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Slope-area thresholds of road-induced gully erosion and consequent hillslope–channel interactions

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ABSTRACT: Pikes Peak Highway is a partially paved road between Cascade, Colorado and the summit of Pikes Peak. Significant gully erosion is occurring on the hillslopes due to the concentration of surface runoff, the rearrangement of drainage pathways along the road surface and adjacent drainage ditches, and the high erodibility of weathered Pikes Peak granite that underlies the area. As a result, large quantities of sediment are transported to surrounding valley networks causing significant damage to water quality and aquatic, wetland, and riparian ecosystems. This study establishes the slope/drainage area threshold for gullying along Pikes Peak Highway and a cesium-137 based sediment budget highlighting rates of gully erosion and subsequent valley deposition for a small headwater basin. The threshold for gullying along the road is $S_{cr} = 0 \cdot 21A^{-0 \cdot 45}$ and the road surface reduces the critical slope requirement for gullying compared to natural drainages in the area. Total gully volume for the 20 gullies along the road is estimated at 5974 m^3, with an erosion rate of 64 m^3 yr^{-1} to 101 m^3 yr^{-1}. Net valley deposition is estimated at 162 m^3 yr^{-1} with 120 m^3 yr^{-1} unaccounted for by gullying. The hillslope–channel interface is decoupled with minimal downstream sediment transport which results in significant local gully-derived sedimentation. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: gully erosion; hillslope-channel coupling; sediment budgets; roads; cesium-137

Introduction

Gully erosion is an important geomorphologic process that occurs in a wide variety of settings (Poesen *et al.*, 2003). Many standard models of gully formation and development focus on mechanisms of headcut retreat in the upslope direction as a result of overland flow, shallow subsurface flow, and piping (Swanson *et al.*, 1989; Bocco, 1991). Gully enlargement in the downslope direction has also been documented in situations where the headcut is physically prevented from retreating upslope, for example, by a road or culvert (de Oliveira, 1989; Moeyersons, 1991; Moges and Holden, 2008). The degree of development in the downslope direction is related to peak discharges, hillslope profile and gradient, and soil erodibility (Moeyersons, 1991). Because roads generally increase surface runoff they may cause concentrated overland flow that initiates gully erosion.

Previous research has demonstrated that gully erosion is a threshold phenomenon determined by critical values for slope and drainage area (Patton and Schumm, 1975; Schumm, 1979; Begin and Schumm, 1984; Montgomery and Dietrich, 1988, 1994; Vandaele *et al.*, 1996). The relationship is described by the power function $S_{cr} = aA^b$, where S_{cr} is the critical slope gradient, A is the drainage area, and a and b are an empirically determined coefficient and exponent with b often approaching $-0 \cdot 4$ (Vandaele *et al.*, 1996). Patton and Schumm (1975) note that achieving the critical slope gradient required for incision does not imply that gullying will necessarily occur, only that sufficient topographic and hydrologic conditions for gullying have been satisfied.

Watersheds associated with roads require smaller critical slope values for a given drainage area compared to watersheds not associated with road surfaces, when all other factors are held constant (Montgomery and Dietrich, 1994; Desmet *et al.*, 1999; Croke and Mockler, 2001; Nyssen *et al.*, 2002; Moeyersons, 2003). Roads extend the channel network and rearrange drainage patterns, thereby increasing flow concentration in drainage ditches and culverts that can lead to channel or gully initiation at points of discharge onto hillslopes (Montgomery, 1994). In situations where culverts release water onto steep and unprotected slopes, gully formation can be rapid and extensive (Jones *et al.*, 2000; Croke and Mockler, 2001; Nyssen *et al.*, 2002; Moeyersons, 2003; Poesen *et al.*, 2003).

Sediment supplied from hillslopes to valley streams by gully erosion is often overlooked even though it can comprise a large percentage of the overall sediment budget of a watershed (Poesen *et al.*, 2003). The nature of sediment delivery from hillslopes to channels is crucial in understanding potential changes in channel morphology. Sediment transport via gully erosion to channel networks often has a cyclic nature whereby sediment accumulates on floodplains only to be transported when a flood of large enough magnitude can remove the deposit (Harvey, 1994). When streams lack defined floodplains, gullies often deliver sediment directly into the channel (Wainwright, 2006). In mountain and headwater environments, the degree of hillslope–channel coupling becomes extremely important in determining the extent and effects of environmental disturbances because the two geomorphic zones are typically adjacent (Harvey, 2002).

The degree of coupling has significant implications for the transfer of materials from hillslopes to channels. In well-coupled systems, the transfer of materials and energy from the hillslope to the channel is relatively continuous in space and occurs synchronously. In poorly coupled systems, the transfer of materials and energy is discontinuous in space and time and is often disrupted by buffers such as floodplains (Brunsden and Thornes, 1979; Harvey, 2001; Harvey, 2002; Wainwright, 2006). The distinction is not absolute as most systems display a degree of coupling between the two extremes, with many systems having a cyclic or episodic pattern of coupling and decoupling (Harvey, 2001; Michaelides and Wainwright, 2002). The nature of hillslope–channel coupling is important because it determines rates of sediment transport, storage, and deposition from the hillslope to the channel; the rate of morphological change of the hillslope and channel; and how environmental disturbances are propagated in space and time through watersheds, indicating the overall landscape sensitivity (Brunsden, 1993; Harvey, 2001).

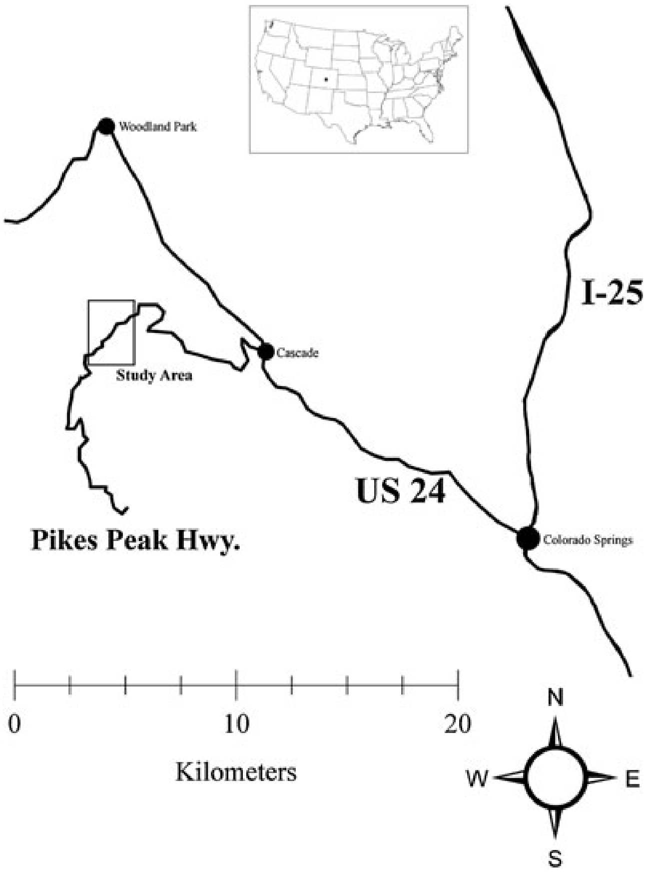

Figure 1. Pikes Peak Highway is located west of Colorado Springs off US Highway 24 at Cascade, Colorado and ends at the summit of Pikes Peak (4300 m). The majority of the road is located within the Pike-San Isabel National Forest and is approximately 30 · 5 km in length.

