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Historical debris-flow occurrence in Rocky Mountain National Park, Colorado, USA

Sara L. Rathburn[a,*], Annette I. Patton[a], Eric L. Bilderback[b]

[a]*Department of Geosciences, Colorado State University, Fort Collins, CO 80523-1482, USA*
[b]*National Park Service Geologic Resources Division, Lakewood, CO 80228, USA*

Abstract

Debris-flow characteristics of initiation and runout are compared across the Continental Divide in Rocky Mountain National Park (RMNP), Colorado, USA to evaluate the influence of lithology, topography, and anthropogenic activities. Previous research indicates that 30 debris flows within the last century were large enough to transport sediment to valley bottoms and main stem channels and create new debris fans. Ten of the debris flows occurred on the east side of the Continental Divide and 20 on the west side. Those on the east side initiated after an extreme rainstorm in September 2013, whereas those on the west side occurred on the hillslope below an earthen ditch (12 flows) or on the natural hillslope (8 flows). Of those on the west side, four of the five largest debris flows initiated at the ditch. Comparing debris-fan area, transport distance, and elevation of initiation, we find greater variability in transport distance and elevation from east side debris flows, some of which entered alluvial channels and traveled >4 km under highly fluidized conditions. In contrast, the presence of the ditch on the west side limited the elevation of initiation, contributing area and hence, debris-flow transport distance. Lithologic differences between the east and west sides influences debris-supply conditions. On the east side, weathering-limited basins reduce source material and require a longer time to recharge convergent topographic source areas. Transport-limited hillslopes on the west side provide ample source material for debris flows, including till deposits and weathered volcanic rocks. Fan areas are comparable, and debris-flow morphology is generally similar across the Continental Divide. Recent anthropogenic and climatic disturbances, however, indicate that new patterns of debris-flow occurrence must be considered in the future. The increased occurrence of debris flows is an alert to park management who address hazards and risks to park staff, visitors and infrastructure. Furthermore, the high elevation of initiation for these modern debris flows expands the range of expected debris-flow hazards.

Keywords: Debris flows, sediment supply, anthropogenic disturbance

1. Introduction

Debris flows are part of the natural disturbance regime in mountainous landscapes that alter hillslopes and connect uplands to valley bottoms through processes of sediment transfer. In the semi-arid Rocky Mountains, large naturally occurring debris flows are primarily associated with wildfire (Cannon et al., 2001), surface runoff generated during extreme rainfall (Menounos, 2000; Godt and Coe, 2007; Coe et al., 2014), and rapid snowmelt (Brabb et al., 1989) that saturates hillslope materials. Anthropogenic causes of debris flows include overtopping or piping through earthen dams (Jarrett and Costa, 1984; Pitlick, 1993), and/or ditches (Clayton and Westbrook, 2008; Grimsley et al, 2016), and failures associated with road or building construction and maintenance (Highland, 2012). In Rocky Mountain National Park (RMNP), north central Colorado, USA (Fig. 1) both natural and anthropogenic debris flows have occurred historically and in the recent past. Research into debris-flow characteristics, both natural and human-induced

* Corresponding author e-mail address*: sara.rathburn@colostate.edu*

in RMNP, is important for an improved process-level understanding of debris flows and for hazard awareness and prediction.

Here we summarize the current literature on debris flows in RMNP and compare debris-flow characteristics across the Continental Divide in the park. Our main objective is to address how debris-flow attributes including fan area, transport distance, and elevation of initiation differ on east and west sides of the park. In addition, we address the management implications of debris flows in RMNP for hazard prediction in a changing climate, and with increasing annual visitors and mounting costs of maintaining park facilities and transportation infrastructure.

