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Geologic versus wildfire controls on hillslope processes and debris flow initiation in the Green River canyons of Dinosaur National Monument

Isaac J. Larsen [a,*], Joel L. Pederson [a], John C. Schmidt [b]

[a] *Department of Geology, Utah State University, Logan, UT 84322-4505, USA*
[b] *Department of Aquatic, Watershed, and Earth Resources, Utah State University, Logan, UT 84322-5210, USA*

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Abstract

As in many areas of high relief, debris flows are an important process linkage between hillslopes and the Green River in the canyons of the eastern Uinta Mountains, yet the physical conditions that lead to debris flow initiation are unknown. A recent episode of enhanced debris-flow and wildfire activity provided an opportunity to examine the geomorphic impact of fire and the processes by which weathered bedrock is transported to the Green River. Field investigations and analysis of elevation and precipitation data were undertaken in 15 catchments with recent debris flows to determine how surficial geology, wildfire, topography, bedrock strength, and meteorology influence hillslope processes. The recent debris flows were triggered by intense summer rainstorms. The dominant debris flow initiation mechanism, the firehose effect, occurred when overland flow generated on bedrock hillslopes cascaded down steep cliffs onto colluvium, causing failure. Sixty percent of the debris flows occurred in unburned catchments. However, 15% of the burned catchments in the study area produced debris flows over the study period, whereas only 7% of the unburned catchments did. Thus, fire was not the primary driver of debris flows, but fire-related events did contribute to the increased debris flow activity. The geomorphic impact of wildfire in the eastern Uinta Mountains is not as great as in transport-limited settings with regolith-mantled hillslopes. The strong rocks and dry climate of the study area cause hillslopes to be very steep and weathering-limited, with high runoff ratios and a dearth of regolith. As a result, there is little vegetation, and thus we hypothesize that burning does little to change hillslope processes. The suite of hillslope processes in the eastern Uintas are like those documented in the similarly dry Grand Canyon, but differ from other locations in the western U.S. where wildfire is a primary control on debris flow processes.

Keywords: Debris flows; Wildfire; Bedrock; Eastern Uinta Mountains; Green River

1. Introduction

Debris flows can be significant geologic hazards and an important geomorphic process in high-relief landscapes (Costa and Weiczorek, 1987). Debris flows form an important link between hillslopes and channel networks, because they transport large volumes of

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[*] Corresponding author. Current address: Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University, Fort Collins, CO 80523-1401, USA.

E-mail address: larseni@warnercnr.colostate.edu (I.J. Larsen).

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sediment from hillslopes to adjacent valleys (Webb et al., 1988; Benda, 1990; Grant and Swanson, 1995; Webb et al., 2000; Benda et al., 2003; Eaton et al., 2003). Debris flows also play a key role in shaping the morphology of the mainstem valley into which they flow, as is the case with the Green River in the canyons of the eastern Uinta Mountains in Dinosaur National Monument. There, coarse-grained debris flow deposits create fan–eddy complexes, which are the fundamental geomorphic unit of debris–fan affected canyons (Schmidt and Rubin, 1995).

Fan spacing and shape determine the locations of expansion gravel bars, eddy bars, and channel-margin deposits. Close spacing of debris fans causes steeper canyon-scale gradient (Grams and Schmidt, 1999; Larsen et al., 2004; Magirl et al., 2005). Since 1997, debris flows in 15 tributaries aggraded fans and rapids in the Green River corridor in Dinosaur National Monument (Martin, 2000; Larsen, 2003). Several of these debris flows deposited coarse sediment within the mainstem channel, altering the morphology of the Green River (Larsen et al., 2004).

Despite the importance of debris flows to channel morphology in the Colorado Plateau, the processes that initiate debris flows and thereby link hillslopes in tributary catchments with the mainstem valley of the Green River are poorly understood. No debris-flows were documented between 1993 and 1997 (Grams and Schmidt, 1999). The recent debris flow activity in Dinosaur National Monument might be linked to wildfires, because wildfires burned a total of 34 km^2 in several tributary catchments of the Green River in 1996 and 2001.

Fires are either viewed as a significant contributor to debris-flow generation or as an insignificant factor in the Intermountain West. For example, fires are a significant factor in debris-flow initiation in the Yellowstone region and west-central Colorado because fires remove protective organic litter from soil-mantled hillslopes and increase overland flow production during rainfall events (Meyer and Wells, 1997; Cannon et al., 2001b). In contrast, fires do not contribute to debris-flow activity in the Grand Canyon region. Rather, high intensity rainfall on steep, rocky hillslopes generates infiltration-excess overland flow that leads to colluvium failure and debris flows (Griffiths et al., 2004).

The recent debris-flow and wildfire activity in the eastern Uinta Mountains, located at the interface between the Colorado Plateau and the Rocky Mountains, provides an opportunity to examine the physical factors that lead to debris-flow generation and to assess the geomorphic significance of wildfires. Here, we describe process linkages among bedrock strength, topography, colluvium storage, and debris-flow initiation and we describe the influence of wildfire on hillslope processes in this steep, weathering-limited environment.

2. Debris flow initiation processes

Debris flows are a type of granular mass flow whose motion is governed by changes in Coulomb friction and internal pore-fluid pressure (Iverson, 1997). Debris-flow initiation can occur from failure of bedrock, colluvium, or alluvium (Costa, 1984). The specific physical conditions that trigger debris flows vary greatly, because debris flows occur in diverse physiographic and climatic environments.

Rock strength influences debris flow activity because it imparts a control on both the susceptibility of bedrock slope failure and the local production rate of colluvium (Wohl and Pearthree, 1991; Schmidt and Montgomery, 1996; Coe et al., 1997; Bovis and Jakob, 1999). Landscape steepness and the extent to which colluvium covers bedrock on hillslopes influence the regional susceptibility of debris flows. However, measurements that relate bedrock strength and colluvium cover to debris-flow generation are relatively few.

Debris flows most commonly mobilize from landslides, which occur when rainfall elevates pore pressure and adds weight to the hillslope, causing failure (Varnes, 1978; Caine, 1980; Wieczorek, 1987). However, streamflow falling onto colluvium can also trigger debris flows through a process called “the firehose effect” (Johnson and Rodine, 1984). The firehose effect commonly occurs in ephemeral channels in cliff-and-bench topography where colluvium accumulates below cliff bands. High intensity rainfall leads to floods (Fryxell and Horberg, 1943; Berti et al., 1999; Griffiths et al., 2004) that pour over cliffs or bedrock steps directly onto colluvium, which fails and mixes with the water to form a debris flow (Griffiths et al., 2004). Although rainfall is an important precursor to debris flow initiation whether mobilization occurs from saturated landslides or the firehose effect, the intensity and duration of the rainfall events that trigger debris flows are difficult to determine in dry environments (Griffiths et al., 1997; Ben David-Novak et al., 2004).

