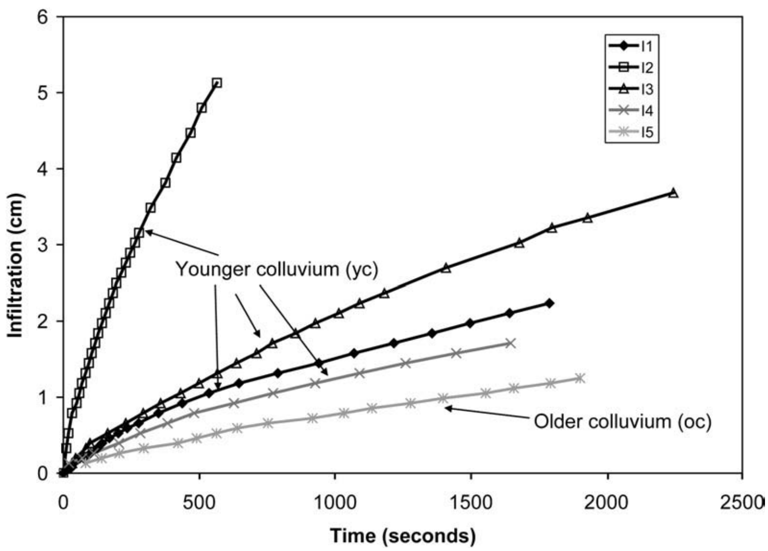


Fig. 15. Diagram showing results from measurements of infiltration. See Fig. 3 for measurement locations. Initial soil moisture for all tests ranged from 9 to 12%.

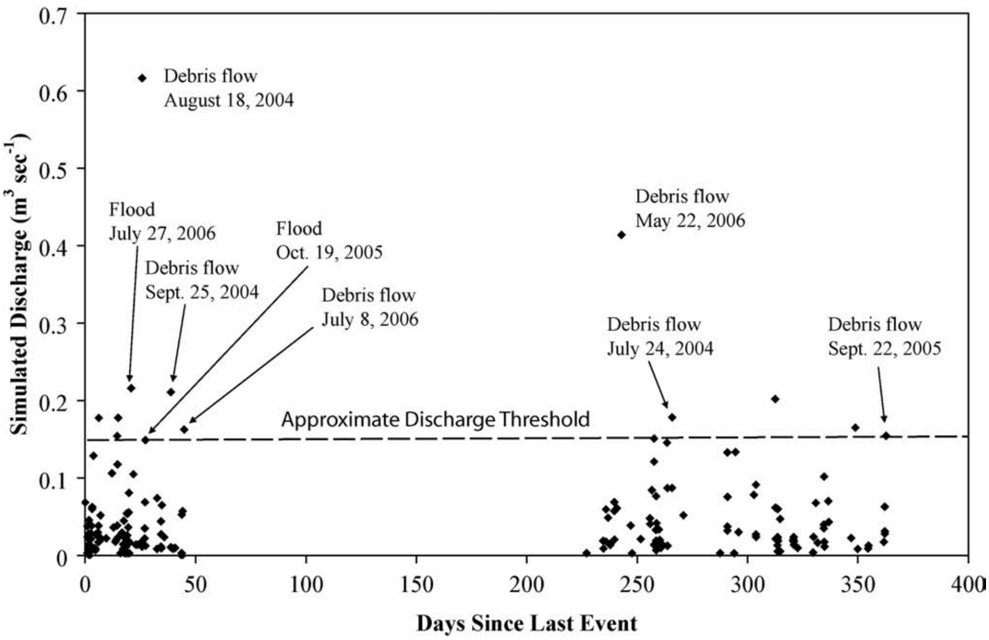


Fig. 16. Diagram showing modeled peak discharge for rainfall bursts during the monitoring period. Large gap in data between 60 and 230 days represents late fall to early spring periods of time.

Sediment supply controls where debris flows initiate in the study basin. Bovis and Jakob (1999) indicated that the conditions of sediment supply in debris flow basins are fundamental to understanding and predicting debris flows and this is certainly the case in the study basin. During short periods (perhaps 60 days or less) in most summers, the 4th order channels in the study basin are depleted of sediment because of flushing by debris flows. When threshold exceeding rainfall occurs during these sediment-depleted times, water-rich runoff, rather than debris flows, flows into the 5th order channel. When this occurs, field observations indicate that sediment entrainment occurs in the 5th order channel at and near its junction with 4th order channels (Fig. 10). The sediment in the 5th order channel is at least 3 m thick, and is consistently supplied with fresh dry ravel and rock-fall deposits. We therefore consider the supply of sediment in the 5th order channel to be essentially unlimited. We hypothesize that this is why debris flows can occur in the basin so close together in time, because an adequate supply of sediment always exists.