Study Area

Pikes Peak Highway is located within Pike-San Isabel National Forest and is part of the United States National Forest system (Figure 1). The road is partially paved and begins at Cascade, Colorado (2250 m) and ends at the summit of Pikes Peak (4300 m). The roadway is historic, originating as an unpaved carriage road in the 1800s. The modern Pikes Peak Highway was created in 1916 to accommodate automobiles and is approximately 30 · 5 km, with most of the road surface asphalt paved since 2003. The presence of Pikes Peak Highway in steep, mountainous terrain has caused significant erosion due to the concentration of runoff from the road surface and adjacent drainage ditches. This concentrated overland flow causes gullying on roadside slopes that deliver large quantities of sand and gravel from the road surface and sediment from hillslopes to the surrounding stream valleys (Figure 2). Consequently, water quality in surrounding watersheds has degraded causing damage to aquatic, wetland, and riparian environments (USDA Forest Service, unpublished monitoring plan, 2002, pp. 1–16).

The road is lined on its sides along the majority of its length with drainage ditches (Figure 3). Ditches drain either through culverts or directly onto slopes that deliver water and sediment to surrounding basins (Figure 4). Bedrock throughout the region is Pikes Peak granite, a plutonic igneous rock containing large amounts of coarse-crystalline orthoclase that weathers easily into highly erodible grus.

The study area focuses on a 5 · 2 km segment of the road from km 11 · 3 to km 16 · 5 with an elevation range between 2750 m and 3150 m (Figure 5). This elevation range is entirely below tree-line, entirely asphalt paved, and represents one of the densest areas of gullying along the road. The slopes off the road in the study area are steep, ranging from 10 to 40%. Thin soils overlie often-exposed bedrock and slopes are strewn with large amounts of grus. The slopes are forested, densely in some basins, with small wetland reaches in the valleys. Mean dry season (May–October) precipitation is approximately 300 mm based on records from the nearby Glen Cove Snotel telemetry site nearby and a precipitation gauge in the study area. The Snotel site records an additional 470 mm of precipitation, mostly in the form of snow or ice, in the wet season from November to April (United States Department of Agriculture (USDA) National Resources Conservation Service (NRCS), 2010). Runoff from the study area drains into two local

Figure 2. Gullying due to surface runoff discharge from the Pikes Peak Highway road surface. This site is the largest gully by volume in the study area. Source: Troendle *et al.*, unpublished report. 2010, pp 1–34. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Figure 3. An incised drainage ditch associated with Pikes Peak Highway. Source: Troendle *et al*., unpublished report. 2010, pp 1–34. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Figure 4. A gully formed at a culvert outlet. Gullies in the study area are developing in the downslope direction. Source: Troendle *et al*., unpublished report. 2010, pp 1–34. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

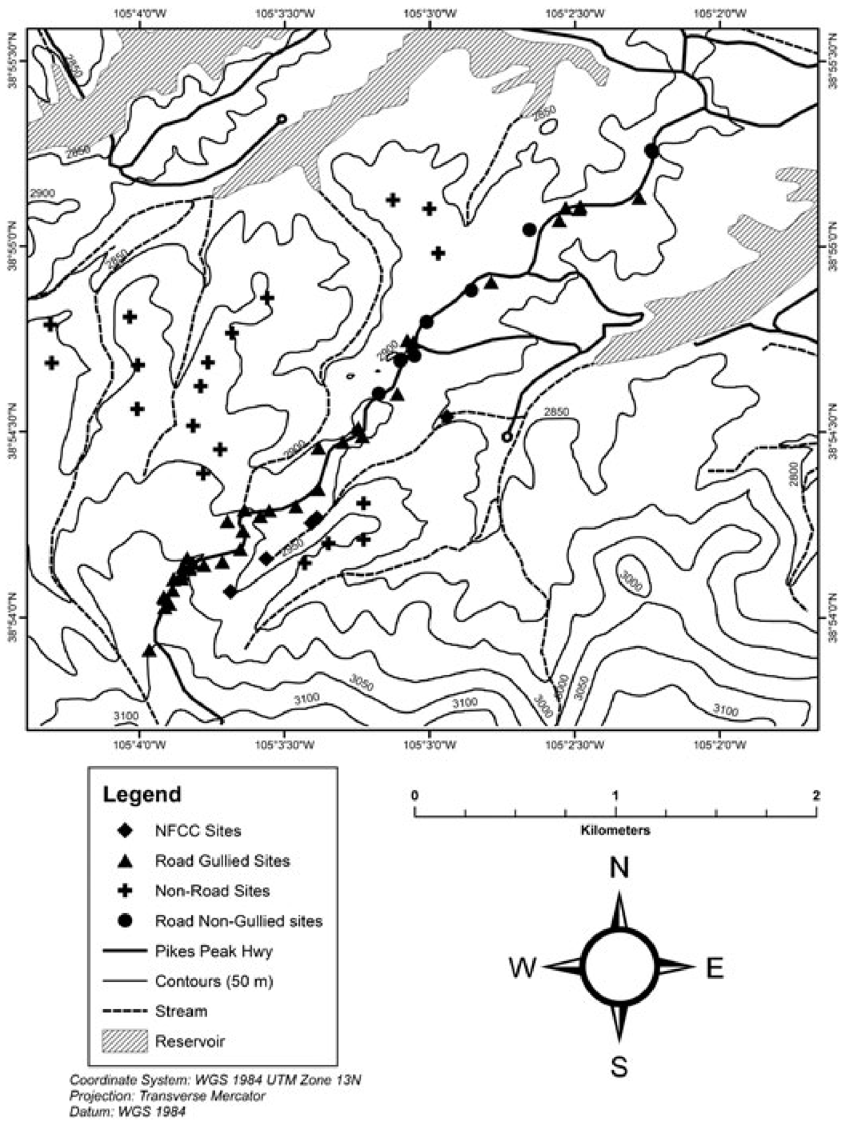

Figure 5. Map of the study area located in the Pike-San Isabel National Forest with 20 road gullied sites, seven road non-gullied sites, and 19 non-road sites are located within the study area. Road km 11 to km 17 of Pikes Peak Highway is shown (along with reservoir access roads).

reservoirs via two headwater stream basins. The North Fork Crystal Creek basin is located to the southeast of the study area road segment (Figure 6). This valley is highly impacted by gullying that occurs along the entire length of road in the study area.