Fires decrease infiltration, increase overland flow rates, and lower the threshold of entrainment of sediment from hillslopes (e.g., Swanson, 1981; Wondzell and King, 2003; Moody et al., 2005). These conditions increase watershed susceptibility to debris flows, especially via the process of progressive sediment bulking (Parrett, 1987; Wohl and Pearthree, 1991; Meyer and Wells, 1997; Cannon and Reneau, 2000; Cannon et al., 2001a,b; Meyer et al., 2001). In this case, increased overland flow causes extensive rill and gully erosion on burned hillslopes. The overland flow entrains and transports large concentrations of sediment into the drainage network and scours channels. A debris flow forms when sufficient eroded material is entrained relative to the volume of water (Meyer and Wells, 1997; Cannon et al., 2001b). Our goal is to assess the relative importance of these geologic, hydrologic, and wildfire controls on debris flow initiation in the steep, dry canyons of the eastern Uinta Mountains.

3. Study site

The Green River flows across the eastern Uinta Mountains, forming three spectacular canyons: Canyon of Lodore (hereafter referred to as Lodore Canyon), Whirlpool Canyon, and Split Mountain Canyon (Fig. 1). In the high-relief topography adjacent to the river, tributary headwaters occur near the elevation of the canyon rim and drain to the Green River in steep ephemeral channels that fall hundreds of meters to the canyon floor (Fig. 2).

The Green River flows southward, roughly perpendicular to the axis of the east–west trending anticline of the Uinta Mountains (Hansen, 1986). The anticlinal structure, along with local faulting, causes the elevation of bedrock units to vary. The Neoproterozoic Uinta Mountain Group orthoquartzite forms the canyon walls in the northern part of Lodore Canyon. The base of the lowest exposed Paleozoic sedimentary bedrock occurs at the top of the canyon walls in the central part of Lodore Canyon. Paleozoic bedrock (including the cliff-forming Madison limestone, Upper Morgan Formation, and Weber sandstone), as well as slope-forming shales of the Lower Morgan Formation, occur at progressively lower elevation on the canyon walls in the southern part of Lodore Canyon. Near the end of Lodore Canyon, the

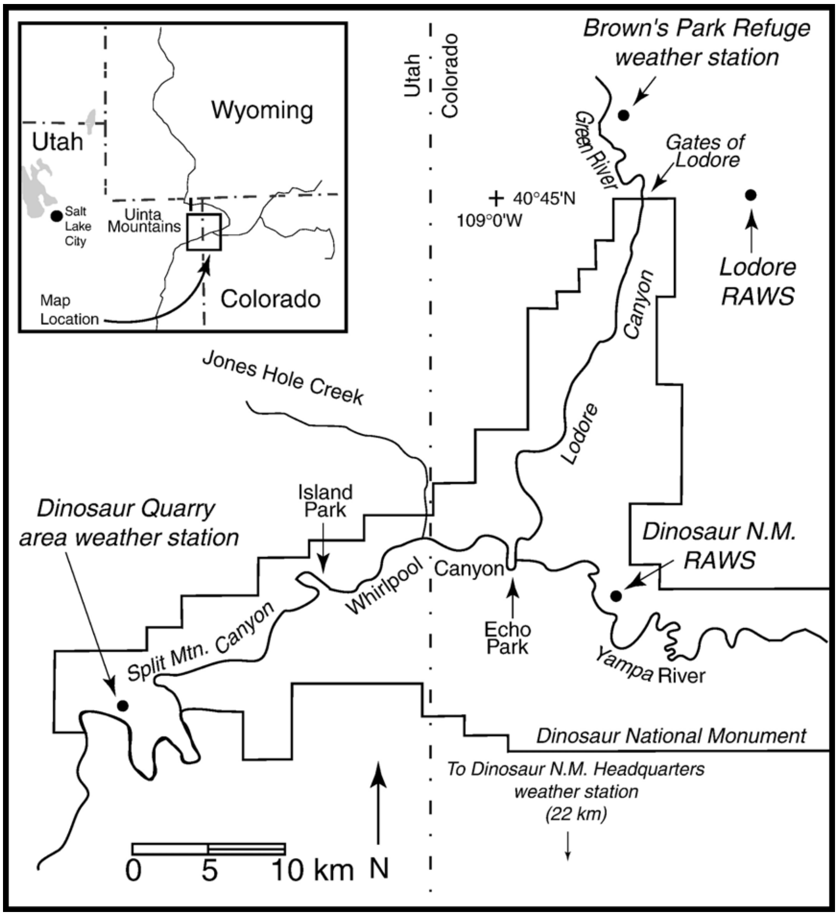

Fig. 1. Map of Dinosaur National Monument and nearby meteorological stations.

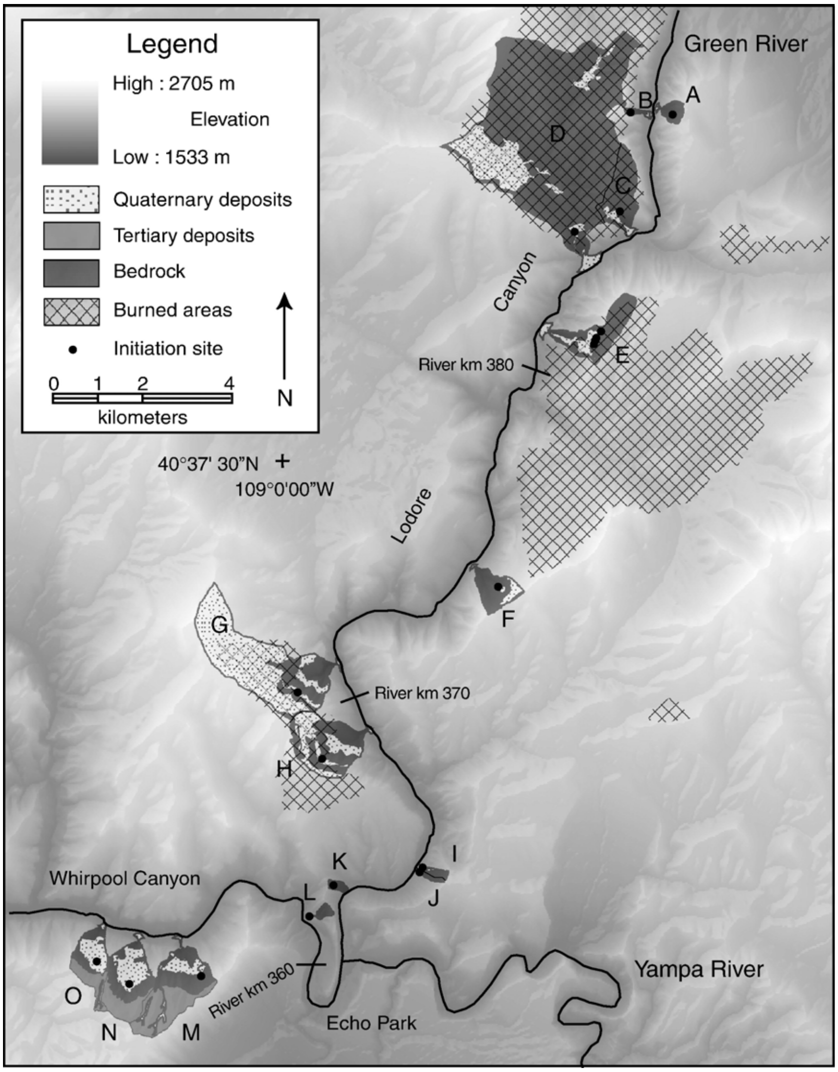

Fig. 2. Simplified surficial geology of study catchments in Lodore and Whirlpool Canyons based on mapping completed during this study. Hatched lines show the areas that burned in 1996 and 2001. The letters adjacent to each catchment correspond to data in Table 1.

canyon walls are locally composed of vertically bedded Paleozoic bedrock resulting from deformation associated with the Laramide Mitten Park Fault. The southern end of Lodore Canyon occurs where the Yampa River joins the Green River in Echo Park. Further downstream is Whirlpool Canyon (Fig. 2), where the same Paleozoic rocks occur in tributary catchments. Bedrock structure controls drainage patterns in the area, and nearly all major tributaries and many of the smaller drainages are subsequent to these structures (Grams and Schmidt, 1999).

The semiarid climate of the eastern Uinta Mountains supports a pinyon-juniper (*Pinus edulis–Juniperus osteosperma*) woodland. Organic litter accumulates directly beneath tree canopies, but intercanopy spaces are characterized by a sparse undergrowth of grasses. Mean annual precipitation ranges from 21 to 30 cm, 35% of which occurs between June and September. Summer rainfall is greatest on the southern and eastern flanks of the mountain range and is related to relatively moist monsoonal air masses that move northward and orographically rise over the Uinta Mountains (Harper et al., 1981).

4. Methods

Field investigations took place in the 15 catchments that experienced recent debris-flow activity (Fig. 2). Surficial geology and bedrock were mapped at 1:12,000 scale in each study catchment and digitized into a geographic information system (GIS). Debris-flow initiation sites were identified by field inspection or by locating the sites from distant vantage points where steep topography made foot access impossible. In both cases, each debris-flow initiation site was located on 1:12,000 scale aerial photographs and digitized into a GIS. The initiation sites were identified between one month and five years after the debris flows occurred.

Based on field evidence, the debris flow initiation process was assigned to one of three categories: i) the firehose effect, ii) shallow landsliding, or iii) progressive sediment bulking. Field evidence for firehose-effect debris-flow generation included evidence of streamflow upstream from the cliff band or bedrock step and evidence for a debris flow that initiated in colluvium immediately below. Initiation sites were marked by freshly scoured, or failed, colluvium located within or near an ephemeral channel, and levees and mudlines on scoured gully walls extended downstream from colluvium failure points. Upstream from the cliff bands, evidence for streamflow included the presence of well-sorted deposits and lack of mudlines or significant scour. Field evidence for shallow landslide initiation of debris flows included tension cracks in colluvium, steep, planar failure surfaces, and exposed, underlying bedrock. Evidence for progressive sediment bulking included the presence of rills on lower hillslopes, increasing channel scour in the downstream direction, and the presence of debris-flow levees further downstream. At sites where progressive sediment bulking triggered debris flows, the initiation site was mapped at the point where levees first appeared. Field topographic surveys of the debris fan at the outlet of each watershed were the basis for estimating the volume of each recent debris-flow deposit, similar to methods of Webb et al. (1999). The volume estimates are considered minimum values; some deposits were subsequently eroded by the Green River and deposition sometimes occurred upstream from the watershed outlet.

Burn severity in the areas burned by wildfire in 2001 was classified based on the degree of organic litter combustion and alteration in the color of mineral soil, following the criteria of Wells et al. (1979). Because these criteria are difficult to apply several years following wildfire, the degree of tree mortality was used to categorize burn severity in the areas that burned in 1996.

Soil–water repellency is often cited as a cause of increased overland flow following fires (e.g., DeBano, 2000; Letey, 2001), and we evaluated its likelihood in the study area. Soil–water repellency was measured using the critical surface tension method to determine if soils were likely to become water-repellent following burning (Watson and Letey, 1970; Huffman et al., 2001). The measurements were made within one month of a summer 2002 wildfire that burned 19 km^2 in Dinosaur National Monument, most of which drains to the Yampa River. Soil–water repellency could not be evaluated for older fires, because the strength of water repellency can decrease dramatically within one year of burning (MacDonald and Huffman, 2004).

Slope, area, and elevation data collected from a 30-m digital elevation model (DEM) were used to calculate mean catchment slope, the slope of each initiation site, the topographic contributing area upstream from each initiation site, and catchment hypsometric integrals. We used a chi-square test to determine if there was a significant difference in the frequency of debris flows from burned versus unburned catchments.

Rock-mass strength was evaluated for nonshale bedrock units using semiquantitative methods similar to those of Selby (1980). Rock elastic rebound for each bedrock unit was measured at ≥ 50 points with a Schmidt Hammer. Schmidt Hammer data were combined with observations and measurements of weathering and joint characteristics to categorize the strength of each bedrock unit. Values of shale strength were estimated from published values (Selby, 1980).

Twenty-five samples of shale, colluvium, and recent debris-flow material were collected for clay mineral analysis to determine if there was a link between the spatial distribution of clay-bearing strata and recent debris-flows (Larsen, 2003). Samples of oriented clays were glycolated and X-rayed to identify clay minerals (Moore and Reynolds, 1997). The X-ray patterns were modeled to quantify the relative percentages of illite, kaolinite, and smectite in each sample using the NEWMOD software (Reynolds and Reynolds, 1995), with an accuracy of ±5% (Moore and Reynolds, 1997). The proportion of sand, silt, and clay in each sample was determined by the hydrometer method (Gee and Bauder, 1986).

Eyewitness accounts provided data concerning the timing of some debris-flow events, but many of the debris flows were first discovered several days after they occurred. Thus, the precision of the estimated date of debris flow occurrence is between 1 and 7 days. In the instances where there is poor precision, the timing of debris-flow activity was estimated from rainfall records from nearby gages. Daily precipitation records from three weather stations surrounding the field area (NCDC, 2003) were used to determine daily rainfall totals for all debris flow-events (Fig. 1). Hourly precipitation data collected at two Remote Automated

Weather Stations (RAWS) were used to calculate maximum 1-h rainfall (e.g., 12:00–13:00) for each debris flow-producing storm (WRCC, 2003). The 24- and 1-h rainfall totals were compared with a precipitation atlas (Miller et al., 1973) to determine the recurrence interval of each debris flow-producing rainfall event. Summer, defined here as June–September, rainfall totals for 1993–2002 were compared with historic mean rainfall to investigate whether debris flow activity was related to seasonal rainfall.

5. Results

5.1. Surficial geology

Detailed mapping in the catchments with recent debris flows indicates that the proportion of bedrock (or bedrock with thin, discontinuous colluvium) ranges from 19% to nearly 100%, but is generally between 50% and 80% (Fig. 2, Table 1). The hillslopes are thus weathering-limited in terms of sediment supply, like hillslopes in many dry environments (e.g., Yair and Enzel, 1987; Pederson et al., 2001). Colluvium derived from rockfall and other mass-wasting processes occurs at the base of cliffs throughout Lodore and Whirlpool Canyons, and several fresh scars on bedrock were indicative of recent rockfall activity (Larsen, 2003). Colluvium also occurs on bedrock ledges within the cliff and bench topography of the canyons and, at a smaller scale, within bedrock hollows located in the axes of steep drainages. Shales typically form lower-angle slopes that are the storage location of colluvial wedge deposits that may be as much as 3 m thick.

5.2. Initiation of debris flows

Eleven of the 15 debris flows that reached the Green River between 1997 and 2002 occurred in Lodore Canyon and four debris flows occurred in Whirlpool Canyon (Fig. 2). Twelve of the 15 recent debris flows initiated via the firehose effect. Two debris flows were initiated from shallow landsliding within burned areas and one was initiated from sediment bulking on an unburned hillslope.

Debris flows that initiated via the firehose effect began when overland flow generated in the catchment headwaters cascaded down steep channels or over cliffs onto colluvium stored in hollows and on bedrock benches (Fig. 3). The colluvium failed, initiating debris flows that continued down-channel (Fig. 3). Failure

Table 1
Characteristics of the catchments with recent debris flows

River kilometer[a]	Date of debris flow	Catchment area[b] (km^2)	Contributing area above initiation site[b] (km^2)	Slope of initiation site (m m^{-1})	Year burned	Area burned (%)	Bedrock area (%)	Mean catchment slope[c] (m m^{-1})	Hypsometric integral[d]	Deposit volume (m^3)
385.0-A	8/15/2001	0.25	0.04	1.1	Unburned	–	92	0.8	0.74	25
384.8-B	8/15/2001	0.11	0.01	2.7	2001	55	79	1.0	0.56	240
381.8-C	8/15/2001	0.74	0.14	1.2	2001	92	90	0.6	0.63	875[e]
380.6-D	8/15/2001	10.71	10.2	0.5	2001	99	84	0.4	0.59	770
378.7-E	9/19/1997	0.88	0.26, 0.01, 0.16, 0.16[f]	1.0, 1.0, 1.2, 1.2[f]	1996	74	77	0.5	0.69	37.5
373.0-F	9/19/1997	0.27	0.02	0.7	Unburned	–	79	0.8	0.62	30
368.6-G	6/17/1998	2.48	0.07	1.0	1996	55	19	0.4	0.70	7.5
367.0-H	9/19/1997	0.95	0.09	0.5	1996	63	48	0.6	0.60	2100
363.5-I	8/15/2001	0.09	0.01	1.0	Unburned	–	69	0.6	0.57	24
363.5-J	8/15/2001	0.04	0.01	0.8	Unburned	–	86	0.6	0.56	10
362.1-K	7/25/2002	0.03	0.003	0.5	Unburned	–	94	0.5	0.58	54
356.8-L	7/25/2002	0.01	0.01	0.6	Unburned	–	100	0.5	0.65	18
353.1-M	7/30/1999	1.51	0.04	0.7	Unburned	–	81[g]	0.4	0.78	150
352.3-N	7/30/1999	1.13	0.10	0.6	Unburned	–	62[g]	0.6	0.67	4300[e]
351.5-0	7/30/1999	0.98	0.07	0.6	Unburned	–	56[g]	0.5	0.71	30

[a] River kilometers measured from the confluence of the Green and Colorado Rivers, distances increase upstream, letters match locations in Fig. 2.

[b] Calculated with D-infinity algorithm (Tarboton, 1997).

[c] The average slope of all of the DEM grid cells within the catchment.

[d] The hyposometric integral is the area beneath the curve in a plot of normalized catchment elevation versus normalized catchment area (Strahler, 1952).

[e] Volume includes only deposits in the Green River; excludes large deposits on fan surface.

[f] There are four separate initiation sites in the river kilometer 378.7 catchment.

[g] One-third to one-half of which is Tertiary Brown's Park Formation.

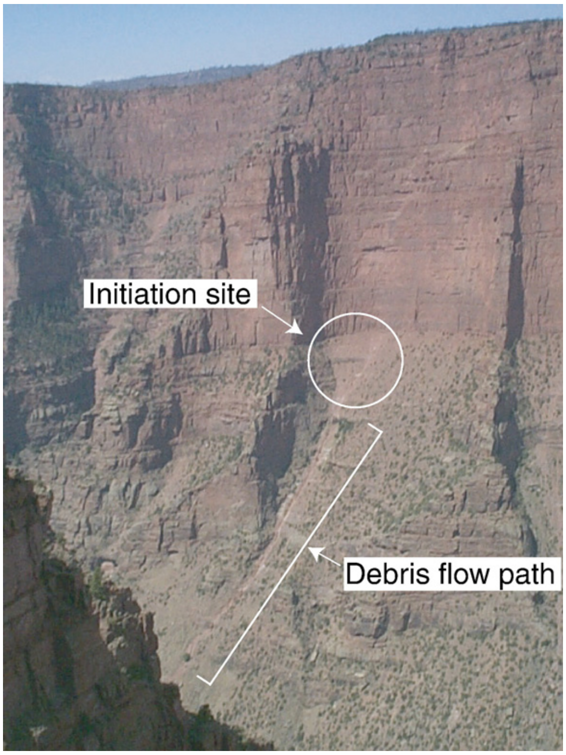

Fig. 3. The debris flow initiation site located at river kilometer 384.8 in Lodore Canyon. The debris flow initiated when overland flow generated on dominantly bedrock slopes at the canyon rim cascaded down a cliff onto colluvium. The debris flow continued downslope where it scoured colluvium from downslope storage areas and deposited 240 m^3 of material on a debris fan. Fifty-five percent of the watershed burned in 2001. The area where colluvium failed is circled.

volumes were not surveyed, but measured deposit volumes were typically greater than the visual estimates of colluvium failure volumes. This indicates that debris flows increased in volume after failure by entraining downstream colluvium.

Exceptions to the firehose effect mechanism were observed in three study catchments. Debris flows initiated from shallow landsliding in two catchments in Lodore Canyon, at river kilometers 367.0 and 368.6 (Fig. 2). Shallow landslides completely removed 1–2 m of colluvium from the hillslopes, exposing underlying shale. Isolated blocks of intact colluvium on the failure plane and tension cracks in upslope colluvium suggest the landslides were translational in nature. The debris flows in these two catchments likely initiated when storms wetted the colluvium, causing blocks of landslide material to slide off the shale slope and over steep cliffs where they mobilized into debris flows. This area burned at moderate severity in 1996. However, the presence of springs, trees with trunks that bend to accommodate sliding, rotated colluvial blocks, and hummocky topography within the burned area and in adjacent unburned portions of the catchments indicate that landslide activity began prior to the recent fires (Larsen, 2003). The recent debris flows were triggered by failure of material located within the toes of these much larger, pre-existing landslides.

A third initiation type occurred at river kilometer 356.8 (Fig. 2) where infiltration-excess overland flow led to rill and gully erosion on an unburned hillslope, resulting in debris flow generation via sediment bulking. The hillslope at river kilometer 356.8 is adjacent to the Mitten Park Fault and is composed of vertically dipping Lower Morgan Formation shale, with a few limestone beds that are <0.5 m thick. Infiltration-excess overland flow on bare, unburned shale slopes led to rill erosion in the catchment headwaters and gully erosion of regolith where overland flow was confined by resistant limestone beds in the downstream portion of the catchment. Levees were first present ~ 30 m downstream from the drainage divide, indicating debris flow passage from high in the watershed.

5.3. Topographic and bedrock characteristics

The study catchments, like all tributary catchments in Lodore and Whirlpool Canyons, are very steep, with mean catchment slopes between 0.4 and 1.0 m m^{-1} (Table 1). Tributary catchments have a large proportion of their area at high elevations above the canyon rim (Table 1, Fig. 4). Below the canyon rim, slopes and tributary channels drop steeply to the Green River (Fig. 4). Debris flow initiation sites are located within the steep portion of the watershed below the canyon rim, where local slopes at initiation sites range from 0.5 to 1.2 m m^{-1}. There is not an inverse relationship between slope and drainage area at the failure-initiation points in this landscape (Fig. 5). This differs from landscapes with soil or regolith-mantled hillslopes, where the local slope at channel heads or debris-flow initiation sites decreases with increasing contributing area (e.g., Montgomery and Dietrich, 1988; Cannon et al., 2001b). In fact, slope remains fairly constant with increasing contributing area, suggesting that slope alone (and not contributing area) is a key physiographic threshold variable for debris-flow initiation (Fig. 5).

Rock mass strength measurements show that the cliff-forming bedrock units, regardless of being limestone or sandstone, are uniformly strong throughout the study area. Mean Schmidt Hammer R values for the cliff-forming bedrock units ranges from 50 to 63, and they have similar weathering and jointing characteristics

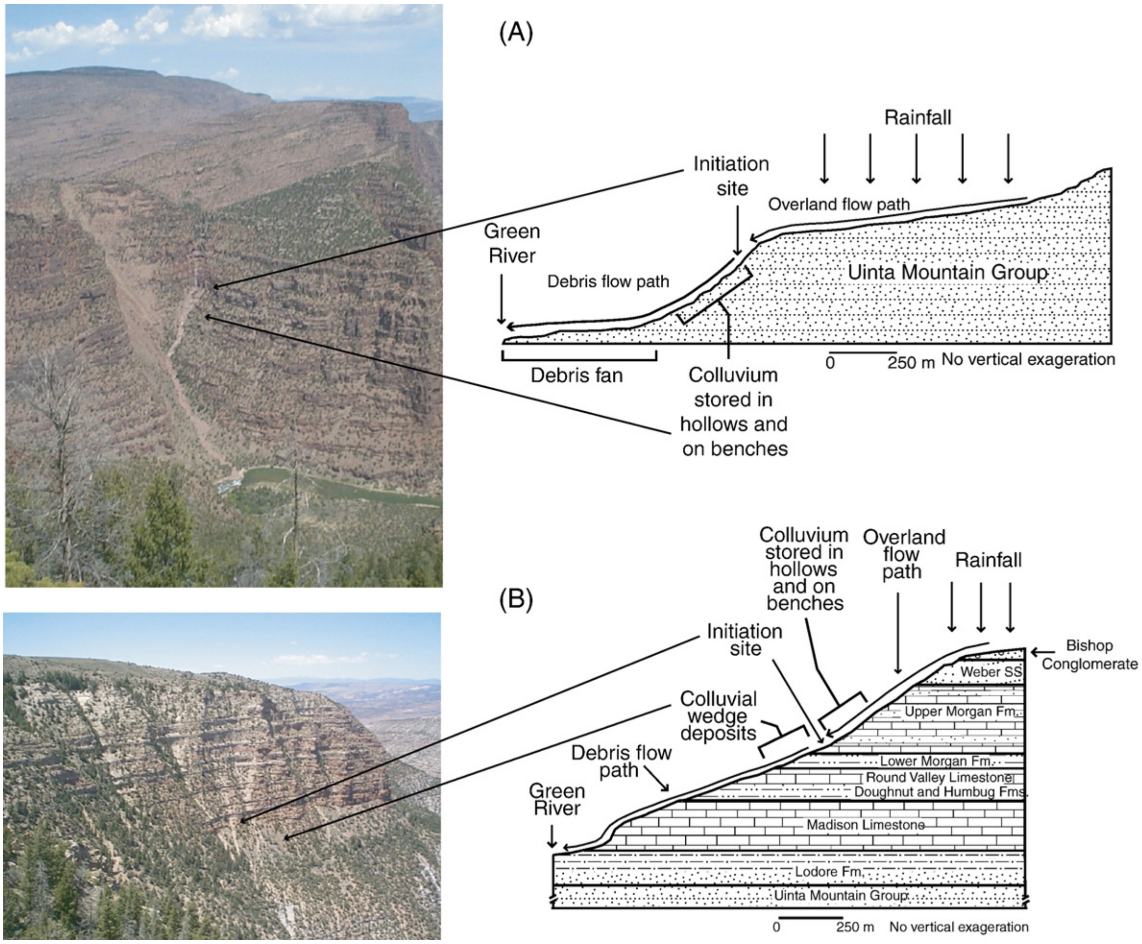

Fig. 4. (A) Catchment at river kilometer 381.8 in Lodore Canyon showing the locations of runoff generation, colluvium storage, and debris-flow initiation that are representative of catchments underlain by the Uinta Mountain Group. Approximately 92% of the watershed burned in 2001. Overland flow generated on bedrock slopes of the high elevation, upper catchment cascaded down a cliff onto colluvium stored on a bedrock bench. The colluvium failed, initiating a debris flow that increased in volume as it scoured colluvium from down-slope deposits. Approximately 875 m^3 of material was deposited in the Green River, forming a new rapid. (B) Catchment at river kilometer 352.3 in Whirlpool Canyon showing typical characteristics of catchments underlain by Paleozoic bedrock. The catchment was not burned. The debris flow initiated when overland flow generated on shallow regolith and bedrock slopes poured down cliffs formed by the Weber sandstone and Upper Morgan Formations. Field observations indicate that the overland flow poured over a 10-m bedrock step onto colluvium stored in a bedrock hollow at the base of the Upper Morgan Formation, causing failure. The debris flow increased in volume as it scoured bed and bank material from a gully incised in colluvium deposited on the lower-angle shale slopes of the Lower Morgan Formation before reaching the debris fan and Green River.

and are categorized as "strong" in the Selby (1980) classification system (Table 2). Schmidt Hammer measurements could not be obtained for slope-forming shales, but 'R' values for incompetent rocks generally range from 10 to 40 (Selby, 1980). The low strength and the fissility of the shales place them in the "weak" category (Table 2). The predominance of hard bedrock in the study catchments clearly has an influence on topography as well as sediment generation and transport.

The presence of specific clay minerals has been linked to debris flow activity in Grand Canyon. There, abundant kaolinite and illite derived from terrestrial shales is considered to be an important contributor to debris flow mobility and long travel distances (Griffiths et al., 1996). In our study sites, the clay-sized fraction of colluvium and recent debris-flow deposits ranges from 7% to 23%. Together, illite and kaolinite comprised nearly 100% of the three clay minerals we analyzed; only two samples contained trace amounts of smectite (Larsen, 2003). Surficial deposits derived from weathering of the Uinta Mountain Group contain predominantly kaolinite, whereas illite is more abundant in surficial deposits derived from Paleozoic rocks.

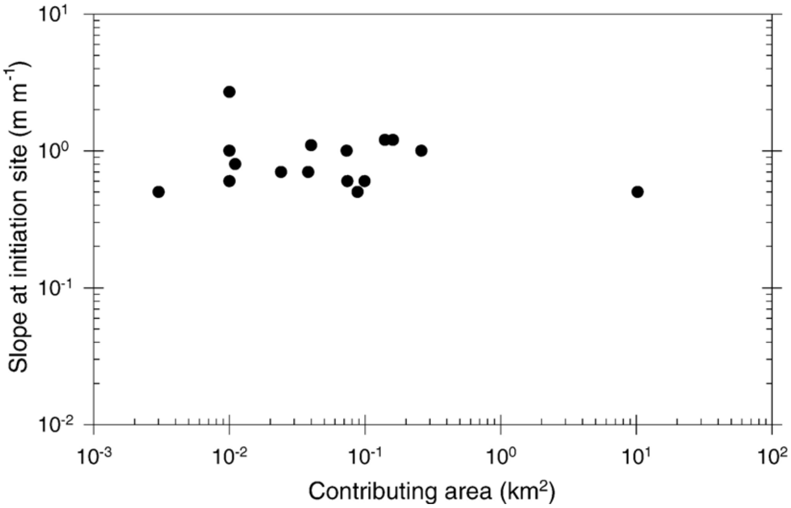

Fig. 5. Slope versus contributing area for initiation sites of study debris flows. Initiation site slope changes little with increasing contributing area, contrary to the inverse slope–area relation observed in regolith-mantled landscapes. This implies that slope specifically is the stronger physiographic factor for debris-flow initiation.

5.4. Precipitation

Debris flows were triggered when daily rainfall between 0 and 23 mm was measured at the nearest weather station. These common rainfall events are all smaller than the 28 mm, 2-year recurrence storm. Hourly rainfall at the nearest RAWS stations ranged between 1 and 11 mm, which was also less than the 15 mm, 2-h recurrence event. However, study catchments are no closer than 5 km to the weather stations, and rainfall associated with the small-scale convective storms that the triggered recent debris flows was probably poorly represented by these distant gages.

Analysis of summer precipitation indicates that the frequency of debris flows is not related to seasonal precipitation (Fig. 6). However, record high precipitation occurred in some months when debris flows occurred. Record high precipitation was recorded at the Dinosaur Quarry area and Dinosaur National Monument Headquarters weather stations in September 1997, while near-record rainfall occurred at the Brown's Park Refuge weather station (Fig. 6). Rainfall associated

Table 2
Schmidt Hammer *R* values, joint characteristics, weathering characteristics, and calculated rock-mass strength for bedrock in Lodore and Whirlpool Canyons[a]

Parameter	Uinta Mountain Group	Lodore Fm.	Madison limestone	Lower Morgan Fm.	Upper Morgan Fm.	Weber sandstone
Lithology	Orthoquartzite	Sandstone	Limestone	Shale[b]	Sandstone, limestone	Sandstone
Mean Schmidt Hammer R	62=20	50=18	63=20	*5–10*	59=18	52=18
Weathering	Slight=9	Slight–moderate=8	Slight=9	Moderate=7	Slight=9	Slight–moderate=8
Mean joint spacing	27 cm=17	17 cm=15	26 cm=17	0.2 cm=2	15 cm=14	15 cm=14
Joint orientation	Fair=14	Favorable to Fair=16	Fair=14	Fair=14	Fair=14	Fair=14
Width of joints	1–5 mm=5	0.1–1 mm=6	0.1–1 mm=6	0.1–1 mm=6	0.1–1 mm=6	1–5 mm=5
Continuity of joints	Continuous–no infill=5	Continuous–no infill=5	Few continuous=6	Continuous–no infill=5	Continuous–no infill=5	Few continuous=6
Outflow of groundwater	None=6	None=6	None=6	None=6	None=6	None=6
Total rating	76=strong	74=strong	78=strong	45–50=weak	72=strong	71=strong

[a] Ranking from Selby (1980).

[b] Shale strength values from Selby (1980).

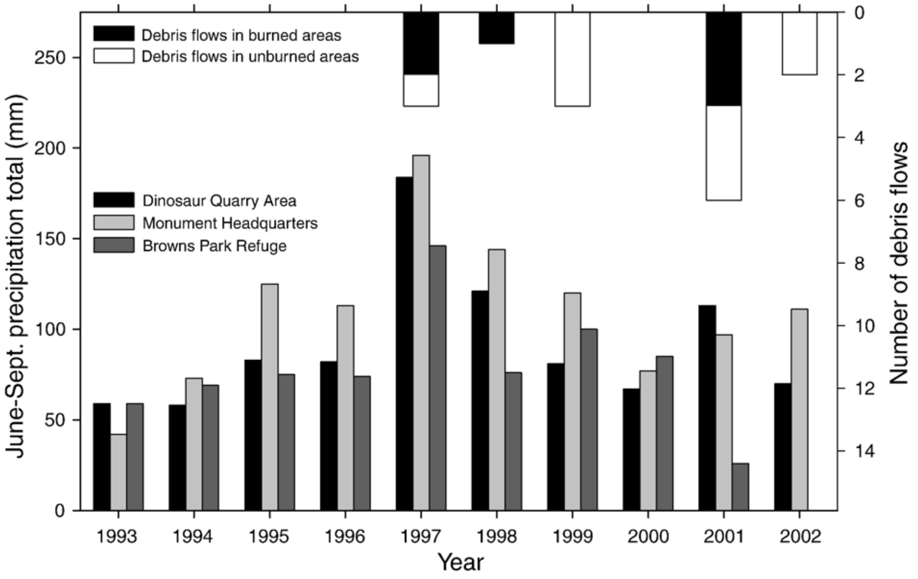

Fig. 6. Annual summer rainfall and the number of debris flows from 1993 to 2002 for Lodore and Whirlpool Canyons. Mean June–September precipitation for the three weather stations is 60–110 mm. Record monthly precipitation occurred at the Dinosaur Quarry Area station in August and September 1997 and July 2001. Record and near-record monthly precipitation was measured for September 1997 at the Dinosaur National Monument Headquarters and Brown's Park Refuge stations, respectively. Wildfires occurred in 1996 and 2001.

with this September storm triggered three debris flows (Table 1). However, other years with debris flows had near-to-below average summer precipitation (Fig. 6).

5.5. Hillslope response to wildfire

The six study catchments that burned in 1996 and 2001 did so at high and moderate severities. Four of the catchments burned at high severity, resulting in nearly complete tree mortality and consumption of organic litter. Two study catchments burned at moderate severity, with only ~50% tree mortality. These two catchments are located in Lodore Canyon at river kilometer 368.6 and 367.0 where the debris flows initiated from shallow landsliding.

Thirty-nine of the 171 significant tributaries in Lodore and Whirlpool Canyons were partially or entirely burned and six (~15%) of those produced debris flows. Nine debris flows (~7%) occurred in the other 132 unburned catchments. The difference in the frequency of debris flows from burned and unburned catchments was not statistically significant (chi-square = 2.76, $p = 0.097$). However, when more than half of the catchment area burned, a debris flow generally occurred (Fig. 2). In regolith-mantled areas that burned, the absence of rill and gully systems on hillslopes suggests post-fire sediment bulking was not the mechanism that generated the debris flows. Debris flows in burned and unburned catchments initiated by the firehose effect.

The higher proportion of debris flows from burned catchments cannot be attributed to increased runoff caused by soil water repellency. Soil water repellency was not detected in the Yampa River tributaries that burned at high severity during 2002 (Larsen, 2003). Additionally, no debris flows reached the Yampa River following the 2002 wildfire.

6. Discussion

6.1. Geologic controls on hillslope processes

Debris-flows in the eastern Uinta Mountains occur primarily from factors associated with the geology and topography of the landscape, whereas wildfires play a secondary role. Hillslopes in tributary catchments have a high proportion of exposed bedrock and lack continuous colluvium (Figs. 3 and 4). The exposed bedrock leads to high runoff ratios and streamflow generation in ephemeral gullies that then pours over cliffs onto colluvium, leading to failure and debris flows.

The steep topography of tributary catchments is a function of the strong bedrock that is present throughout the canyons. The topography, in turn, is an important control on sediment transport processes. The slopes of debris-flow initiation sites are all >0.5 m m^{-1}, but contributing areas vary considerably, as is evident in the lack of an inverse slope–area relation for debris flow initiation (Fig. 5). An inverse slope–area relation does not exist because debris flows initiate in the steepest portion of the tributaries, between the canyon rim and valley floor. The contributing area above the canyon rim varies considerably among tributaries, and likely needs to only exceed a threshold value in order to produce sufficient runoff to trigger a debris-flow. Among the study catchments, there is no threshold of drainage area size where the dominant sediment transport process changes from debris flow to stream flow, as has been observed in the Yellowstone region (Meyer and Wells, 1997).

The canyons of the Colorado Plateau have similar geologic, topographic, and climatic characteristics, and debris-flow initiation via the firehose effect may be a ubiquitous process throughout the Plateau. Debris-flow processes in the eastern Uinta Mountains are similar to those in Grand Canyon, where the firehose effect is also the dominant debris flow initiation mechanism (Griffiths et al., 2004). Dinosaur National Monument has strong bedrock that forms cliffs and weak shales that form slopes where colluvium is stored, similar to Grand Canyon. Nearly all the recent debris flows in Dinosaur National Monument initiated from colluvium failure, similar to Grand Canyon where 78% of debris flows initiate from colluvium (Griffiths et al., 2004). The rainfall conditions in the eastern Uinta Mountains also mimic those from Grand Canyon, where debris flow occurrence is not related to seasonal precipitation and most debris flows are triggered by localized summer thunderstorms that effect only a few catchments (Webb et al., 2000).

Debris flows that reach the Colorado River in Grand Canyon most frequently initiate from distinct geologic formations characterized by shales (Griffiths et al., 2004). In contrast, debris flows that reach the Green River in Lodore Canyon commonly initiate in catchments with little or no shale, though gradual slopes underlain by shales are locally important for colluvium storage. The clay mineralogy of colluvium in the eastern Uinta Mountain is similar to that in Grand Canyon, where illite and kaolinite are also abundant. However, unlike Grand Canyon, clay-rich bedrock does not appear to control the spatial distribution of debris flows (Griffiths et al., 1996, 2004). Debris flows in the eastern Uinta Mountains may reach the Green River despite the contribution of abundant clay-rich material from shales because of the relatively short travel distance between initiation sites and the Green River. All of the recent debris flows traveled less than 1.5 km, whereas debris flows in Grand Canyon can travel as far as 22 km (Webb et al., 1989).

6.2. Wildfire controls on hillslope processes

Wildfires are probably not the primary driver of debris-flows in the eastern Uinta Mountains because there was not a significant difference between the proportion of debris flows from the burned and unburned catchments that we studied. One of the main factors that influence post-fire geomorphic response in a given landscape is the degree to which physical processes are regulated by vegetation (Swanson, 1981). If vegetation is important, then fire has the potential to disrupt that role. The dry climate causes hillslopes in the Uinta Mountains to be sparsely vegetated. Burning has little effect because vegetation and the organic litter it provides have little influence on hydrologic and geomorphic processes. Thus, hillslope response to wildfire in the eastern Uinta Mountains is not as dramatic as in forests with regolith-mantled hillslopes where burning can greatly increase overland flow, erosion, and debris flow activity (i.e., Meyer and Wells, 1997; Cannon et al., 2001b). However, debris flows were common when a high proportion of the watershed area burned, suggesting that fire may play a secondary role to geologic factors as a control on debris flows. Removal of vegetation from hillslopes by burning may increase overland flow by reducing interception and causing soil sealing from raindrop impact. Potential increases in overland flow from fires are likely small, because the pre-fire vegetation density is already low and hillslopes are primarily low-infiltration bedrock and thin colluvium. However, small increases in overland flow may lower the rainfall threshold for firehose-effect triggered debris flows. The lack of rain gages in the immediate study area makes it impossible to determine if rainfall thresholds for initiation were lower in burned catchments.

Few studies have addressed the impact of fire on surficial processes in pinyon-juniper woodlands, but results are generally consistent with our findings. Both increased and decreased infiltration rates were measured following a prescribed fire in a Nevada pinyon-juniper woodland (Roundy et al., 1978). Little hillslope erosion was measured following a wildfire in a pinion-juniper woodland in Nevada, because pre-fire vegetation densities were already very low (Germanoski and Miller, 1995). However, significant entrenchment of valley bottoms occurred following the fire because removal of dense grass from valley bottoms lowered the threshold for gully initiation (Germanoski and Miller, 1995). Hydrologic studies conducted in an unburned

New Mexico pinion-juniper woodland showed that runoff from bare soil was 30–70% greater than from vegetated patches (Reid et al., 1999). Therefore, removal of vegetation by fire could increase runoff in pinyon-juniper woodlands.

Though our observations are limited to 15 debris flow events, additional evidence supports our finding that fire has a limited influence on debris flow activity. Previous accounts of debris flow activity in the eastern Uinta Mountains have not cited fire as a contributing factor (Graf, 1979; Hammack and Wohl, 1996) and the period between 1997 and 2002 would have been an increased period of debris-flow activity even without the fire-related events (Fig. 6). The lack of debris flows following the 19-km^2 fire in catchments tributary to the Yampa River also indicates that the link between debris flows and fire is not as strong on the weathering-limited hillslopes of the eastern Uinta Mountains as it is in forested settings with transport-limited hillslopes.

7. Conclusions

We conclude that bedrock and topographic characteristics of the eastern Uinta Mountains are primary controls on debris-flow initiation and that fire is a secondary factor. The role of vegetation and fire in regulating hillslope processes is similar to that of Grand Canyon, where debris-flow activity is governed exclusively by geologic and physiographic factors (Griffiths et al., 2004), but differs from that of forested ecosystems with regolith-mantled hillslopes where fire can be the dominant control on debris flow initiation (e.g., Meyer and Wells, 1997; Cannon et al., 2001b).

Debris flows in the eastern Uinta Mountains initiate from failure of colluvial wedges by overland flow via the firehose effect and to a lesser degree, landsliding and sediment bulking within channels. The most common process linkage involves a sequence where i) rockfall, rock avalanche, and mass-wasting processes transport weathered bedrock from cliffs to colluvial deposits located on bedrock benches, hollows, and shale slopes; ii) summer storms produce infiltration-excess overland flow on bedrock slopes in the upper elevation portions of catchments; iii) overland flow cascades down the cliffs, impacting and saturating colluvium; iv) colluvium fails, initiating debris flows that increase in volume as they scour material stored in downslope portions of the catchment; and v) debris flows are deposited on fans or in the Green River.

These processes are not primarily influenced by wildfire because the dry climate results in hillslopes with low vegetation density. Since vegetation does little to regulate runoff and erosion, burning has a relatively small effect on the hillslope processes that contribute to debris flows. The main controls on debris flow activity are bedrock and topographic properties. The combination of steep bedrock hillslopes, high runoff ratios, and steep escarpments results in the initiation of debris flows via the firehose effect. Debris flow initiation and hillslope processes in Dinosaur National Monument are similar to those in Grand Canyon, where bedrock plays a similar role in forming steep slopes and controlling colluvial sediment storage, but differs from forested ecosystems where removal of vegetation by fire is a primary control on debris flow initiation.

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