These 4th and 5th order channel junctions also tend to be major breaks in slope; most 4th order channels have an average slope of about 40°, whereas the 5th order channel has about a 14° slope. Because of this major break in slope, at least part of the entrainment process at the channel junctions is probably by the firehose process. Once debris flows have formed and are flowing in the 5th order channel, field observations indicate that channel incision and further entrainment of material by the debris flows themselves are minimal. These observations are in general agreement with observations by Rickenmann et al. (2003) and Iverson et al. (2005). Rickenmann et al. (2003) conducted field and laboratory debris flow experiments and observed that channel erosion during debris flows tended to be inversely related with sediment concentration. That is, more fluid rich flows tended to erode and entrain greater amounts of channel material. Iverson et al. (2005) conducted flume experiments and found that steady water floods and dam-break floods (which we consider to be roughly equivalent to a firehose effect), entrained sediment and transformed into debris flows.

Based on modeling simulations, our estimate for the minimum amount of runoff discharge required to initiate debris flows is about 0.15 m^3/s (Fig. 16). Although this appears to be a fairly low threshold, a comparison to an empirical threshold for specific surface-water runoff discharge (Q_T) required to initiate debris flows from sediment in channels (proposed by Tognacca et al., 2000), suggests that it

Table 4
Summary of results

Date, type of event in 5th order channel	Rainfall burst intensity (mm/h), duration (h)	Maximum travel distance (m)	Antecedent hillslope soil moisture at 1 cm depth (volumetric percent)	Antecedent hillslope soil moisture at 29 cm depth (volumetric percent)	Antecedent channel soil moisture at 45 cm depth (volumetric percent)	Elapsed time since previous flow event (days)	Modeled peak discharge from west channel at intersection with east channel (m^3/s)
July 24, 2004, Debris flow	13.34, 0.53	1700	Not available	Not available	Not available	>265	0.18
August 18, 2004, Debris flow	27.43, 0.58	1700	Not available	Not available	Not available	24	0.62
September 25, 2004, Debris flow	16.46, 0.42	<1400	Not available	Not available	Not available	37	0.21
September 22, 2005, Debris flow	10.57, 0.82	1220	7	4	20	362	0.15
October 18 or October 19, 2005, Flood	5.95, 1.37	1700 (flood), <100 (small debris flows in basin)	8	7	20	26 (for previous debris flow)	0.15
May 22, 2006, Debris flow	26.49, 1.08	300	4	5	Not available	215 (for previous flood), 242 (for previous debris flow)	0.41
July 8, 2006, Debris flow	9.63, 0.63	1700	7	4	Not available	262 (for pervious flood), 47 (for previous debris flow)	0.16
July 27, 2006, Flood	25.40, 0.25	1700 (flood), <100 (small debris flows in basin)	9	5	Not available	280 (for previous flood), 18 (for previous debris flow)	0.21

is not. The threshold of Tognacca et al. (2000) is defined as:

$$Q_T = \left(\frac{\rho_s}{\rho_w} - 1\right)^{0.5} * (g^{0.5}) * \left(\frac{d_m^{1.5}}{(\tan\theta)^{1.17}}\right) \quad (7)$$

where Q_T is a specific discharge expressed as discharge per unit length of channel (m^2/s), ρ_s and ρ_w are the densities (kg/m^3) of channel sediment and water (1000 kg/m^3), g is gravitational acceleration (9.81 m/s^2), d_m is the mean grain size (m) of channel sediment, and θ is the slope angle (degrees) of the channel.