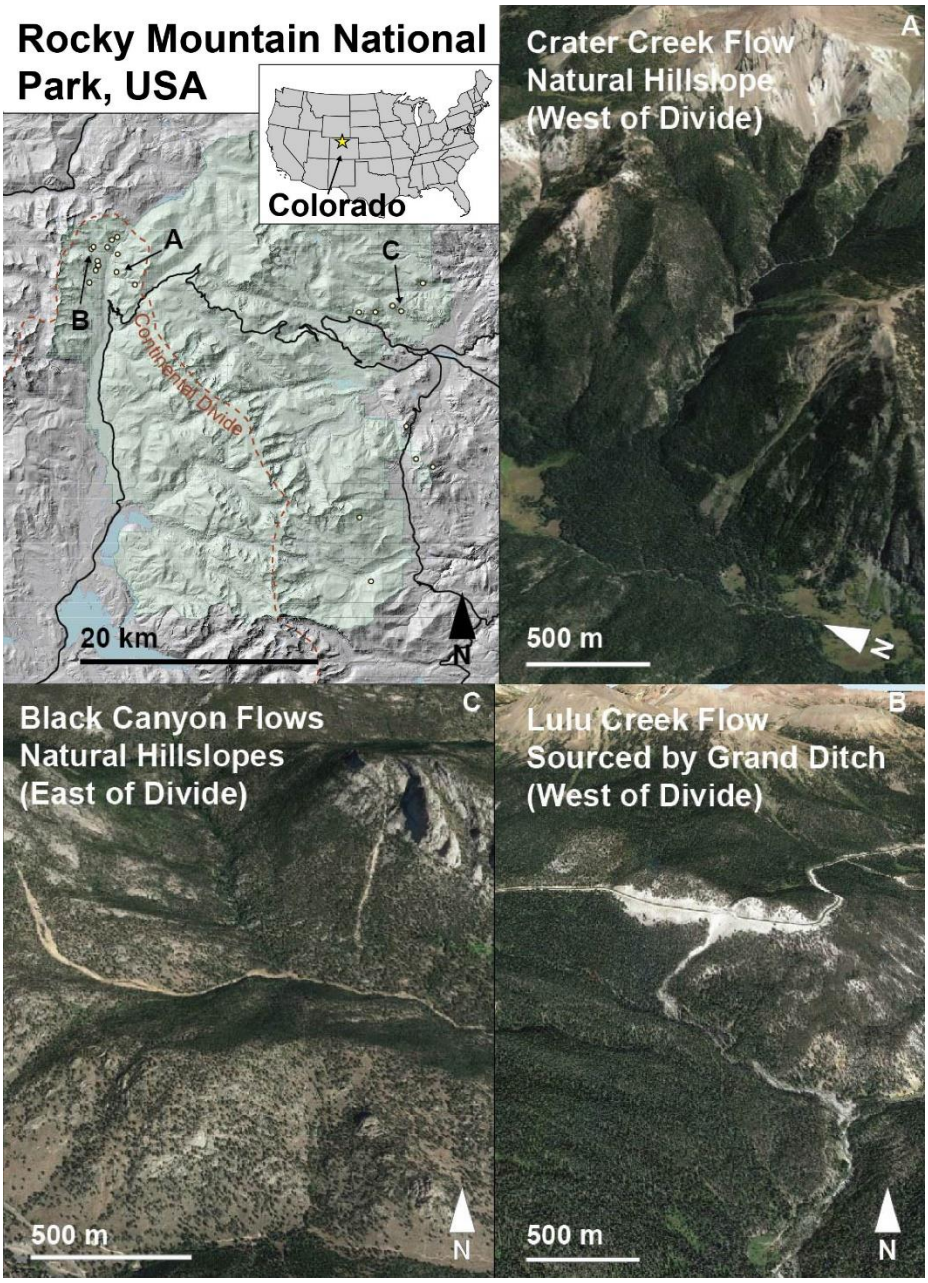

Fig. 1. Location map of the study sites on the east and west side of the Continental Divide in Rocky Mountain National Park, Colorado, USA (green shaded area). Dots indicate locations of historical debris flows addressed in this analysis. Google Earth images of debris flows within A) and B) the Upper Colorado River valley on the west side of the Continental Divide, and C) resulting from the September 2013 storms on the east side of the Continental Divide. Capital letters and arrows on the map show locations of debris flows in the Google Earth images and Grand Ditch on the west hillslope above the Colorado River.

