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Rates of gully erosion along Pikes Peak Highway, Colorado, USA

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Abstract: Pikes Peak Highway is a partially paved road between Cascade, CO and the summit of Pikes Peak (4300 meters). Significant gully erosion is occurring on the hillslopes due to the concentration of surface runoff along the road surface and adjacent drainage ditches. As a result, large quantities of sediment are transported to the surrounding valley stream networks causing significant damage to riparian, wetland, and aquatic environments. This study addresses the rates of gully erosion along the Pikes Peak Highway.

Keywords: gully erosion, roads, mountains, hillslopes

Introduction

Gully erosion commonly occurs in mountain watersheds where surface runoff is impacted by the presence of roads crossing steep hillslopes. Watersheds associated with roads require smaller critical slope values for a given drainage area for gully initiation compared to watersheds not associated with road surfaces, holding all other factors constant (Montgomery & Dietrich 1994; Desmet et al. 1999; Croke & Mockler 2001; Nyssen et al. 2002; Moeyersons 2003). Roads extend the channel network and rearrange drainage patterns, thus increasing flow concentration in drainage ditches and culverts that can lead to channel or gully initiation at points of discharge from the road surface to the 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 & Mockler 2001; Nyssen et al. 2002; Moeyersons 2003; Poesen et al. 2003).

Gully development in the downslope direction has been observed on several occasions (de Oliveira 1989; Moeyersons 1991; Moges & Holden 2008). This is opposed to the standard model of gully formation by headcut retreat due to plunge-pool action by overland flow and subsurface piping that cause destabilization of the gully head (Bocco 1991). Downslope progression of gullies has been observed on steep slopes where the headcut is physically blocked and prevented from retreating upslope by the presence of a road (Moeyersons 1991). The initial incision is usually due to concentrated overland flow or a small mass wasting event. Gullies erode and enlarge in the downslope direction due to concentrated overland flow that creates a series of potholes forming small hydraulic drops downslope. If they enlarge enough and merge, a distinct gully can develop and extend to the valley floor. The degree of development in the downslope direction is related to peak discharges, hillslope profile and gradient, and soil erodibility (Moeyersons 1991). Gullies observed in this study appear to have developed through the latter set of processes.

Nachtergaele et al. (2001) and Moges & Holden (2008) 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) 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.