For the modeled 4th order channel in the study basin, the channel width is about 2 m, and the mean grain size is about 0.01 m. Given the channel width, our modeled discharge threshold of 0.15 m^3/s yields a specific discharge threshold of about 0.075 m^2/s. Using values of $\rho_s = 2650$ kg/m^3 and $\theta = 40°$ in Eq. (7), the Q_T for the 4th order channels is about 0.005 m^2/s, well below our modeled specific discharge threshold of 0.075 m^2/s. Performing the same calculation for the 5th order channel, with a $\theta = 14°$, yields a Q_T of 0.020 m^2/s, which is also well below our modeled specific discharge threshold. This indicates that debris flows may be initiated in this larger channel even in the absence of overland flow from colluvium; flow off bedrock is likely enough to create debris flows. Additionally, we interpret these results to mean that small-scale sediment entrainment probably begins at specific discharge values less than 0.075 m^2/s, but that the 0.075 value is reasonable for large scale entrainment that is easily noticeable and hazardous. An example of small-scale entrainment that probably occurred at specific discharges less than 0.075 m^2/s is the sediment entrainment in rills on older colluvium in the basin (see Fig. 6D). For these rills, the parameters used in Eq. (7) are essentially the same as those used for the 4th order channel.

7. Conclusions

Our observations indicate that debris flows in the Chalk Cliffs study basin were initiated when rainfall created surface runoff from consolidated colluvium and steep bedrock cliffs. This runoff transformed into debris flows by entraining sediment in rills and channels through firehose and progressive bulking processes. The type and location of entrainment processes were dynamic and depended on variations in sediment supply and channel geometries. Debris flows, initiating in rills on colluvium, had flow volumes smaller than 1 m^3 and tended to be located immediately downslope from cobble- and boulder-rich patches in the colluvium. These small debris flows supplied sediment to 4th and 5th order channels, where water runoff from bedrock transformed channel sediment into larger debris flows. Between debris flows, these channels were rapidly refilled by rock falls from cliffs and by dry ravel from incised colluvial deposits. During periods when sediment was temporarily depleted in steep, 4th order channels, sediment was available in the 5th order channel that drains the entire basin. Therefore, given adequate rainfall, debris flows occurred in sequence over very short time frames. The shortest time between debris flows during the monitoring period was 24 days.

Debris flows were initiated by rainfall exceeding $I=6.61(D)^{-0.77}$, where I is rainfall intensity (mm/h), and D is duration (h). The approximate minimum runoff discharge required to entrain channel sediment is 0.15 m^3/s. Colluvium in the basin was unsaturated immediately prior to, and during debris flows. Antecedent, volumetric moisture levels in colluvium at depths of 1 cm and 29 cm ranged from 4–9%, and 4–7%, respectively. During debris flows, peak moisture levels at 1 cm and 29 cm ranged from 10–20%, and 4–12%, respectively. Channel sediment at a depth of 45 cm was unsaturated before and during debris flows; antecedent moisture ranged from 20–22%, and peak moisture ranged from 24–38%. Although we have no measurements from shallow rill and channel sediment, we infer that it was unsaturated before debris flows, and saturated during debris flows.

Some results from this study are applicable to other semi-arid to arid mountainous regions that experience debris flows triggered by short-duration, moderate-to-high intensity rainstorms. First, our results show that high antecedent moisture levels in hillslope and channel sediment are not required for debris flows initiated by runoff. Surface-water runoff from bedrock can rapidly entrain loose sediment with very low moisture levels (about 4–10% in this study). Second, locations of entrainment of sediment by runoff (i.e., debris flow initiation) can vary within a basin as a function of variations in the thickness of channel fill and the refilling of channels (following debris flows) by rock fall and dry ravel processes. In basins with multiple sources of loose sediment (i.e., 4th and 5th order channels in this study), or where channels are quickly replenished from hillslopes, the time between successive debris flows can be very short, especially when rainfall bursts exceed rainfall thresholds by large amounts. The intensity of the rainfall burst that triggered the debris flow within 24 days of the previous flow in this study exceeded the threshold value by about 2.5 times. That said, it appears that water-dominated flows (floods) are most likely in windows of time immediately following debris flows when sediment supplies are at least somewhat reduced. Both floods documented in this study occurred within 30 days of a debris flow and were triggered by rainfall bursts that were only slightly above rainfall threshold values (burst intensity values were within 5 mm/h of threshold values). Lastly, as demonstrated in this study, a combination rainfall and simulated surface-water discharge thresholds can be useful in understanding and predicting debris flows generated by runoff and sediment entrainment.

Acknowledgements

We thank Cherokee Pursall for developing the calibration equation for the soil moisture probes, Xavier Amblard and Jon McKenna for conducting the grain size analyses, and Bill Schulz for help with the Guelph hydraulic conductivity measurements. Eric and Leta Dahlberg, Bob Warren, Joe Nelson, and Travis Collins provided debris flow timing information. We are grateful to Mark Reid, Fausto Guzzetti, Mario Parise, Paul Santi, Jack Vitek, and Gerry Wieczorek for their thoughtful, constructive reviews of this paper.