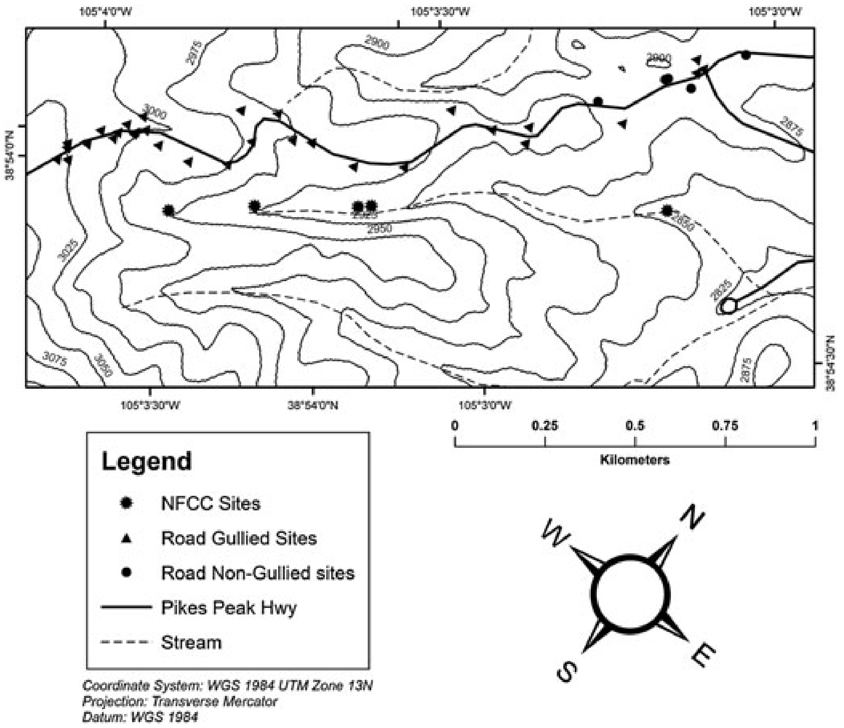

Figure 6. The North Fork Crystal Creek valley is shown. Most of the gullies in the study area deliver sediment to this stream valley that drains into Crystal Reservoir.

The presence of Pikes Peak Highway in steep, mountainous terrain has caused significant gullying on the surrounding hillslopes (Figure 1). The road-induced disturbance manifests itself in certain locations and propagates through the system with specific spatial and temporal patterns. This study investigates the slope/drainage area threshold for gully formation and the rates of gully erosion and downslope deposition in one watershed highly impacted by Pikes Peak Highway. Topography and the location of drainage ditches and culverts are crucial factors in explaining the spatial nature of the disturbance in the study area. The relationship between slope, drainage area, and gullying determines the minimum topographic and hydrologic requirements for incision and subsequent gullying. The rate of gully erosion on hillslopes and the rate of deposition, storage, and removal of sediment in stream valleys indicate the temporal nature of the disturbance caused by the road. In order to gain a clear understanding of the spatial and temporal nature of the disturbance created by Pikes Peak Highway, four primary research questions were formulated for the study area:

1. What is the rate of gully erosion on hillslopes?
2. What is the rate of deposition in stream valleys?
3. What is the slope/drainage area threshold required for gullying along the road?
4. How does the threshold compare to locations not impacted by the road?

Methods

Gully surveys

Gullies were defined as distinct channels formed at or near the point of discharge from the road surface and extending down the hillslope. Gullies were surveyed with a measuring tape and global positioning system (GPS) in a series of segments representing consistent dimensions or in between major inflection points for the entire length of the channelized feature. Maximum depth (d), maximum width (w), and length (l) measurements were recorded for each segment. Volumetric estimates were made under the assumption that all gully cross-sections are geometrically shaped between a triangle and a rectangle. The lower estimate of volume (V) for each segment was calculated using the equation:

$$V = 0.5 \times w \times d \times l$$

This equation represents the lower estimate of volume based upon triangular cross-section dimensions. The upper estimate for each segment was calculated using the equation:

$$V = w \times d \times l$$

This equation represents a rectangular cross-section. Each segment was assigned a ratio of 0·5, 0·6, 0·7, 0·8, 0·9, or 1·0 based upon site-specific details about the morphology of individual gullies recorded in the field. These ratios represent various geometric possibilities based upon trapezoidal cross-sections (Figure 7). A ratio of 0·5 represents a perfectly triangular cross-section, while a ratio of 1·0 represents a perfectly rectangular cross-section. Individual gully volume was calculated by multiplying the rectangular volume by the assigned coefficient. Based on the estimate of total gully volume for the study area, erosion rates were calculated using the date of road construction completion in 1916.

In addition to cross-section surveys, gullies were mapped using a GPS. Waypoints were recorded at the upper and lower limits of each gully segment. If a site did not show distinct evidence of incision or gullying or was only incised partially down the hillslope, a waypoint was recorded at the point of discharge from the road surface. The waypoints of gullied sites were plotted in a geographic information system (GIS) as point features, edited to create line features, and subsequently smoothed to better represent gully planform geometry. The waypoints of non-gullied sites were simply mapped as point features. The resulting map of gullies was used to delineate

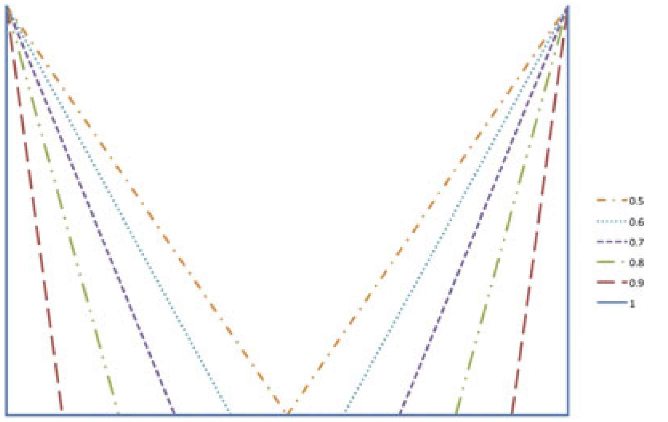

Figure 7. Six potential gully cross-section morphologies with associated coefficient. Field notes were used to assign a volume coefficient to each individual gully. The rectangular volume of each gully was multiplied by the assigned coefficient to achieve a more accurate estimate. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

drainage area and determine slope of individual gullies when layered over a radar-derived 5 m digital terrain model (DTM), a 5 m ortho-rectified radar image, and 7 · 5 minute US Geological Survey (USGS) digital raster graphic in a GIS.