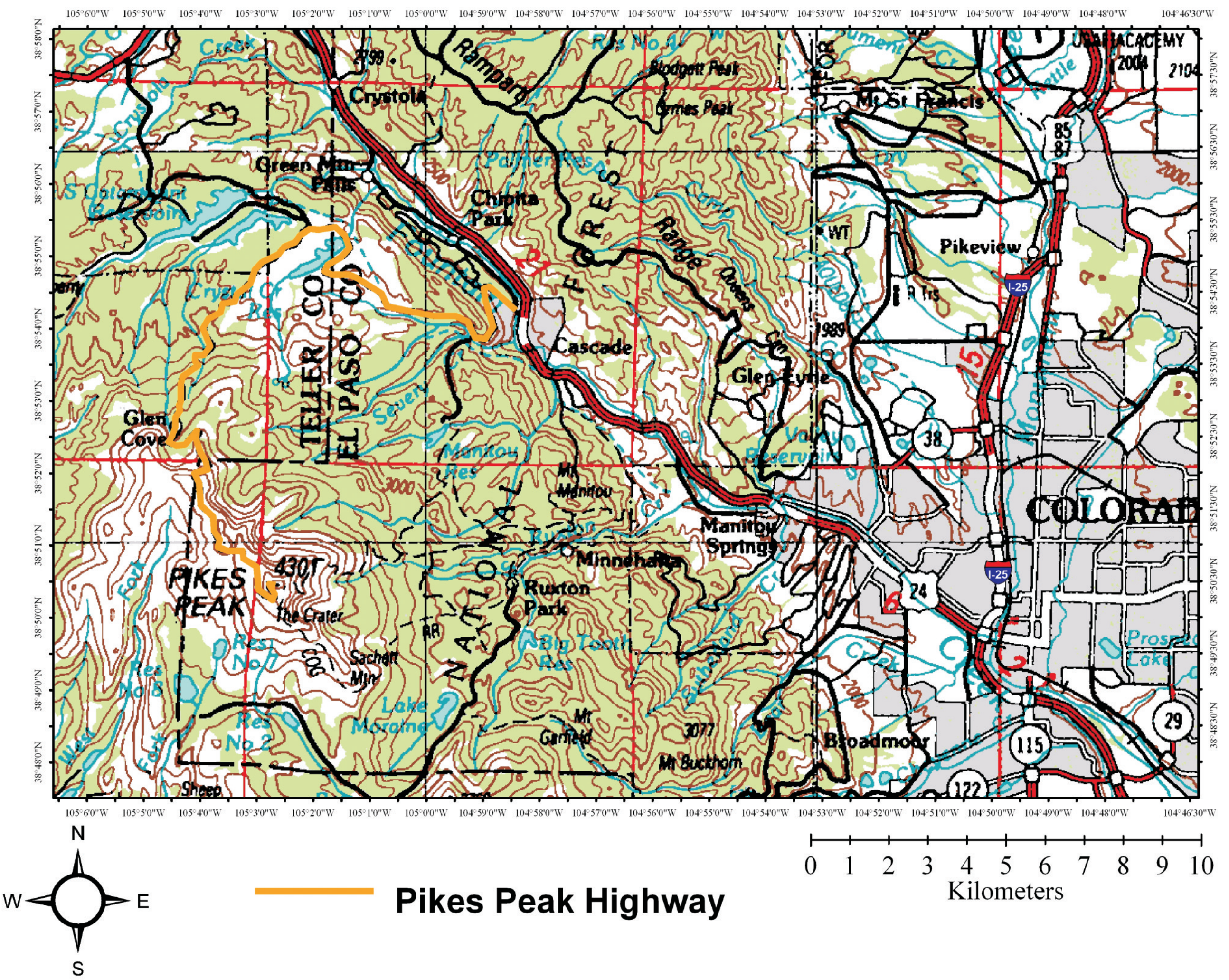

Fig. 1. Pikes Peak Highway is located west of Colorado Springs off U.S. Highway 24 at Cascade, CO and ends at the summit of Pikes Peak (4300 m). The majority of the road is located within the Pike-San Isabel National Forest and is approximately 30.5 km in length

Pikes Peak Highway has caused significant gullying on hillslopes in the Pikes Peak Highway watershed (Fig. 1) and is adversely affecting water quality and wetland and riparian habitat (Fig. 2). This study investigates rates of gully erosion on surrounding hillslopes along a segment of Pikes Peak Highway.

Study area

Pikes Peak Highway is a partially paved road between Cascade, CO and the summit of Pikes Peak at 4,300 m a.s.l. (Fig. 1). This mountain roadway was first built in the late 1800s as a carriage road to the summit and was later improved for automobiles in 1916. It is approximately 30.5 km, with the majority

Fig. 2. Gullying due to concentrated surface runoff from Pikes Peak Highway and associated drainage ditches