References

Amoozegar, A., 1989. Comparison of the Glover solution with the simultaneous-equations approach for measuring hydraulic conductivity. Soil Science Society of America Journal 53, 1362–1367.

Berti, M., Simoni, A., 2005. Experimental evidences and numerical modeling of debris flow initiated by channel runoff. Landslides 2, 171–182.

Berti, M., Genevois, R., Simoni, A., Tecca, P.R., 1999. Field observations of a debris flow event in the dolomites. Geomorphology 29, 265–274.

Bosch, D.D., 2004. Comparison of capacitance-based soil water probes in coastal plain soils. Vadose Zone Journal 3, 1380–1389.

Bouwer, H., 1966. Rapid field measurement of air entry value and hydraulic conductivity of soil as significant parameters in flow system analysis. Water Resources Research 2 (4), 729–738.

Bovis, M.J., Jakob, M., 1999. The role of debris supply conditions in predicting debris flow activity. Earth Surface Processes and Landforms 24, 1039–1054.

Campbell, C.S., 2004. Calibrating ECH_2O Soil Moisture Probes. Decagon Application Note, Decagon Devices, Inc., Pullman, Washington. 4 pp.

Cannon, S.H., 2001. Debris-flow generation from recently burned watersheds. Environmental and Engineering Geoscience VII (4), 321–341.

Cannon, S.H., Gartner, J.E., Parrett, C., Parise, M., 2003. Wildfire-related debris flow generation through episodic progressive sediment bulking processes, western USA. In: Rickenmann, D., Chen, C. (Eds.), Debris Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Millpress, Rotterdam, The Netherlands, pp. 71–82.

Cannon, S.H., Gartner, J.E., Wilson, R.C., Bowers, J.C., Laber, J.L. 2008. Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California. Geomorphology 96, 250–269 (this volume). doi:10.1016/j.geomorph.2007.03.019.

Chow, V.T., 1959. Open Channel Hydraulics. McGraw–Hill, New York. 680 pp.

Christensen, G.H., 2003. Surveying debris flow velocities in Chalk Creek Canyon, Colorado. Geological Society of America Abstracts with Programs 35 (5), 40.

Coe, J.A., Glancy, P.A., Whitney, J.W., 1997. Volumetric analysis and hydrologic characterization of a modern debris flow near Yucca Mountain, Nevada. Geomorphology 20, 11–28.

Coe, J.A., Godt, J.W., Parise, M., Moscariello, A., 2003. Estimating debris-flow probability using debris-fan stratigraphy, historic records, and drainage-basin morphology, Interstate 70 Highway Corridor, Central Colorado. In: Rickenmann, D., Chen, C. (Eds.), Debris Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Millpress, Rotterdam, The Netherlands, pp. 1085–1096.

Coe, J.A., McKenna, J.P., Baum, R.L., Godt, J.W., Pursall, C., 2005. Monitoring initiation conditions for runoff-generated debris flows in unburned basins, central Colorado. Geological Society of America Abstracts with Programs 37, 36.

David-Novak, H.B., Morin, E., Enzel, Y., 2004. Modern extreme storms and the rainfall thresholds for initiating debris flows on the hyperarid western escarpment of the Dead Sea, Israel. Geological Society of America Bulletin 116, 718–728.

Davies, T.R., Phillips, C.J., Pearce, A.J., Zhang, X.B., 1992. Debris flow behavior: an integrated overview. Erosion, Debris Flows, and Environment in Mountain Regions, IAHS Publication, vol. 209. International Association of Hydrological Sciences, Christchurch, New Zealand.

Dillon, G.D., Grogger, P.K., 1982. Mudflows of Mt. Princeton/Chalk Creek, Chaffee County, Colorado. Geological Society of America Abstracts with Programs 14 (6), 309.

Elrick, D.E., Reynolds, W.D., 1992. Methods for analyzing constant-head well permeameter data. Soil Science Society of America Journal 56, 320–323.

Emmett, W.W., 1978. Overland flow. In: Kirkby, M.J. (Ed.), Hillslope Hydrology. John Wiley, Chichester, U.K., pp. 145–176.