A total of four gullied sites were removed from analysis due to random, but significant GPS errors making volume, slope, and drainage area calculations inaccurate. Seven sites along the road were considered non-gullied because there was some visual evidence of concentrated flow and minor rilling but no distinct gully was present. Six gullies along the road were networked or branched and considered one individual site. Two sites along the road were considered outliers due to a significant lack of vegetation and the abrupt change in morphology that differed from all other sites and were removed from analysis. The total number of sites along Pikes Peak Highway used for statistical analysis in this study was 27, with 20 gullied sites and seven non-gullied sites.

Slope and drainage area

Gully slope was calculated by dividing the difference in elevation between the upper and lower limits of the channel by the total length of the gully. These limits were defined by the uppermost and lowermost waypoints recorded during surveying, and corresponding elevations were derived from the DTM. In situations where gullies were multi-threaded or dendritic, slope was calculated based upon the master channel. Due to uncertainties about where gully initiation occurred on the slope and to account for the branched nature of some of the sites, the delineated basins include all areas that contribute runoff to any portion of the gully. This would include alterations to drainage area induced by the road surface. In this study, drainage area is used as a proxy for discharge at a particular site (Sidorchuk, 1999).

Slope and drainage area for the seven non-gullied sites associated with the road were calculated based upon a hypothetical gully following the steepest flow path to the valley bottom. In addition, 19 non-gullied sites were identified as non-impacted by the road and selected for comparison to road-related sites. These sites were topographically similar to gullied and non-gullied sites along the road, but were in watersheds not directly influenced by the road surface. Slope and drainage area for these non-road impacted sites were also estimated by assuming the steepest flow path of a hypothetical gully to the valley bottom.

Slope and drainage area distributions for all three groups were tested for normality using a Shapiro–Wilk test for all three types of sites to determine if parametric or non-parametric analysis was appropriate. As a result, three difference of means *t*-tests were performed between the three groups to test for statistically significant differences in mean slope and mean drainage area.

Valley deposition

Valley cross-section surveys were measured at five representative reaches at 43 m (Site 1), 278 m (Site 2), 547 m (Site 3), 600 m (Site 4), and 1434 m (Site 5) downvalley in the North Fork Crystal Creek stream valley (Figures 8A and 8B). A measuring tape was placed horizontally across the valley approximately 2 m above the ground surface. The height of the tape above the surface was measured every 1 m across the valley to determine changes in the surface elevation. Soil cores were taken across the valley to establish the depth of the deposit based upon the depth of bedded floodplain silt deposits.

Soil pits were excavated in the North Fork Crystal Creek stream valley at Site 1, Site 3, and Site 5 to obtain samples at various depths for cesium-137 (^{137}Cs) concentration analysis. Samples were taken from every 10 cm section until the bottom of the coarse-grained gully-derived sediment was reached and floodplain silt was present. A bulk sample was taken at Site 5 from the upper 18 cm, which is the depth of the water table at this location. Gamma spectroscopy was used to determine relative concentrations of ^{137}Cs of each 10 cm increment in order to determine the location of the 1963 ground surface. Cesium-137 is a radioactive nuclide that was produced as a result of thermonuclear weapons testing beginning in 1954. The Nuclear Test Ban Treaty was signed in 1963 and 96% of ^{137}Cs fallout had occurred by 1970, reaching a peak in 1963 (Appleby, 1997). Cesium-137 fallout is absorbed by fine silt and clay particles and the fallout of this nuclide over the last half-century has allowed a dating technique to be developed that is used widely for decade-scale analyses of erosion and sedimentation. Cesium-137 concentrations in soil deposits can be used to obtain rates of deposition or erosion based upon the known dates of initial and peak ^{137}Cs fallout or comparison to established reference cores in the study area (Lee, 1999; Li *et al*., 2003).

Cross-sectional area (in m^2) at each site was plotted as a function of distance downvalley (in meters) and a volumetric deposition rate (in m^3) estimated for the entire basin by calculating the area under the curve. An initial date of deposition in 1916 was used for all sites to obtain a time-averaged deposition rate for the entire valley, assuming the deposit represented net aggradation since the modern road was constructed. Local deposition rates were also calculated for Site 1 and Site 3 for the last 46 years representing post-1963 deposition based upon ^{137}Cs radiometric dating for comparison.

a

b

Figure 8. Representative portions of the upper (A) and lower (B) reaches of the North Fork Crystal Creek valley. Source: Troendle *et al.*, unpublished report. 2010, pp 1–34. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Results

Gully surveys

Table I shows summary statistics for volume, volume coefficient, maximum width, maximum depth, and width/depth ratio for all 20 gullied sites along the road. Total gully volume in the study area is estimated at 5974 m^3, with a mean individual gully volume of 299 m^3. There is substantial variability in individual gully volume, with the smallest gully approximately 5 m^3 and the largest approximately 1138 m^3. The range for all parameters excluding the volume coefficient was large. Median values for all variables except the width/depth ratio were smaller than corresponding mean values.

Erosion rates

Based on an estimated date of gully initiation in 1916 and a current total gully volume of 5974 m^3 as of summer 2009, the gully erosion rate is 64 m^3 yr^{-1}. The lower estimate of gully volume is 3627 m^3 based upon triangular gully geometry with a corresponding erosion rate of 39 m^3 yr^{-1}. The upper estimate for gully volume based upon rectangular gully geometry is 7254 m^3 with an erosion rate of 78 m^3 yr^{-1}. However, the exact date of the onset of gullying is unknown. Therefore, this is a time-averaged estimate of sediment yield in the study area that assumes a constant rate through time. Field observations indicate that sediment transport downslope to the valleys occurs only during and shortly after precipitation events or snowmelt and that there are significant variations in discharge throughout the study area.

Slope and drainage area

The relationship between slope, drainage area, and gullying in the study area is shown in Figure 9. The threshold equation for gullying in the study area is $S_{cr} = 0 \cdot 21A^{-0 \cdot 45}$. All 20 gullied sites along with the road plot above this threshold, while six of the seven non-gullied sites associated with the road plot below this threshold line. All six non-gullied sites not associated with the road plot well above the threshold and above most of the gullied sites associated with the road. No gullies were observed in the study area or surrounding region on slopes not impacted by the road surface. The scatter plots display an inverse relationship between the slope and drainage area required for gullying for all sites associated with the road. A smaller slope gradient is required for gullying with larger drainage area, while steeper slopes are required for gullying to occur in smaller drainage areas. A similar, but less distinct, pattern is noted with the six non-gullied sites not associated with the road.

Summary statistics for slope and drainage area for all sites are shown in Table II. Gullied sites associated with the road have higher mean, median, and maximum values for both slope and drainage area compared to non-gullied sites associated with the road. Non-gullied sites not associated with the road have the highest mean and median slope and drainage area of all three groups.

A Shapiro–Wilk test was used to test the variables of slope and drainage area for the three groups for departure from a normal distribution curve. The null hypothesis is that the data do not depart from a normal distribution and could not be rejected for either slope or drainage area for all three groups indicating that the data are normally distributed. Based on these

Table I. Summary statistics of mean, median, minimum, maximum, and range for gully morphology variables for the study area.

	Mean	Median	Minimum	Maximum	Range	Total
Road gullied sites (n = 20)						
Volume (m^3)	298 · 70	94 · 60	5 · 02	1137 · 65	1132 · 63	5974 · 05
Volume coefficient	0 · 75	0 · 70	0 · 60	0 · 90	0 · 30	—
Length (m)	147 · 63	125 · 99	69 · 65	326 · 22	256 · 57	2952 · 52
Maximum width (m)	3 · 47	2 · 58	0 · 95	7 · 51	6 · 56	—
Maximum depth (m)	1 · 38	0 · 97	0 · 24	6 · 00	5 · 76	—
Width/depth ratio	3 · 18	3 · 37	1 · 17	5 · 17	4 · 00	—

Note: Total sums are given for volume and length. The volume coefficient was the ratio multiplied by the rectangular volume to achieve a better estimate of volume based upon field observations.

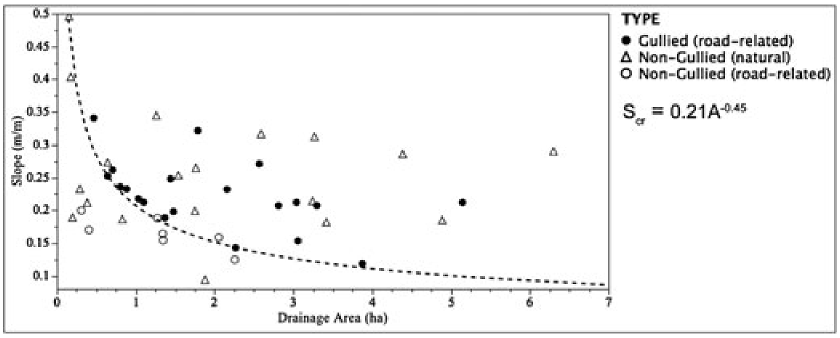

Figure 9. The threshold for gullying based upon slope gradient and drainage area for the study area. The threshold line is a best-fit estimate of the necessary critical slope required based upon the distribution of points representing the lower limit of gullied sites along the road.

Table II. Summary statistics of mean, median, minimum, maximum, and range of slope and drainage area.

	Mean	Median	Minimum	Maximum	Range
Road gullied sites (n = 20)					
Slope (m/m)	0·22	0·22	0·12	0·34	0·22
Drainage area (ha)	2·00	1·63	0·47	5·15	4·68
Road non-gullied sites (n = 7)					
Slope (m/m)	0·17	0·16	0·12	0·20	0·08
Drainage area (ha)	1·28	1·34	0·31	2·26	1·95
Non-road non-gullied sites (n = 19)					
Slope (m/m)	0·26	0·25	0·09	0·50	0·41
Drainage area (ha)	2·05	1·75	0·15	6·30	6·15

Note: Slope was measured for the entire length of the gully and drainage area includes any area that contributes runoff to the entire length of the gully. Non-gullied sites were based on a hypothesized gully along the steepest flow path to the valley bottom.

results, a one tailed parametric difference of means *t*-test was used to test for differences in slope and drainage areas between: (1) gullied and non-gullied sites along the road, (2) non-gullied sites along and away from road, and (3) gullied sites along the road and non-gullied sites away from road. The null hypothesis for all tests was that there are no statistically significant differences between the two groups under consideration ($\alpha = 0 \cdot 05$). The results indicate that there are not significant differences in slope and drainage area for sites along the road with two exceptions. Gullied sites associated with the road have significantly steeper slopes ($p = 0 \cdot 001$) and larger drainage areas ($p = 0 \cdot 044$) than non-gullied sites along the road and non-gullied sites away from the road have significantly steeper slopes than non-gullied sites along the road ($p = 0 \cdot 001$). However, the null hypothesis could not be rejected for all other comparisons. Gullied sites along the road are not significantly steeper than non-gullied sites away from the road ($p = 0 \cdot 929$) and do not have significantly larger drainage areas ($p = 0 \cdot 542$). Drainage areas are not significantly different between non-gullied sites along and away from the road ($p = 0 \cdot 068$).

Valley deposition

Total deposited gully volume in the North Fork Crystal Creek basin between Site 1 and Site 5 is 3894 m^3 with a time-averaged rate of 42 m^3 yr^{-1} when using 1916 as the date of the onset of gullying. Estimates for cross-sectional area since 1916 are 26·8 m^2 (Site 1), 20·8 m^2 (Site 2), 7·8 m^2 (Site 3), 6·8 m^2 (Site 4), and 6·0 m^2 (Site 5). The net deposition rate or the annual change in storage volume in the North Fork Crystal Creek basin between Site 1 and Site 5 is estimated at 162 m^3 yr^{-1}. The total estimate is notably higher than the estimate of 42 m^3 yr^{-1} for gullying, leaving 120 m^3 yr^{-1} of sediment deposition attributed to sources other than gullying.

Cesium-137 analysis showed peak activity at a depth of 0·65 m for Site 1 and 0·45 m for Site 2 (Figures 10A and 10B). These depths represent the 1963 ground surface. Peak ^{137}Cs activity could not be determined for Site 5 since only one sample from the upper 18 cm was analyzed. The cross-section area representing material deposited since 1963 is approximately 6 m^2 and 7·5 m^2 for Site 1 and Site 3, respectively. Estimates for deposition rates based on changes in cross-

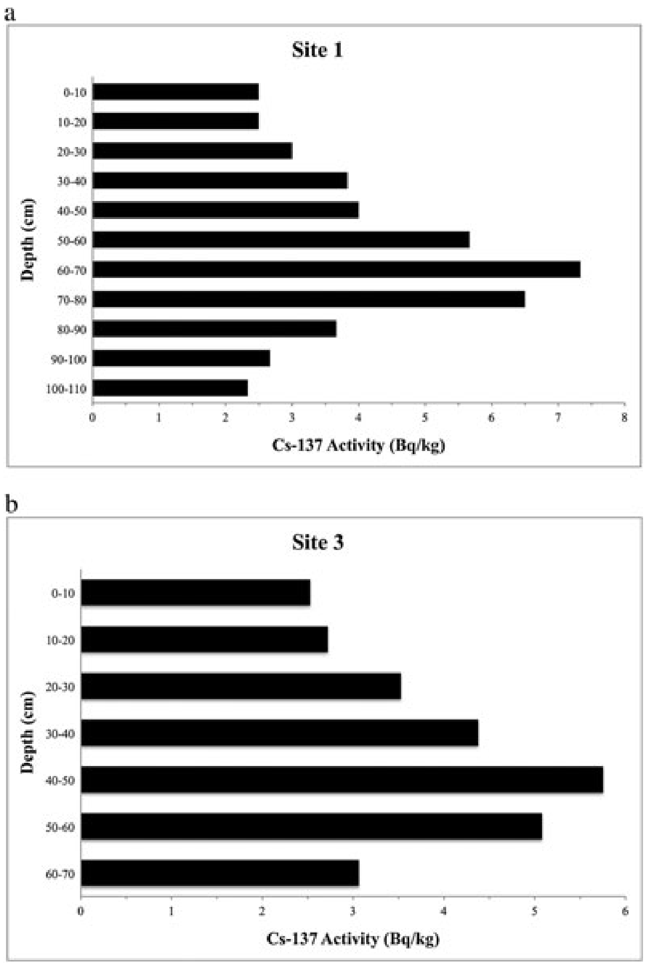

Figure 10. Cesium-137 activity for Site 1 (A) and Site 2 (B) in the North Fork Crystal Creek basin. Peak ^{137}Cs activity represents 1963 ground surface and is observed at a depth of 65 cm for Site 1 and 45 cm for Site 3.

sectional area from 1916 to 1963 are 0 · 44 m^2 yr^{-1} and 0 · 01 m^2 yr^{-1} at Site 1 and Site 3, respectively (Table III). The estimated rates of post-1963 deposition based on ^{137}Cs dating are 0 · 13 m^2 yr^{-1} (Site 1) and 0 · 16 m^2 yr^{-1} (Site 3).

Discussion

Gully surveys and erosion rates

The calculated erosion rate of 64 m^3 yr^{-1} is a time-averaged estimate of erosion from 1916 to 2009. Therefore, it provides an estimate of a mean amount of sediment removed from the slopes via gully erosion and delivered to the valley in any given year. The total estimate of gully volume as of summer 2009 for the 20 gullies in the study area is 5974 m^3. The estimate for gully volume has a lower bound of 3630 m^3 and an upper bound of 7260 m^3, based upon triangular and rectangular channel dimensions, respectively. Using these lower and upper limits to calculate volumetric erosion rates yields estimates of 39 m^3 yr^{-1} and 78 m^3 yr^{-1}, although the estimate of 64 m^3 yr^{-1} is the best estimate based upon the incorporation of field observations on site specific geometry.

Methods used in this study are consistent with Nachtergaele *et al.* (2001) and Moges and Holden (2008) who estimated volume of downslope migrating gullies by field measurements of segments between inflection points in the gully course, as suggested by Moeyersons (1991). Moeyersons (1991) defines 'forward' erosion as the progressive downslope erosion from an initial incision point created by concentrated overland flow or shallow landsliding that develops down the slope with a stable headcut or upslope extent. Moeyersons (1991) showed that when estimating erosion rates of gullying in the downslope direction, erosion estimates should be based on changes in width, depth, and length of the gully and not headcut retreat, even when the initial incision occurs at the mid-slope position.

Field observations indicate that runoff is not uniformly delivered to all sites for any given precipitation event. The proportion of runoff released at each site varies significantly based upon the intensity of the precipitation event. This factor is complicated by largely undocumented changes to the road design and engineering that has occurred over the last 93 years. Considerable differences in discharge at individual sites relating to culvert locations, ditch locations, and erosion mitigation structures over almost a century are possible. The time span of almost a century probably contained significant changes in total precipitation and rate of snowmelt in the study area. The rate of erosion is most likely not uniform between the gullies or uniform within an individual gully over long time periods.

One major assumption is that the gullies began to form soon after the construction of the modern road in 1916. The lack of information regarding the onset of gullying complicates the reliability of the calculated erosion rates. It is possible that gullying began to occur years after the construction of the modern Pikes Peak Highway, and even more likely that over time changes to the road have significantly altered runoff pathways and related discharge rates at individual sites. However, ^{137}Cs concentrations indicate that gullying began prior to 1963 (Figures 10A and 10B).

Table III. Deposition rates (m^2) for the entire study area and North Fork Crystal Creek basin upstream of Site 3 based upon various potential dates for the initiation of gullying.

Site	1	2	3	4	5
Distance downvalley (m)	43	278	547	600	1434
Deposit area (m^2) (1916–2009)	26 · 8	20 · 8	7 · 8	6 · 8	6 · 0
Deposit area (m^2) (1916–1963)	20 · 8	—	0 · 3	—	—
Deposit area (m^2) (1963–2009)	6 · 0	—	7 · 5	—	—
Deposition rate (m^2 yr^{-1}) (1916–2009)	0 · 29	0 · 22	0 · 08	0 · 07	0 · 06
Deposition rate (m^2 yr^{-1}) (1916–1963)	0 · 44	—	0 · 01	—	—
Deposition rate (m^2 yr^{-1}) (1963–2009)	0 · 13	—	0 · 16	—	—

Note: The maximum age estimate is represented by the completion of the modern road surface improved for automobiles in 1916. 1963 represents a minimum estimate based upon ^{137}Cs analysis.

Slope and drainage area

The threshold line for gullying based upon slope and drainage area in the study area is $S_{cr} = 0 \cdot 21A^{-0 \cdot 45}$. All 20 gullied sites associated with the road plot at or above this line. Five non-gullied sites associated with Pikes Peak Highway plot below the threshold line, with one site plotting just above the threshold line. This is consistent with Patton and Schumm's (1975) interpretation that gullying is not guaranteed to occur even when the slope/drainage area relationship surpasses the threshold. The data support the hypothesis that a critical slope for all possible drainage areas must be achieved for gullying to occur.

Findings for the study area are consistent with the literature on slope and drainage area thresholds for gullying. Vandaele *et al.* (1996) found that slope/drainage area thresholds are allometric with a consistent scaling exponent of approximately −0 · 4 across a wide variety of environments, land uses, and climate zones. The observed value of this exponent for the Pikes Peak Highway study area is −0 · 45. This indicates that although the study area is highly impacted by the presence of the road surface over highly weathered Pikes Peak granite, the slope of the threshold line for gullying remains near −0 · 4. Vandaele *et al.* (1996) and Montgomery and Dietrich (1994) attribute this similarity in the scaling exponent *b* across many different landscapes to common channel initiation mechanisms including concentrated overland flow and shallow landsliding. The gullies in the study area are developing in the downslope direction via concentrated overland flow. The value of *a* for the Pikes Peak Highway study area was 0 · 21. Vandaele *et al.* (1996) showed a range for the constant *a* between 0 · 0035 and 0 · 35 for 10 studies, with higher values associated with steeper slopes and shallow landsliding as the incision mechanism, and lower values associated with gentler slopes and rilling. The constant *a* is influenced by the methods used to derive the values of slope and drainage area, as well as variations in geology, geomorphic setting, vegetation, and climate.

The road surface lowers the critical slope for a given a drainage area required for gullying in the study area. This is consistent with the findings of Montgomery and Dietrich (1994); Desmet *et al.* (1999); Croke and Mockler (2001); Nyssen *et al.* (2002), and Moeyersons (2003), whose research shows lower critical slope values required for gullying in drainage basins associated with roads. In this study, no gullies were observed away from the road so a threshold equation for gullying away from the road could not be established for comparison. However, Figure 9 shows that some non-gullied sites unassociated with the road plot well above the threshold line for gullying along the road and even above most of the gullied sites associated with the road. Furthermore, no significant differences in drainage area or slope was found between gullied sites and non-gullied sites away from the road. This implies that the road is a direct factor in the formation of gullies and alters the slope and drainage area requirements for gullying in the impacted basins along Pikes Peak Highway. The change in the threshold could be quantified if gullies were observed away from Pikes Peak Highway and their respective slope and drainage areas were plotted. This threshold would have a similar value for the scaling exponent *b*, but a different value for the constant *a*. This would produce a threshold line that would require higher critical slope values for a given drainage area compared to gullies along the road.

Valley deposition

Comparison of erosion and deposition rates for the North Fork Crystal Creek basin indicates that the majority of sediment in the basin is not derived from gully erosion. This unaccounted for sediment reflects the volume of sediment derived from sheetwash, hillslope and mass wasting processes, and road surface sand and gravel transported to the valley via gullies. However, sediment is not moving through the system efficiently so it can be assumed that transport of sediment downstream from Site 5 approaches 0 m^3 yr^{-1} in most years. This assumption could be erroneous in years where large floods occur and the system is no longer transport-limited. The road was unpaved for almost a century and required routine additions of sand and gravel to ensure it was passable for automobiles. The exact amount of road surface sand and gravel stored in the valley is unknown, but could potentially account for sediment not derived from gullies. Therefore, the sediment budget for the North Fork Crystal Creek basin from Site 1 to Site 5 includes 42 m^3 yr^{-1} of gully-derived sediment and 120 m^3 yr^{-1} from other fluvial processes and past road surface gravel erosion, resulting in a net deposition rate of 162 m^3 yr^{-1}. However, this calculation is based on a time-averaged rate of valley sedimentation of the entire 93-year period although the rate of gullying and other geomorphic processes most likely changed over time.

This change is noted in a comparison of cross-sectional area deposition rates for Site 1 and Site 3 from 1916 to 1963 and 1963 to 2009. The data show that the deposition rate has slowed drastically at Site 1 but has actually increased at Site 3. Cesium-137 analysis at Site 1 indicates that hillslope sediment production and gullying were very active with greater than 2 m of valley aggradation prior to 1963, equivalent to 78% of the current deposit. However, 96% of deposition at Site 3 occurred after 1963. This is equivalent to a 70% reduction in the deposition rate at Site 1 and a 1600% increase in the deposition rate at Site 3 from 1916 to 1963. The most likely explanation of this drastic change in deposition rates is that gully erosion slowed substantially by 1963, drastically reducing sediment yield from the hillslopes and creating an opportunity for sediment transport downstream from Site 1. Local deposition rates would vary significantly over time and space within the study area if gullies had stabilized only a few decades after the construction of the modern road as valley processes would begin to dominate creating opportunities for erosion, transport, and storage. This would also create significant variation in the contribution of gully erosion to total sediment yield of the basin throughout time.

Deposition rates in the North Fork Crystal Creek valley have not been constant, evidenced by the ^{137}Cs data. Deposition rates have varied at an individual site and between sites before and after 1963, making it very possible that gully erosion has accounted for a large range of total sediment yield in the North Fork Crystal Creek basin. Sidorchuk (1999) showed that approximately 35% of gully volume occurs over the first 5% of the gully's age and nearly 80% of gully volume occurs in the first half of the gully's life. Table III supports this model, showing that Site 1 experienced nearly 77% of its total aggradation in the first half of the gully's lifetime. Nachtergaele *et al.* (2002) demonstrated that gully volume increases following a negative exponential curve, where gully volume increases rapidly after initiation only to slow significantly over time. Poesen *et al.* (2003) showed gully erosion could account for a range of 10% to 94% of total fluvial sediment yield at the watershed scale. This large range would indicate the importance of the temporal scale of analysis in constructing watershed sediment budgets. Using time-averaged rates or current rates can possibly lead to erroneous assumptions about the movements of sediment within a basin over long time periods.

The inability of North Fork Crystal Creek to transport the sediment delivered by the surrounding hillslopes represents decoupling of the hillslope–channel system. Harvey (1994, 2001) showed that sediment delivered from a hillslope is often temporally decoupled from the stream valley due to insufficient stream discharge or deposition that is spatially disconnected from the channel. Once sufficient discharge is achieved or a flood of large enough magnitude occurs sediment can be transported downstream. The North Fork Crystal Creek basin is a low order stream channel with no tributaries other than the gullies, and has a small yet distinct floodplain along most of its length. Sediment transport downvalley only occurs after high intensity, low frequency precipitation events. In some locations, the transfer of gully-derived sediment is direct from the slope to the channel. At many other sites, sediment from gullies is deposited on the floodplain adjacent to the channel. This would imply that the system is temporally decoupled, unable to move sediment delivered directly into the channel until sufficient discharge is achieved. Additionally, there is spatial decoupling of the hillslope–channel interface as the channel is buffered causing aggradation of the floodplain away from the channel.

Gullies with width/depth ratios greater than one are usually the result of high intensity, low frequency rainfall events (Svoray and Markovitch, 2009). This supports the findings in the study area that high intensity, low frequency thunderstorms are the primary mechanism of gullying. The average width/depth ratio in the study area is greater than three and the minimum width/depth ratio is greater than one. There are no discharge measurements for the North Fork Crystal Creek watershed. However, the model proposed by Harvey (1994, 2001) fits the nature of sediment deposition and hillslope–channel decoupling in the North Fork Crystal Creek valley. The presence of coarse-grained gully sediment along the entire length of the stream valley and not just at locations where gullies enter the valley indicates that sediment does move through the system. However, sediment production from the hillslopes has occurred at a faster rate than sediment transport downvalley due to insufficient discharge and the presence of a small floodplain making downstream sediment transport irregular.

Other considerations

There are several limitations to the conclusions drawn in this study. The results of this research may not be applicable to the entire length of Pikes Peak Highway. While the entire length of the study area is currently asphalt paved, portions of the road at higher elevations are dirt and gravel, although the entire road will be paved in the future. This changes several assumptions about the concentration of runoff from the road surface and the relationship between precipitation intensity and discharge at individual sites. For example, several sites in the study area receive runoff from paved drainage ditches, which concentrates the runoff and increases the runoff velocity. Portions of the road that are unpaved usually do have associated drainage ditches adjacent to the road surface. However, the lack of asphalt pavement on the road surface and drainage ditches maintains a higher surface roughness and thereby does not increase the runoff velocity to the same degree as paved portions of the road.

The road configuration and various geomorphic factors change significantly above tree-line. There are many more road switchbacks above tree-line, whereby the pathway of the road changes by nearly 180º as a method of decreasing the gradient. Additionally, the average grade of the road is much steeper. This leads to increased runoff velocities, the release of runoff to hillslopes at each switchback, and smaller drainage areas required for gullying due to the steeper slope gradients. This is different from the study area because most gullies occur adjacent to the road since it usually occupies a ridge-top position as opposed to the cut and fill road design that occupies mid-slope positions above tree-line. Other changes above tree-line are reduced soil depth, reduced vegetation cover, and increased bedrock exposure. The differences above tree-line compared to the study area appear qualitatively significant, thus limiting the conclusions of this study area to forested, asphalt paved roads in montane and subalpine watersheds.

Results of this study reflect the current arrangement of the road surface and gullies. However, as discussed previously, the existence of the modern road for almost a century makes it very likely that significant alterations influencing the location and severity of gullying have occurred in the past. For example, several culverts have been removed or plugged, diversions have been created to re-route runoff pathways, and the majority of the road has recently been paved. Takken *et al.* (2008) concluded that a weak slope/drainage area existed for channel or gully initiation, most likely as a consequence of nearly a century of climatic variability, local moisture variability, and anthropogenic changes to the road configuration and runoff pathways in three watersheds associated with logging roads in southeastern Australia. While the slope/drainage area threshold for the gullying along the Pikes Peak Highway is distinct, climatic variability and anthropogenic changes to the road substantially limit estimations of erosion and deposition rates in this study. Without specific data and information regarding the changes made to Pikes Peak Highway throughout its 93 year history, it is unknown if the current spatial and temporal patterns of gullying in the surrounding watersheds are primarily due to climatic variability or anthropogenic changes.

Conclusion

The presence of roads in steep, mountainous terrain alters the surface hydrology of the area by concentrating runoff, changing runoff pathways, and rearranging drainage networks. These alterations to the natural drainage system often cause severe gully erosion, diminished water quality, and damage to aquatic, wetland, and riparian habitat in watersheds such as those impacted by Pikes Peak Highway. The cut and fill design of mountain roads, the presence of switchbacks, and related drainage ditches and culverts can destabilize slopes and concentrate runoff by discharging it onto the hillslope. The paving of the roadway and drainage ditches has eliminated the need for additional sand and gravel to maintain the road surface. However, it has most likely increased runoff velocity on the road surface and in drainage ditches by lowering surface roughness and reducing sediment load. The highly weathered and erodible Pikes Peak granite that underlies the entire study area is a primary factor in the occurrence of severe gullying. Once a gully has incised downward and removed thin layers of soil and vegetation, coarse, non-cohesive grus deposits are easily eroded from the hillslopes by discharge from short duration, high intensity thunderstorms that occur during the summer.

This study demonstrates that Pikes Peak Highway alters the threshold required for gullying when compared to natural or non-impacted basins in the area. Analysis of deposition in one impacted stream valley shows that hillslopes are temporally decoupled from the channel in the North Fork Crystal Creek basin, with large deposits of sediment in the upper extent of the valley and smaller deposits in the middle and lower portions of the stream. Discrepancies in the deposit depth are most likely due to increases in discharge that occur moving downvalley which allow for more sediment transport to occur in the middle and lower reaches of North Fork Crystal Creek.

The excessive sedimentation of stream valleys has severely damaged water quality, mountain wetlands, and riparian and aquatic habitat in basins affected by Pikes Peak Highway. The decoupled nature of the hillslope–channel system in Pikes Peak Highway watersheds causes the effects of the environmental disturbance to be severe. The majority of sediment ends up being stored locally in valleys and not transported through the system. This results in large-scale deposition of sediment in headwater basins that is unable to be moved due to insufficient discharge. In a headwater basin, the introduction of a significant environmental disturbance in the form of a road surface could have immense consequences for the rest of the drainage network as headwater basins provide most of the water and sediment to stream networks. In directly coupled hillslope–channel systems, sediment moves through the basin rather quickly either dissipating the intensity of the disturbance or possibly moving it downstream. However, in systems that are transport limited, as is the case of North Fork Crystal Creek, the effects of the disturbance are magnified resulting in large-scale deposition and minimal sediment transport. This demonstrates that decoupled systems are dynamic with periods of indirect and direct interaction between the hillslope and the channel responding to the disturbance on its own spatial and temporal scale.

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