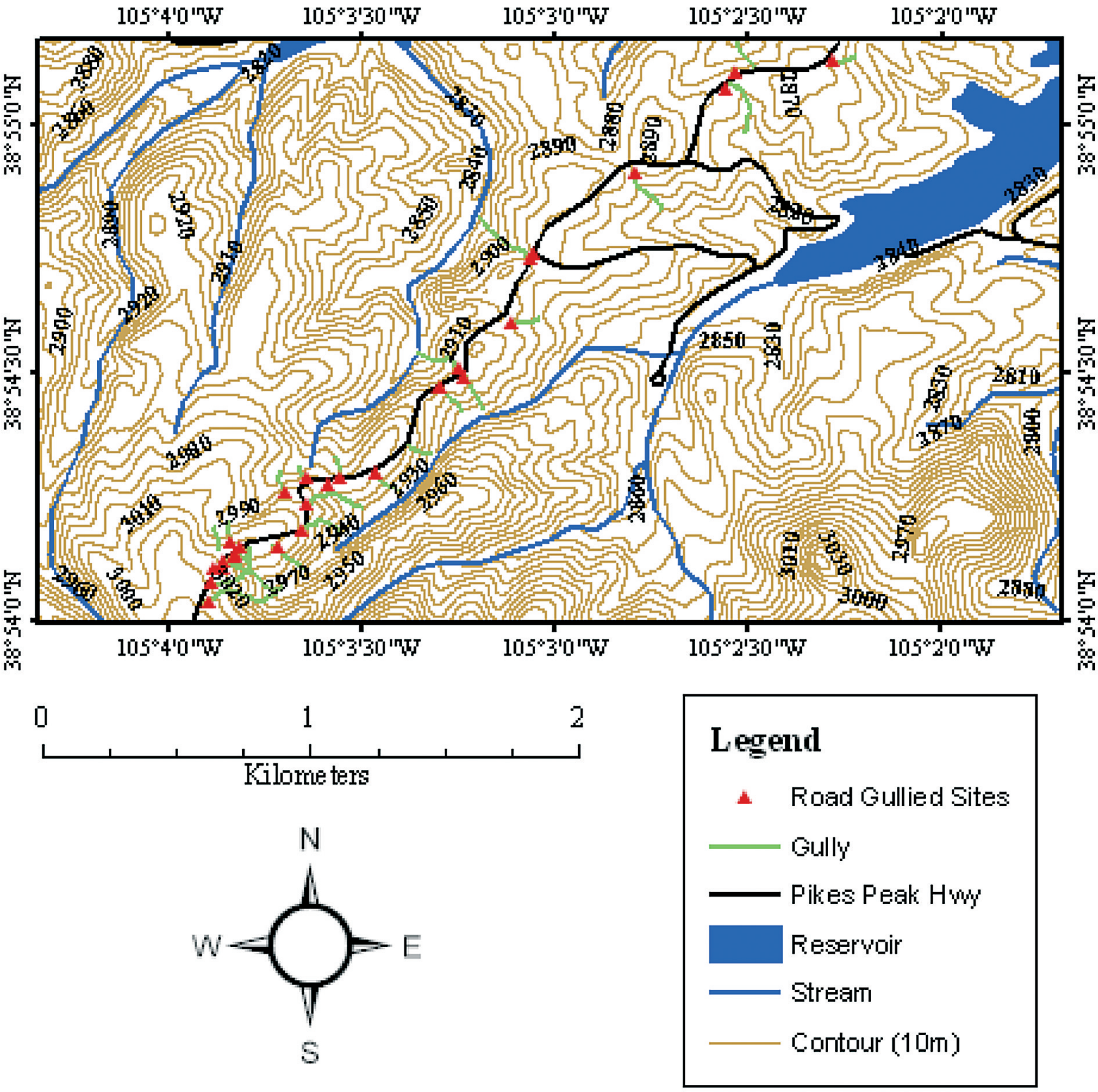

Fig. 3. Map of the study area located in the Pike-San Isabel National Forest with 20 gully sites along the road. Road km 11 to km 17 of the Pikes Peak Highway is shown (along with reservoir access roads)

of the road surface fully paved. The road is administered and monitored by the United States Department of Agriculture Forest Service in conjunction with the City of Colorado Springs, Colorado.

The study area in this research consists of a 5.2 km segment of the road from km 11.3 to km 16.5 (Fig. 3). The elevation range of this road segment is 2,750 m to 3,150 m and its overall orientation is northeast to southwest. This elevation range is ideal because it is below tree-line, entirely asphalt paved, and represents one of the densest areas of gullying along the roadway. The slopes off the road in the study area are steep, ranging from 10 percent to 40 percent. Bedrock is Pikes Peak granite, a plutonic igneous rock containing large amounts of coarse-crystalline quartz and orthoclase that weather easily into highly erodible grus. 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 Glen Cove snow telemetry (Snotel) site nearby and a precipitation gauge in the study area (USDA NRCS 2010). 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. Runoff from the road drains into two reservoirs via two headwater stream basins. The North Fork Crystal Creek basin, located to the southeast of the study area road segment, is more highly impacted by gullying, which occurs along the entire length of the valley. The majority of the sediment provided by gullying in the study area is deposited in the North Fork Crystal Creek basin, which runs approximately parallel to the Pikes Peak Highway for the entire study area (Fig. 3).

Methods

A gully was defined as a distinct channel formed at or near the point of surface runoff discharge from the road surface and extending to the valley floor. Gullies were surveyed with a measuring tape and 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. 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. A ratio of 0.5 represents a perfectly triangular cross-section, while a ratio of 1.0 represents a perfectly rectangular cross-section. Ratios between 0.5 and 1.0 represent various geometric possibilities based upon a trapezoidal cross-section. 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 (1):

$$V = 0.5*w*d*l \quad (1)$$

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 (2):

$$V = w*d*l \quad (2)$$

This equation represents a rectangular cross-section. Individual gully volume was calculated by multiplying the rectangular volume by the assigned coefficient. Based on an estimate of total gully volume for the study area, erosion rates were calculated based upon the date of road construction completion ninety-three years ago in 1916.

Results

Table 1 shows summary statistics for volume, volume coefficient, maximum width, maximum depth, and width/depth ratio for all twenty gullied sites along the road. Total gully volume in the study area is estimated at 5,974 m^3, with a mean individual gully volume of 299 m^3. There is significant variability in individual gully volume, with the smallest gully approximately 5 m^3 and the largest approximately 1,138 m^3. The range for all parameters excluding the volume coefficient was very large. Median values for all variables except the width/depth ratio were smaller than corresponding mean values.

Based on an estimated date of gully initiation in 1916 and a current gully volume of 5,974 m^3 as of summer 2009, the time-averaged gully erosion rate is 64 $m^3\ yr^{-1}$. The estimate for gully volume has a lower bound of 3,630 m^3 and an upper bound of 7,260 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 $m^3\ yr^{-1}$.

Since the exact date of the onset of gullying is unknown these values represent a minimum erosion rate. It also assumes a constant rate through time though we suspect that rates are higher during some periods in the past. 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.

Table 1. Summary statistics of mean, median, minimum, maximum, and range for gully morphology variables for the study area. 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

Road gullied sites (n=20)	Mean	Median	Minimum	Maximum	Range	Total
Volume (cu. m)	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	–

Discussion

The calculated erosion rate of 64 $m^3\ yr^{-1}$ is a time-averaged estimate of erosion from 1916 to 2009 and based upon the incorporation of field observations on site specific geometry. Therefore, it provides an estimate of a mean amount of sediment removed from the slopes and delivered to the valley in any given year, being particularly useful in constructing a sediment budget for impacted watersheds. However, erosion rates are certainly not uniform between the gullies or uniform within an individual gully over long time periods.

Field observations indicate that runoff is not uniformly delivered to gullies during precipitation events and the proportion of runoff released at each site varies 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 ninety-three years most likely resulting in significant discrepancies in discharge at individual sites. Additionally, the time span of almost a century certainly contained significant changes in total precipitation and rate of snowmelt in the study area.

One major assumption in these calculations 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 accuracy 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.

Based on a comparison of volumetric estimates for erosion and deposition for the North Fork Crystal Creek basin, it is likely that significant gully erosion did not begin to occur until well after 1916. However, the exact date of the onset of gullying is unknown, although Cesium^{-137} concentrations (data not shown) indicate that it began prior to 1954. Therefore, 1916 represents the maximum age and 1950 the minimum age for the gullies creating a lower estimate of 64 $m^3\ yr^{-1}$ and an upper estimate of 101 $m^3\ yr^{-1}$ for the twenty gullies. Other potential erosion rates based upon various years for the onset of gullying for the study area are shown in Table 2.

This research is an excellent example of gullying in the downslope direction. The road and associated drainage ditches concentrate surface runoff that is discharged onto hillslopes. This results in incision on surrounding hillslopes and the formation of gullies. These gullies are prevented from moving upslope by the road surface and have no distinct headcut, thus can only erode in the downslope direction. The gullies often enlarge moving downslope as more runoff is directed to the gully channel from the surrounding basin. Additionally, the gullies in the study area are a direct link from the road to the stream valleys serving as the mechanism for transferring the environmental disturbance from the road to the stream valleys.

Table 2. Potential volumetric gully erosion rates for the study area

Onset of gulling	Erosion rate – study area [cu. $m^3\ yr^{-1}$]
1916	64
1920	67
1930	76
1940	87
1950	101

Conclusion

The presence of Pikes Peak Highway in high elevation Rocky Mountain terrain significantly alters the surface hydrology of the area by concentrating runoff, changing runoff pathways, and rearranging drainage basins. The highly weathered and erodible Pikes Peak granite that underlies the study area complicates the balance between discharge and road surface sediment. Once a gully has incised downward and removed thin layers of soil and vegetation, coarse grus deposits are easily moved by discharge from short duration, high intensity thunderstorms that occur during the summer. This results in significant gullying on the hillslopes surrounding Pikes Peak Highway linking the disturbance to the valley stream networks where large quantities of sediment are deposited.

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