Emslie, M.A., 1991. Structural fabrics and hydrothermal alterations along the west flank of the Rio Grande Rift at Chalk Cliffs, central Sawatch Range, central Colorado. Colorado School of Mines, Masters Thesis T-4008, Golden, Colorado, pp. 67.

Fredlund, D.G., Morgenstern, N.R., Widger, R.A., 1978. Shear strength of unsaturated soils. Canadian Geotechnical Journal 15, 313–321.

Fryxell, F.M., Horberg, L., 1943. Alpine mudflows in Grand Teton National Park, Wyoming. Geological Society of America Bulletin 54, 457–472.

Gabet, E.J., 2003. Sediment transport by dry ravel. Journal of Geophysical Research 108 (B1), 2049. doi:10.1029/2001JB001686.

Garbrecht, J., Martz, L.W., 1997. The assignment of drainage directions over flat surfaces in raster digital elevation models. Journal of Hydrology 193, 204–213.

Glancy, P.A., Bell, J.W., 2000. Landslide-induced flooding at Ophir Creek, Washoe County, western Nevada, May 30, 1983. U.S. Geological Survey Professional, Paper 1617. Reston, Virginia, p. 94.

Godt, J.A., Coe, J.A., 2007. Alpine debris flows triggered by a 28 July 1999 thunderstorm in the central Front Range, Colorado. Geomorphology 84, 80–97. doi:10.1016/j.geomorph.2006.07.009.

Griffiths, P.G., Webb, R.H., Melis, T.S., 2004. Frequency and initiation of debris flows in Grand Canyon, Arizona. Journal of Geophysical Research 109, F04002. doi:10.1029/2003JF000077.

Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis, Part 4, Physical Methods. Soil Science Society of America, Madison, Wisconsin, pp. 201–228.

Grossmann, R.B., Harms, D.S., Kingsbury, D.F., Shaw, R.K., Jenkins, A.B., 2001. Assessment of soil organic carbon using the U.S. soil survey. In: Lal, et al. (Ed.), Assessment Methods for Soil Organic Carbon. Lewis Publishers, Boca Raton, Florida, pp. 87–104.

Huang, C., Gascuel-Odoux, C., Cros-Cayot, S., 2001. Hillslope topographic and hydrologic effects on overland flow and erosion. Catena 46, 177–188.

Hungr, O., McDougall, S., Bovis, M., 2005. Entrainment of material by debris flows. In: Jakob, M., Hungr, O. (Eds.), Debris-flow Hazards and Related Phenomena. Springer, Berlin Heidelberg, pp. 135–158.

Hürlimann, M., Rickenmann, D., Graf, C., 2003. Field and monitoring data of debris-flow events in the Swiss Alps. Canadian Geotechnical Journal 40, 161–175.

Iverson, R.M., Reid, M.E., LaHusen, R.G., 1997. Debris-flow mobilization from landslides. Annual Review of Earth and Planetary Sciences 25, 85–138.

Iverson, R.M., Reid, M.E., Iverson, N.R., LaHusen, R.G., Logan, M., Mann, J.E., Brien, D.L., 2000. Acute sensitivity of landslide rates to initial soil porosity. Science 290, 513–516.

Iverson, R.M., Logan, M., Denlinger, R.P., Lahusen, R.G., 2005. Transformation of water floods to debris flows: large-scale experiments. Geological Society of America Abstracts with Programs 37 (7), 35.

Jenson, S.K., Domingue, J.O., 1988. Extracting topographic structure from digital elevation data for geographic-information system analysis. Photogrammetric Engineering and Remote Sensing 54 (11), 1593–1600.

Jochim, C.L., 1986. Debris-flow hazard in the immediate vicinity of Ouray, Colorado. Colorado Geological Survey Special Publication 30, 63.

Johnson, A.M., Rodine, J.R., 1984. Debris flow. In: Brunsden, D., Prior, D.B. (Eds.), Slope Instability. John Wiley and Sons, Ltd., Chichester, UK, pp. 257–361.

Kelley, S.A., 1991. Constraints on the timing and magnitude of a mid-Miocene hydrothermal event in the Mt. Princeton batholith, Colorado. Geological Society of America Abstracts with Programs 23, 38.

Kinner, D.A., Stallard, R.F., 2004. Identifying storm flow pathways in a rainforest catchment using hydrological and geochemical modeling. Hydrological Processes 18, 2851–2875.