1.1. Study Site

Rocky Mountain National Park in north central Colorado, is one of the top five-most visited parks in the US with over 4 million visitors annually (NPS; https://irma.nps.gov/Stats/Reports/Park/ROMO). Ranging in elevation from 2300 m in valley bottoms to >4000 m at the highest peaks, the park spans several geomorphic process domains (Montgomery, 1999; Wohl, 2010) and disturbance regimes that shape landscapes within the park. The Continental Divide bisects the park north to south (Fig. 1) and divides it into distinct geologic zones. The east side of the park is underlain primarily by Proterozoic Silver Plume Granite and biotite schist (Braddock and Cole, 1990). Quaternary surficial sediments include local alluvial, colluvial and glacial deposits. Pleistocene glaciation in the region contributed to over-steepened valley walls on both east and west sides of the Continental Divide (Madole et al., 1998). Active erosion by glacier ice was unlikely at the study sites on the east site; however, because they are outside of the maximum extent of Pleistocene glaciation (Madole et al., 1998).The Big Thompson and St. Vrain watersheds flow from mountainous regions in the park eastward to the plains of Colorado.

On the west side of the park, Tertiary volcanic rocks comprise a majority of the exposed bedrock with less biotite schist (Braddock and Cole, 1990). Within the headwaters of the Colorado River, the dominant lithologies are latite, rhyolite welded tuff, and undifferentiated volcanic rocks that are in places hydrothermally altered to bentonite. Till of Pinedale age mantles hillslopes below Grand Ditch, an unlined, earthen canal that brings water from the Colorado River basin across the Continental Divide to the Cache la Poudre basin (Fig. 1). Alluvial sediments fill the valley bottom of the Upper Colorado River basin.

2. Previous Debris-Flow Research

Some of the earliest work on debris flows in the Colorado Front Range is presented by Caine (1984) who qualitatively linked geomorphic processes to elevation. Working directly south of RMNP, Caine (1984) labeled the debris-flow hazard as “slight” at elevations between 2800 m and treeline (3350 m). In RMNP specifically, Menounos (2000) developed a Holocene debris-flow chronology from a high elevation lake (3320 m) on the east side of the Continental Divide. He used tephrochronology, radiocarbon dating, soil formation and lake cores to document 2800 years of debris-flow activity into Sky Pond. Also on the east side in RMNP, Patton et al. (2018) investigated the controls on debris-flow occurrence after an extreme storm in September 2013. The authors evaluated topographic properties, slope variables, and soil characteristics at 11 debris-flow sites and 30 undisturbed control hillslopes that received similar cumulative rainfall. On the west side of the divide, Grimsley et al. (2016) developed a debris-flow chronology for the Upper Colorado River valley to investigate the influence of failure of the 19th century earthen ditch on debris flow initiation, magnitude and frequency over the last century. A total of 20 debris flows were mapped and aged using dendrochronology, 12 on the hillslope below Grand Ditch, and 8 on the natural hillslope. In addition, Rubin et al. (2012) and Rathburn et al. (2013) assessed aggradation within the Upper Colorado River valley using shallow geophysics and radiocarbon dating, and channel response to a 2003 debris flow (Fig. 1), respectively, to understand the disturbance in the context of historical range of variability.

Herein, our summary of the current literature focuses on the work of Patton et al. (2018) and Grimsley et al. (2016) because both focused on inventorying debris flows large enough to descend to valley bottoms in RMNP (Table 1), affecting the geomorphology of trunk channels and valley floors in recurring patterns over the last century. In addition, their data provides sufficient sample sizes for a meaningful comparison east to west across the park. Finally, both studies evaluated the influence of lithology, topography, and anthropogenic disturbance, where possible.

We note that the time series of historical debris flows is biased toward high-frequency, low-magnitude events because large events tend to obliterate depositional evidence of earlier, smaller flows. In addition, the data set of historical debris deposits focuses on events that build fans which are preserved in the sedimentary record. We acknowledge that other debris flows have occurred for which we have no record. We present more specifics of the results on the east and west sides of the Continental Divide, and add a new analysis comparing debris-flow characteristics of fan surface area, transport distance, and elevation of initiation. Understanding the relative magnitudes, transport distances and initiation locations of debris flows will improve hazard expectations and mapping into the future.

2.1. East Side of Continental Divide in Rocky Mountain National Park

The field data collected by Patton et al. (2018) included measuring slope angle and categorizing slope morphology, mapping and surveying preserved surficial debris-flow deposits and erosional scars of flows that occurred during the September 2013 rainstorm in the Colorado Front Range. This study also evaluated exposure of previously buried stratigraphic layers, and analyzed ^{10}Be in quartz from debris-flow boulders at one site to age the multiple levee-forming flows. Remote analyses included using raster data from a 10-m DEM and calculating contributing area and slope curvature. Results indicate that 10 debris flows large enough to transport sediment to valley bottoms resulted from the September 2013 storms. The authors found that 10 of the 11 mapped debris flows initiated from hillslopes that were south-, west-and east-facing. Patton et al. (2018) also noted that 8 of the 11 debris flows (73%) resulting from the September 2013 rainstorms initiated at sites of convergent topography and at >2800 m, unusually high elevation for debris flows in Colorado. This is contrasted against the >1100 debris flows that were trigged by the September 2013 storms, of which 95% initiated at elevations <2600 m (Coe et al., 2014). Additionally, the incidence of debris flows in areas of convergent topography, especially colluvial hollows, underscores the importance of local topographic controls on debris flow initiation on the east side of RMNP.

Table 1. Debris-flow study sites in Rocky Mountain National Park with measured geomorphic characteristics.

Site	Aspect	Contributing Area (km^2)	Lithology	Fan Area (m^2)[a]	Transport Distance (km)[b]	Elevation (m)	Source
East Side RMNP							
Mt. Meeker	East	0.05	Granite	13,339	4.35	3451	Patton et al. (2018)
North St. Vrain	East	0.46	Till; granite	0	0.74	2929	Patton et al. (2018)
Twin Sisters	West	0.01	Biotite schist	116,643	1.36	3081	Patton et al. (2018)
Cow Creek	South	0.002	Granite; biotite schist	10,355	0.45	2638	Patton et al. (2018)
Black Canyon North	South	0.001	Granite	8091	0.84	2903	Patton et al. (2018)
Black Canyon South	South-east	0.001	Granite	6252	1.09	2940	Patton et al. (2018)
Bighorn	South-east	0.001	Granite	4630	0.55	2747	Patton et al. (2018)
Lumpy Ridge	South-east	0.001	Granite	2156	0.42	2687	Patton et al. (2018)
Highway 7	East	0.002	Granite; biotite schist	0	0.38	2836	Patton et al. (2018)
Pierson Park	East	0.02	Biotite schist	30,363	3.81	3180	Patton et al. (2018)
Sky Pond	East	2.0	Biotite gneiss/schist	--	--	3320	Menounos (2000)
West Side RMNP[c]							
Below Grand Ditch							
Specimen Cr West	East	0.30	Till; altered tuff	6813	0.28	3105	Grimsley et al. (2016)
Lady Creek	East	0.17	Altered tuff	3376	0.80	3105	Grimsley et al. (2016)
Lulu Creek	East	0.71	Altered tuff	5361	0.88	3105	Grimsley et al. (2016)
Sawmill Gulch	East	0.48	Till	4765	1.74	3105	Grimsley et al. (2016)
Little Dutch Creek	East		Till	6940	0.97	3105	Grimsley et al. (2016)
Misc. West	East	0.13	Till	2477-3993	0.77-0.87	3105	Grimsley et al. (2016)
Big Dutch Creek	East	0.35	Till	37,287	1.30	3105	Grimsley et al. (2016)
Natural Hillslope							
Little Yellow East	West	0.04	Altered tuff	12,131	0.39	3137	Grimsley et al. (2016)
Ellen's Tributary	West	0.63	Biotite schist	12,220	0.38	3048	Grimsley et al. (2016)
Misc. East	West	0.24	Biotite schist	2656-3873	--	--	Grimsley et al. (2016)
Crater Creek	West	3.67	Biotite schist	101,074	2.13	3296	Grimsley et al. (2016)

[a] Ranges indicate the potential for multiple source areas contributing to fan deposition. All other fan areas represent single events.

[b] Some transport distances and elevations on the west side of the Continental Divide are not available because initiation points on the natural hillslope were not readily identifiable in the field or in remote imagery.

[c] 11 sites on the West Side of RMNP are listed, some of which show evidence of multiple debris flows, giving a total of 20 debris flows.

At one site with a 2013 debris flow (Bighorn, Table 1), evidence of multiple past events is preserved as linear debris-flow levees emanating from the same colluvial hollow. Although inheritance of ^{10}Be in debris-flow levee boulders was noted, Patton et al. (2018) concluded that four to seven debris flows occurred at that site within the last 75 ka, two of which occurred in the last 8 ka. Boulders sourced from adjacent rocky outcrops during periglacial processes associated with Quaternary glacial stages were likely transported via debris flow during subsequent wetter periods of the mid-Holocene.

2.2. West Side of Continental Divide in Rocky Mountain National Park

Field methods of Grimsley et al. (2016) included field mapping and surveying, using conifer dendrochronology to age debris flows, and aerial photographic interpretation. Results of that study indicate that 20 debris flows occurred on the west side of the Continental Divide in RMNP. Of these 20, 12 initiated on the east-facing hillslope below Grand Ditch, and the other 8 debris flows occurred on the west-facing natural hillslope. The authors found no substantial difference between debris flows on the hillslope below Grand Ditch versus the natural hillslope. Of the largest five debris flows; however, four originated on the hillslope below Grand Ditch, and all since 1937. Compared to previous work by Menounos (2000), who noted 1-5 debris flows on average in 16 centuries of record, the data on debris-flow frequencies from the west side suggest that the ditch has altered the debris-flow activity in the Colorado River headwaters. These findings are in agreement with Rubin et al. (2012) in an analysis of aggradation rates in an adjacent wetland. Ground penetrating radar surveys and radiocarbon analyses of sediment in the Lulu City wetland (Fig. 1) indicate increased aggradation through increased frequency of debris flows over the last two centuries of human intervention (Rubin et al., 2012).

Grimsley et al. (2016) concluded that valley bottom geometry of the Colorado River is the dominant control on response to debris flows, influencing sediment aggradation in debris fans and the persistence of debris-flow deposits. They found that sediment reaching the main stem Colorado River is transported through more confined valley reaches and retained forming persistent bars where valley geometry widens abruptly.

3. Controls on Debris-Flow Characteristics

Transport distances of debris-flow material are influenced by topography below the initiation site and downslope entrainment of sediment. For example, transport may be either halted or facilitated by entering existing channels. Where debris flows enter channels at acute angles they grow in size by entraining channel alluvium and following the path of the channel. Where debris flows enter channels at near-perpendicular angles or meet low-gradient valley bottoms, the flow path may be truncated (Guthrie et al., 2010, Patton et al., 2018). Debris sediment supply and the rate of hillslope and/or channel recharge also controls debris-flow magnitude and frequency (Bovis and Jakob, 1999). Here we use debris-fan surface area as a proxy for event magnitude, and couple it with transport distances and initiation site to address attributes of the 30 debris flows inventoried in RMNP.

Comparing east and west debris-flow fan areas, transport distances, and elevation of initiation (Fig. 2) indicates greater variability in transport distance and elevation for east side debris flows compared to west side ones. The longest transport distances, associated with debris flows from Mt. Meeker and Pierson Park, 4.3 and 3.8 km, respectively, were highly fluidized and entered existing channels, increasing the supply of sediment and providing a low-resistance flow path down the channel. In addition, east side debris flows initiated at elevations ranging from ~2700-3450 m. The much smaller transport distances and limited range of elevations (3105 m) on the west side are due to the presence of Grand Ditch on the hillslope above the Colorado River limiting the contributing area and hence, the transport distance. Twin Sisters on the east side was the largest fan area measured for all 30 debris flows. This debris-flow fan resulted from an abundance of fluidized sediment on the hillslope and formed as the steep, source hillslope transitioned to the lower-gradient valley bottom. Fan areas are similar, however, on the east and west side of the Continental Divide, with the largest exceeding 100,000 m^2.

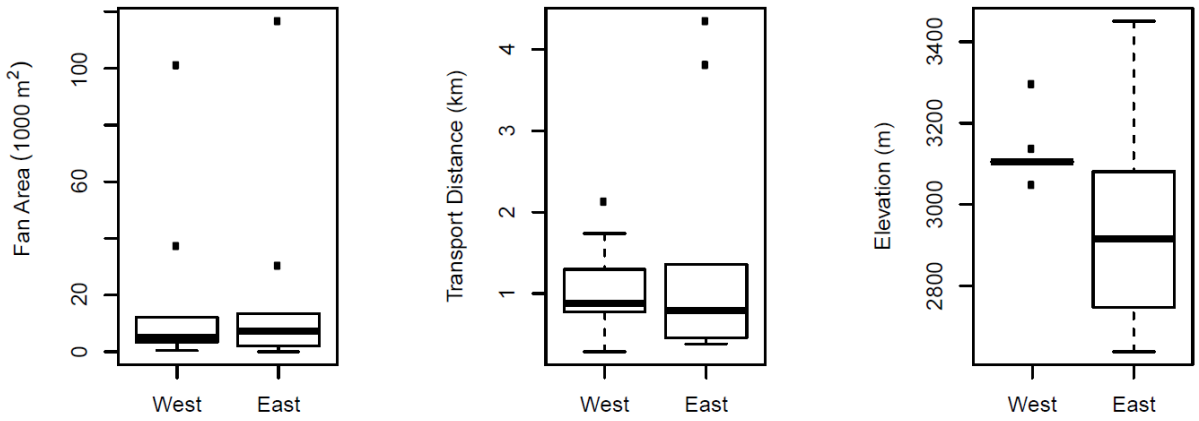

Fig. 2. Comparison between fan area, transport distance and elevation of debris flows on the east and west side of the Continental Divide in Rocky Mountain National Park. Heavy black horizontal line is the median value, end lines are the upper and lower quartiles, whiskers are maximum/minimum values in the population or the distance that is 1.5x the interquartile range, whichever is closest to the median. Dots represent values in the tail of the distribution beyond that distance.

4. Discussion

Clear differences exist between controls on debris-flow initiation east and west of the Continental Divide in RMNP including lithology, slope and channel morphology, and the presence of Grand Ditch. Lithologic differences influence the supply and erodibility of material available to be entrained in debris flows. The supply of sediment on the east side can be considered weathering limited due to the more resistant, unaltered crystalline bedrock, and slower sediment production rates on hillslopes. On the west side, debris-flow occurrence is transport limited due to rapid sediment production from the highly weathered volcanic rocks and thick deposits of till on hillslopes below Grand Ditch.

Differences in slope morphology on either side of the Continental Divide include the hillslope-valley bottom slope transition. This transition influences whether or not debris fans are deposited, and their size, at the base of hillslopes. In an analysis along an interstate corridor in Colorado, Coe et al. (2003) found that debris flows occur frequently on fans at the mouths of basins with steep slopes that transition to a low-slope channel. All of the debris flows evaluated in the Grimsley et al. (2016) study along the Colorado River demonstrated clear fan development where channels reached the low-gradient valley bottom. Hillslope morphology where debris flows occurred on the east side of the divide is more variable, with some flows delivering sediment to broad glacial valleys and some flows occurring entirely in steep fluvially incised valleys.

Despite these known differences in debris-flow initiation and deposition processes, debris-flow morphology is generally similar across the Continental Divide and varying levels of anthropogenic disturbance. Median fan area, transport distance, and elevation are not distinguishable for debris flows on the east and west sides of the Divide. Flows on the east side of the Divide; however, demonstrate a greater range of variability in both transport distance and elevation due to occurrence on hillslopes with diverse topography. Despite the abundance of till and highly weathered bedrock, fan area on the west side is comparable to the east side.

All of the 30 debris flows categorized here initiated at elevations greater than 2650 m. Including the region outside of RMNP, Coe et al. (2014) found that 95% of flows that occurred during the September 2013 storm initiated in canyons and on hogbacks at elevations lower than 2600 m. Flows with the largest scars and longest travel distances occurred at elevations above 2600 m on steep slopes with contributing areas >3300 m^2.

Although debris-flow regimes are likely to change in the upcoming decades, some aspects of the current and future debris-flow hazard in RMNP can be broadly characterized. On the east side of the Divide, colluvial hollows and channels that contributed sediment in 2013 have been deeply scoured, removing much of the loose material available for debris flows. Refilling of the same colluvial hollows may not take place on a human time scale unless the climate mechanisms that drive sediment sourcing and failure change. Thus, future debris flows may not initiate in the same locations or at high recurrence intervals. Other channels that did not scour; however, may show near-term activity.

Based on previous findings, debris flows of various magnitudes and frequencies are likely to continue to initiate at Grand Ditch, under the current ditch conditions, operation and management. Four of the five largest debris flows mapped on the west side initiated at Grand Ditch (Grimsley et al., 2016). The role of ditch operations and presence of hydrothermally altered rock on both sides of the valley is hard to separate, however. On the scale of recent geologic time, based on the last 4000 years of valley aggradation (Rubin et al., 2012), debris flows are frequent events. Even on a human scale, the debris flows might be considered typical, given that the last one occurred in 2003, with four additional large debris flows in the previous seven decades (2003-1937). Although the magnitude of flows on the west side is somewhat limited by the contributing area below Grand Ditch, the frequency of these events allows for significant impact to the morphology and ecology of the Upper Colorado River valley.

5. Implications for Future Management

On both sides of the Continental Divide, the increased incidence of debris flows over the last century in RMNP may be an alert to park staff who address hazards and risks posed to visitors. Even if widespread debris flows appear infrequent on human timescales, public awareness of debris flows is typically low so the consequences of debris flows may be greater than in areas with shorter return periods (Coe et al., 2014). As a federal agency with large holdings of land in the western US, awareness within the NPS of the infrastructure risk and risk to visitors in mass movement-prone areas appears to be growing. In some parts of the western US, the NPS is taking an active role in preparing for landslides as a result of climate change (Coe, 2016). Increased frequency of intense rainstorms (Klos et al., 2014), as well as increased fire intensity, frequency and extent (Abatzoglou and Williams, 2016) may increase landslide frequency in the coming decades. Active measures to respond to increased debris-flow risk include changes to new road construction to avoid areas of elevated landslide hazard, drainage improvements, visitor education, and planning for higher maintenance costs. Proposed changes for trails include managing drainage, stabilizing slopes, and restoring vegetation cover. Where possible, to mitigate debris-flow hazards, future construction should avoid existing debris fans. Where infrastructure already exists on debris fans, removal or protection of facilities should be considered.

Hazards to people and infrastructure are fundamentally similar on both sides of the Continental Divide, although some differences in process and setting may call for slightly different considerations. Specifically, higher population density and visitation on the east side of the park increases risk from debris flows, despite low event frequency. The east side of the park receives a majority of annual visitors and has the bulk of buildings and infrastructure. The town of Estes Park, (population >6,000), adjacent to the eastern RMNP boundary, is a primary center of tourism. Debris flows on the east side of the Divide therefore pose greater hazards to people, buildings, and highways.

On the west side of the Divide, debris fans will continue to be areas of sediment persistence in addition to large bars deposited in wide valley reaches of the Colorado River. The persistence of sediment poses the potential for ongoing remobilization, whereby subsequent high river flows will entrain and transport sediment into sensitive downstream ecosystems and receiving waters, causing renewed deposition, high sediment loads, and possibly impaired water quality.

6. Conclusions

An inventory of previous research on debris flows in RMNP reveals that 30 debris flows large enough to descend to valley bottoms occurred within the last century, affecting the geomorphology of main stem channels and valley floors in recurring patterns. Of the 30, ten debris flows initiated at high elevations on the east side of the Continental Divide, and 20 occurred on the west side. Those on the east side initiated after an extreme rainstorm in September 2013. Of the 20 on the west side, 12 initiated on the hillslope below Grand Ditch, with four of the five largest since 1937. The other 8 debris flows occurred on the natural hillslope. Debris-fan areas are comparable across the Divide, but transport distance and elevation of debris flows are more variable on the east side, where some flows entered alluvial channels and traveled >4 km under highly fluidized conditions. In contrast, the presence of the ditch on the west side constrains the elevation of initiation, contributing area and hence, debris-flow transport distance (<2 km). Thus, the key differences that influence debris-flow characteristics across the Continental Divide include lithology, which influences sediment supply, slope and channel morphology including the hillslope transition to valley bottoms, and the presence of the earthen ditch. On the east side, weathering-limited basins produce less debris supply and require a longer time to recharge convergent topographic source areas. Transport-limited hillslopes on the west side provide

ample source material for debris flows. Increased occurrence of debris flows in RMNP is an alert to park staff members who address risk. Increased knowledge of areas susceptible to debris flow will allow NPS to take an active role in preparing for debris flows to protect park visitors and infrastructure. Elevations that were once considered too high for debris-flow occurrence are now fully within the range of elevations with debris-flow hazards, as indicated by the elevations of initiation for all 30 of the debris flows characterized.

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