Larsen, I.J., Pederson, J.L., Schmidt, J.C., 2006. Geologic versus wildfire controls on hillslope processes and debris flow initiation in the Green River canyons of Dinosaur National Monument. Geomorphology 81, 114–127.

Matsushi, Y., Matsukura, Y., 2006. Cohesion of unsaturated residual soils as a function of volumetric water content. Bulletin of Engineering Geology and Environment 65, 449–455.

Miller, M.G., 1999. Active breaching of a geometric segment boundary in the Sawatch Range normal fault, Colorado, USA. Journal of Structural Geology 21, 769–776.

Moody, J.A., Martin, D.A., 2001. Hydrologic and sedimentologic response of two burned watersheds in Colorado. U.S. Geological Survey Water Resources Investigation Report, vol. 01–4122. Reston, Virginia, p. 142.

Mortimer, P., 1997. Stratigraphic and rheologic analysis of debris flow deposits in Chalk Creek Canyon, Colorado. Thesis for Distinction in Geology, Colorado College, Colorado Springs, Colorado, pp. 99.

Ostenaa, D.A., Losh, S.L., Nelson, A.R., 1981. Evidence for recurrent late Quaternary faulting, Sawatch fault, upper Arkansas valley, Colorado. In: Junge, W.R. (Ed.), Colorado Tectonics, Seismicity, and Earthquake Hazards, Colorado Geological Survey Special Publication.

Pillmore, C.L., 1989. Geologic photogrammetry in the U.S. Geological Survey. Photogrammetric Engineering and Remote Sensing 55, 1185–1189.

Piñol, J., Beven, K., Freer, J., 1997. Modeling the hydrological response of catchments, Prades, Catalonia: the use of distributed models as aids to hypothesis formulation. Hydrological Processes 11, 1287–1306.

Reynolds, W.D., Elrick, D.E., 2002. Constant head well permeameter (Vadose zone). In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis: Part 4 Physical Methods. Soil Science Society of America, Madison, Wisconsin, pp. 844–858.

Reynolds, W.D., Elrick, D.E., Clothier, B.E., 1985. The constant head well permeameter: effect of unsaturated flow. Soil Science 144, 282–299.

Rickenmann, D., Weber, D., Stepanov, B., 2003. Erosion by debris flows in field and laboratory experiments. In: Rickenmann, D., Chen, C. (Eds.), Debris Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Millpress, Rotterdam, The Netherlands, pp. 883–894.

Rivix Limited Liability Company, 2001. RiverTools™ User's Guide release 2001. Research Systems, Inc., Boulder, Colorado, p. 202.

Shannon, J.R., Naeser, C.W., Dewitt, E., Wallace, A.R., 1987. Timing of Cenozoic magmatism in the Sawatch uplift and northern Rio Grande Rift, Colorado. Geological Society of America Abstracts with Programs 19, 839.

Sharp, W.N., 1970. Extensive zeolitization associated with hot springs in central Colorado. Geological Survey Research. U.S. Geological Survey Professional Paper, vol. 700-B. Reston, Virginia, pp. B14–B20.

Takahashi, T., 1991. Debris flow. IAHR Monograph. Balkema, Rotterdam, The Netherlands.

Tongnacca, C., Bezzola, G.R., 1997. Debris flow initiation by channel bed failure. In: Chen, C. (Ed.), Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Balkema, Rotterdam, The Netherlands, pp. 44–53.

Tognacca, C., Bezzola, G.R., Minor, H.E., 2000. Threshold criterion for debris-flow initiation due to channel-bed failure. In: Wieczorek, G.F., Naeser, N.D. (Eds.), Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Balkema, Rotterdam, The Netherlands, pp. 89–97.

Tweto, O., 1978. Northern rift guide 1, Denver-Alamosa, Colorado. In: Hawley, J.W. (Ed.), Guidebook to the Rio Grande Rift, New Mexico Bureau of Mines and Mineral Resources Circular, vol. 163, pp. 13–28.

VanDine, D.F., 1985. Debris flows and debris torrents in the Southern Canadian Cordillera. Canadian Geotechnical Journal 22, 44–68.

Varnes, D.J., 1978. Slope movement types and processes. In: Schuster, R. L., Krizek, R.J. (Eds.), Landslides analysis and control. Transportation Research Board Special Report, vol. 176. National Research Council, Washington, DC, pp. 11–33.

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

Zangar, C.N., 1953. Theory and problems of water percolation. Engineering Monograph, vol. 8. U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado.