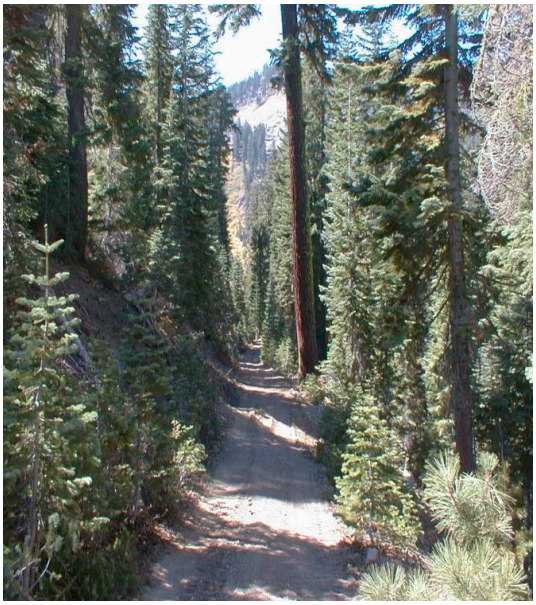
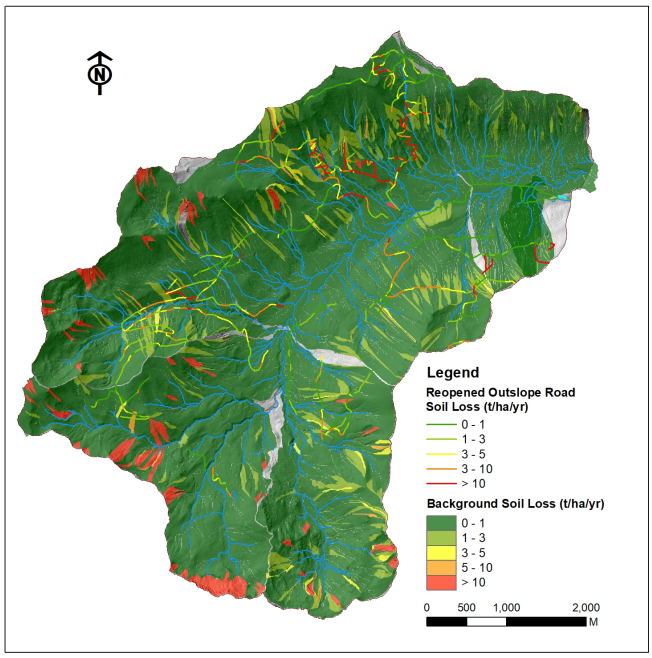
Modeling the Effects of Reopening Abandoned Roads on Hydrology and Soil Loss in a Forest Watershed

Final Report



(Villanueva, 2013)



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Abstract: Reopening abandoned forest roads altars the runoff and soil loss processes in a watershed. In this study, a forest watershed was chosen and abandoned roads were manually identified, aided by a high-resolution LiDAR topographic image and historic photographic images. GIS technologies were the used to describe topographic details and estimate runoff and erosion from a 10-m cell size non-road digital elevation model (DEM) for hillslopes. A 1-m cell size DEM was used to evaluate current effects of the road network, and a modified 1-m DEM to evaluate reopening closed roads with either an insloping or an outsloping design on surface hydrology and the stream network. The GeoWEPP interface to the Water Erosion Prediction Project (WEPP) Model was employed to predict road-related runoff and soil loss from hillslopes and upland channels using a 2m DEM. The WEPP:Road online interface was used to estimate runoff and erosion from current and reopened road segments. The results showed that watershed channel length may be reduced after road removal but increased if abandoned roads were reopened. Road reopening might eliminate some channels and generate new ones by intercepting upstream runoff and changing flow accumulation. Reopening roads by insloping will likely affect the channel network to a greater extent than by outsloping. Modeling results of typical sub-watersheds revealed that the average annual sediment delivery would be increased by 15.5% if roads are reopened using an inslope road profile, and reduced by nearly 20% if all roads are removal. The reduced soil losses from road removal are mainly from reduced channel erosion rather than from hillslope erosion. The sediment delivery ratio increased without the road's effect in blocking overland sediment transport. WEPP-Road modeling results revealed that the average soil loss rates of reopened roads segments could be 7 times higher than the background rate. Soil loss risk was especially high for reopened inslope road segments close to streams or with steep gradients. Reopened roads that pass through silt loam soils are likely to generate more sediment than roads in sandy loam soils. Regression functions were developed to describe the spatial variation of soil loss risk due to road reopening. Critical distance between roads and channels can be determined to help make decisions in abandoned road reopening and watershed management.

Key words: LiDAR; forest road erosion; road management; watershed management

Figure 1. Same road section as shown on the cover page, but after it has been "recontoured" (Villanueva, 2013**).**

1. Introduction

The road network is one of the main disturbances that can result serious soil loss in forested watersheds (Elliot, 2013; Grace III, 2017). In forest watersheds, due to the unique surface soil characteristics and hydrological effects, unpaved roads contribute a large proportion of the sediment although they generally occupy only a small fraction of the area (Reid and Dunne, 1984; Ziegler and Giambelluca, 1997; Motha et al., 2004; Water Boards and NDEP, 2008; Grace III, 2017). Road-related sediment that is routed to water bodies such as lakes and rivers can cause serious damage to the aquatic environment and impair beneficial uses of surface water resources, reducing both water quality, and the reservoir storage capacity (Gucinski et al., 2001; Elliot et al., 2016). It is imperative that the effects of roads on forested watersheds be quantified, and management methods to reduce runoff and sediment delivery evaluated to reduce these undesirable effects.

Unpaved road surfaces are characterized by low infiltration rates and easily generated Hortonian overland flow (Dunne, 1979; Ziegler et al., 2000; Croke and Mockler, 2001). Soil erosion rates on road surfaces can be ten times higher than that observed on agricultural land (Ziegler et al., 2000). Furthermore, roads may change the underlying topography and alter surface hydrology or interact with geomorphic processes (Gucinski et al., 2001; Wemple et al., 2001). Upstream runoff may be intercepted and accumulated along road segments, resulting in increased soil loss from the road surface and ditches (Negishi et al., 2008; Cao et al., 2014; Grace III, 2017). At a watershed scale, road segments can be treated as channels that intercept overland flow. In turn some road segments may enhance the risk for gully initiation and reduce the distance between onsite sediment generation and downstream channels (Katz et al., 2014). Road networks linked with stream networks and may increase stream density within a watershed (Gucinski et al., 2001; Wemple et al., 1996; Croke and Mockler, 2001). Thus the road network may increase watershed peak flow and sediment generation rates (Jones and Grant, 1996; Soulis et al., 2015; Thomaz et al., 2014).

When considering watershed restoration, some unneeded forest roads are abandoned to control soil erosion or promote ecological recovery (Bell, 2000; Switalski et al., 2004; Water Boards and NDEP, 2008). The abandoned roads can be classified as different levels ranging from closed to traffic with natural revegetation to full obliteration with recontouring and the restoration of natural slopes (Figure 1; Coghlan and Sowa, 1998; USDA Forest Service, 2003). After abandonment and treatments such as subsoiling and/or mulching, road surface vegetation will reestablish and soil erosion risks reduced (Figure 1; Switalski et al., 2004; Luce, 1997). Road abandonment followed by mitigation measures can decrease soil bulk density and increase infiltration capability (Bradley, 1997; Luce, 1997; Foltz et al., 2007). In the case of removing a roadbed and the original contour reconstructed (Figure 1), the hydrological influence of road segments can

be considerably reduced, as well as road surface erosion and the risk of landslides (Madej 2001; McClelland et al. 1997; Switalski et al., 2004); compare the road segment on the cover page with Figure 1. However, it is also common to reopen the closed forest roads for management activities such as timber harvesting operations, hazardous fuel reduction practices, and woody biomass utilization efforts (Foltz et al., 2009). Reopening abandoned roads results in the loss of surface vegetative cover and disturbance of the road surface soil usually causing increased surface runoff and erosion (Foltz et al., 2009). In addition, the reconstruction of road cut and fill slopes may change the surface hydrology and accelerate soil erosion both on and off the road. Thus the possible environmental impact before and after reopening the abandoned roads should be evaluated when making decisions in watershed management.

Soil erosion models can be effective tools in predicting soil loss from road surfaces (Elliot et al., 1995; Ziegler et al., 2001; Elliot, 2004; Elliot et al., 2018b and 2019). With the aid of GIS technology and enhanced modeling methods, the influence of the road network on watershed scale hydrology and sediment process can also be evaluated (Brooks et al., 2006; Akay et al., 2008; Araujo et al., 2014; Parsakhoo et al., 2014; Soulis et al., 2015; Elliot et al., 2018b and 2019). The determination of topographical factors, such as road gradient and distance to the stream, are necessary for modeling road sediment delivery within a watershed (Elliot, 2004; Brooks et al., 2006). Watershed scale analysis requires that the road networks should be delineated first and the topographic information about them determined by field survey or GIS methods (Brooks et al., 2006; Soulis et al., 2015; Elliot et al., 2018b and 2019; Black, 2019). However, many of the abandoned roads are not on maps or databases and can be heavily vegetated after long period of disuse. These roads are sometimes referred to as “ghost roads” or “legacy roads.” Such roads can be difficult to identify from satellite images or with field surveys due to their poor visibility and accessibility (Photo on Cover Page). Thus it is challenging to evaluate the influence of reopening abandoned or ghost roads on watershed hydrology and sediment generation.

The LiDAR (Light Detection and Ranging) technology can transmit radio waves through the forest canopy to determine detailed terrain information. In recent years, high resolution LiDAR data have been adopted for precise hydrologic or topographic analysis (Yang et al., 2014; Persendt and Gomez, 2016). LiDAR also can be used to identify and digitize forest road locations (White et al., 2010; Azizi et al., 2014), and road-related overland flow path identification (Sosa-Pérez and MacDonald, 2017). If a LiDAR DEM is available, it may beneficial for evaluating the hydrologic and sediment response to road abandonment, removal or reopening in a forest watershed.

High resolution LiDAR terrain data were available for this study and were used to support runoff and erosion modeling to: (1) evaluate the influence of road opening or removal on watershed hydrology and soil loss risk, and (2) develop management tools that can help to evaluate the risks and benefits of reopening or removing road segments within a sensitive watershed.

2. Methods

2.1 Study area

The study site was the Blackwood Creek watershed on the southwestern part of the Lake Tahoe basin, located just west of the state boundary between California and Nevada, US (Figure 2). The Blackwood watershed area is 29 km^2 and the elevation ranges from 1,898 m to 2,707 m. Volcanic bedrock consisting of andesitic and basaltic rocks predominantly underlies the watershed and serves as the parent material for most of the soils. Overlying the volcanic parent material are numerous fluvial and glacial deposits. The watershed contains “badland” areas that are poorly vegetated with deep gullies that have formed in andesitic labar colluvium; these soils are particularly erodible, while soils on granitic or meta-sedimentary lithologies have lower erodibility (Stubblefield et al., 2009). Wet winters and dry summers characterize the climate with deep snow accumulations at higher elevations. Influences from the Pacific Ocean and orographic effects result in extreme precipitation differences between the west and east sides of the lake, with the wetter

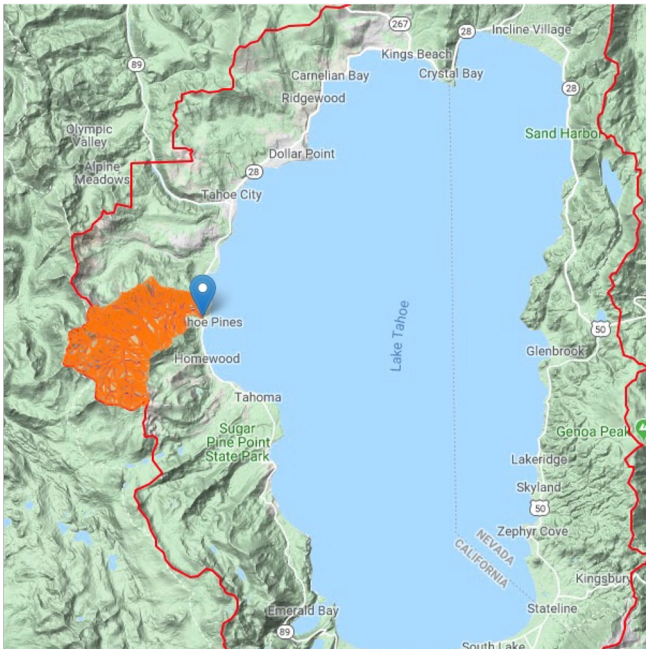

Figure 2. Blackwood Watershed in orange located on the western part of the Lake Tahoe Basin (https://wepp1.nkn.uidaho.edu/weppcloud/).

west-side of the basin receiving nearly five times more precipitation. The watershed's hydrology is dominated by snowfall accumulation and melt, and rain-on-snow events, at lower elevations (Brooks et al., 2016). Aside from the badland areas, vegetation is comprised of mixed conifer forests with significant areas covered by meadows, riparian areas, or bare granite outcrops (Coats et al., 2008).

Blackwood Creek was severely degraded by more than a century of disturbances including gravel mining, logging (late 1800s - 1970) and grazing (1864 - 1982) (Tetra Tech, 2001; Stubblefield et al., 2009). In 1950s, large scale logging began, and extensive logging road systems were constructed throughout the watershed. The associated loss of vegetation and the network of logging roads resulted in heavy erosion. By 1970, the large scale logging operations stopped and several restoration projects were conducted in the following decades (Immeker, 2012). According to the report by California Tahoe Conservancy, the Blackwood Creek watershed still contributes more than 1900 tons of sediment annually, and more than 21.5 tons of fine sediment per square kilometer per year. Stubblefield et al. (2009) stated that "the watershed generates more fine sediment per unit of area than any other watershed in the Tahoe Basin." They also note that the Blackwood Creek watershed has been listed by the California State Water Resources Control Board as "impaired" due to excessive sediment and nutrient loading.

The legacy logging road networks and skid trails in the Blackwood watershed were reported to be major contributors to the large amounts of sediment generated by the Blackwood Watershed (Swanson, 2003). After the logging activities ceased in 1970s, most of the logging roads were abandoned and many naturally vegetated. Some roads, however, are now used for off road vehicle access[1]. In recent years, numerous agencies within the basin have been initiating restoration projects in the watershed to reduce sediment delivery, and more recently, to initiate forest management activities to reduce the risk of wildfire as the forests regenerate (Elliot et al., 2009). To support forest management and other conservation activities, it will be necessary to reopen some of the abandoned roads (Guccinski et al., 2001; Foltz et al., 2009; Elliot, 2013).

[1] http://laketahoerecreation.com/nor_rates/tahoe_ohv_trails.pdf

Figure 3. Abandoned roads in satellite image (a) and LiDAR-based hillshade (b)

LiDAR remote sensing data for the Lake Tahoe Basin were collected by Watershed Sciences, Inc. (WSI) in August 2010. The survey used two Leica ALS50 Phase II laser systems mounted in a Cessna Caravan 208B. A raster elevation data set with a resolution of 0.5 m was created based on the ground return points from the LiDAR flight.

2.2 Road network delineation and terrain modification

After decades of natural restoration, most of the abandoned logging roads in the Blackwood watershed were covered by vegetation and hard to discern even in a high-resolution satellite image (Figure 3a). The high-resolution LiDAR DEM showed the terrain details of road embankments and were therefore used to delineate the abandoned road networks in the watershed (Figure 3b). A "Hillshade Layer" was developed by the GIS to visualize terrain details as shaded relief (Buckley, 2018). The abandoned roads can then be delineated by manually digitizing a linear shapefile feature following the center lines of road traces. To distinguish abandoned roads from other linear features such as old channels, only traces that were connected to the main roads were recognized as part of road network. In addition, a high-resolution satellite image from 2017 was used to differentiate the abandoned roads from the currently active roads. The traces of abandoned roads are sometimes discontinuous and difficult to be tracked with LiDAR hillshade. An aerial image of the year 1969 when many of the abandoned roads were active was used to help identify their location. The delineated road network attributes are summarized in Table 1and illustrated in Figure 4.

Most of the abandoned roads shown in the LiDAR DEM had rough surfaces and in some cases, incomplete road banks. Reopening the abandoned roads requires removal of the vegetation restoring the cut slope and regrading the road surface (Foltz et al., 2009). Therefore, the original LiDAR terrain will need to be changed to reflect the new topography of reopened roads. For this study, all abandoned roads were assumed to be reopened and topography to describe both outslope and inslope road designs were evaluated. A new raster layer was created to a simulate smoothed road surface by: (1) extracting the underlying elevation for road centerlines and smoothing the elevation along roads with 10m size windows, (2) duplicating the elevation parallel the centerlines' elevation to both sides of road surface according to the road width, (3) slightly raising or lowering the elevation of the outer side to form a 4% gradient inslope or outslope road surface

Table 1. Quantitative description of road networks in Blackwood watershed

Type	Count	Width (m)	Length (km)
Current Roads	1	8	10.25
	2	6	5.72
Abandoned Roads	13	6	25.24
	27	5	19.4
	16	4	7.65

design, (4) interpolating the elevations for the road surfaces and using the new elevation pixels to modify the original LiDAR DEM. The two modified DEMs for insloping or outsloping roads now describe the rebuilt road prisms with smoothed road surfaces. These new DEMs were used to predict the surface runoff flow paths for either insloped or outsloped conditions for the reopened roads.

2.3 GIS-based flow stream network spatial analysis methods

In order to evaluate the effect of road networks on surface flow paths and the stream network, GIS hydrological analyses were conducted within the ArcGIS 10.3.1 environment based on the different DEM datasets. The original 0.5m LiDAR DEM was reclassified as 1m DEM and GIS tools were used to delineate channel networks for the current condition with the existing ghost road topography. Both outslope and inslope road-modified 1m LiDAR DEMs were developed to simulate flow paths and extract possible channel networks after road reopening for each design. For a non-roaded condition, the original LiDAR DEM was reclassified as 10-m DEM to mask the road prisms. The channel network for the 10-m DEM was then delineated to show a non-road condition for the watershed, the condition that would result if the roads were completely removed. GIS Spatial overlay and buffer analyses were conducted to explore the spatial relationship between channel networks and road networks.

2.4 Erosion Modelling Methods

The Water Erosion Prediction Project (WEPP) Model is a physically based soil erosion model, and is particularly suited to modeling the conditions common in forests (Elliot, 2004 and 2013). It has been shown to be an efficient tool in estimating soil loss from unpaved forest roads (Elliot et al., 1995; Tysdal et al., 1999; Elliot et al., 2018b and 2019). Two different versions of the WEPP model were applied to simulate runoff and sediment generation as influenced by road networks, a hillslope version and a watershed version (Flanagan and Nearing, 1995). The hillslope version was used for estimating sediment delivery to ephemeral or seasonal channels from individual road segments. The WEPP Watershed Version predicts runoff, erosion and sediment delivery from hillslope polygons and channel segments (Flanagan et al., 2013; Miller et al., 2015). With a high-resolution DEM, the Watershed Version can incorporate the effect of road topography on hillslope, road and channel runoff, erosion and sediment delivery (Elliot and Tysdal, 1999).

GeoWEPP is a GIS wizard that allows users to import and utilize their own detailed terrain, soil and landuse information or to access publicly available spatial datasets for geospatial application of the WEPP Watershed Version (Flanagan et al., 2013). The GeoWEPP model version 10.3 was adopted in the AcrGIS 10.3.1 environment for runoff and soil loss estimations in the Blackwood Creek watershed.

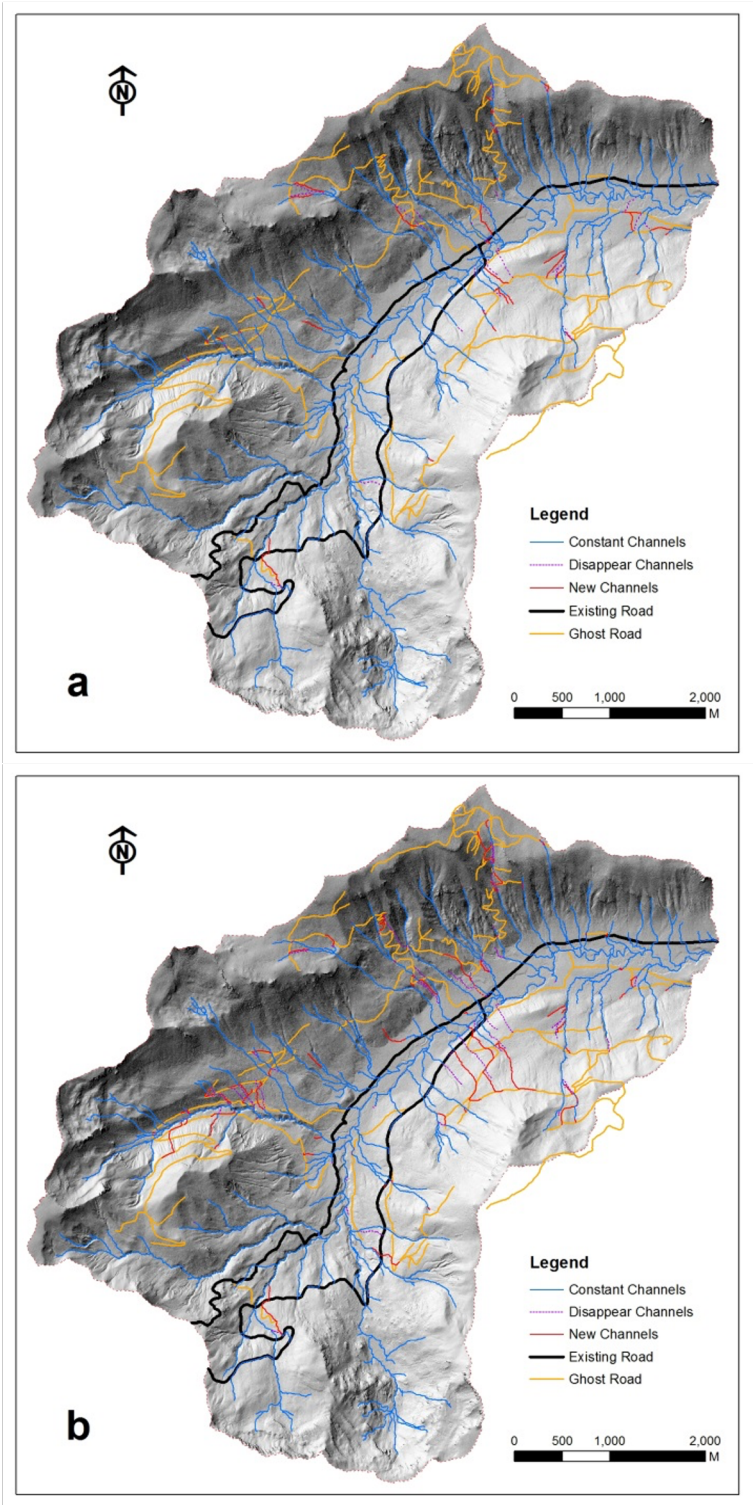

Figure 4. Channel network before and after road reopening (a) for outslope road reopening and b) for inslope road reopening

2.4.1 GeoWEPP application in watershed modeling

Topography, soil and landuse data were preprocessed before running the GeoWEPP wizard to ensure the GIS projections were compatible. Four different terrain datasets were used for GeoWEPP modeling, including the 10m DEM which ignores road effects on overland flow, the original LiDAR DEM that contains topographic details of the current open and abandoned roads on the landscape, and two modified LiDAR DEMs that describe either reopened outsloping or reopened insloping road topography. When running GeoWEPP on a PC, 1-m or finer LiDAR DEM data sets have been observed to generate too many flow paths for a PC to process. Therefore the 1-m DEM that was used for the stream network flowpath analysis was reclassified as a 2-m DEM for watershed scale road, hillslope and channel soil loss prediction.

The 10-m resolution land cover and soil data were downloaded from the Rapid Response Erosion Database (RRED)[2]. Michigan Technological Research Institute (MTRI) developed RRED together with US Forest Service and NASA (Miller et al., 2015). The landuse and soil data were also reclassified as 2-m raster files to be compatible with the 2-m LiDAR-based DEM. In the case of reopened road modelling, the land use and soil properties were revised to describe the unpaved road surface for those cells that were associated with the roads.

Within GeoWEPP, the TOPAZ program delineated channel networks (Flanagan et al., 2013). A critical source area (CSA) of 0.5 ha was specified to generate a channel network to link most of the hillslopes within the Blackwood watershed to Blackwood Creek. Because the 2-m resolution DEM data set is too large for the entire watershed to be processed in a single run, we divided the watershed into sub-watersheds and ran the WEPP Watershed model for each one. Within the Blackwood Creek watershed we selected 10 sub-watersheds with road networks to determine the road influence on runoff and erosion. The average area of the selected sub-watersheds was about 50 ha.

The stochastic climate file for all the watersheds was built from statistics from the observed daily temperature and precipitation data from the Tahoe City Cross Station. The station is located 7 km northeast of the center of the Blackwood Creek Watershed. All the simulations were run for 20 years of stochastic weather.

2.4.2 WEPP:Road application for road segment modeling

The WEPP:Road interface to the WEPP Model was adopted to simulate the soil erosion from possible reopened roads by individual segment[3]. This interface is one of the online tools developed by the USDA Forest Service for the WEPP model to easily predict soil erosion for a wide range of road conditions (Elliot, 2004). WEPP:Road can estimate runoff, erosion and sediment delivery from forest roads by modeling the process as three overland flow elements: a road, a fillslope, and a forested buffer (Elliot and Hall, 1997). The input parameters are daily climate, soil texture and gravel addition, road design, road topographic factors, road width and management information.

Road networks in a watershed need to be divided into segments before erosion modeling (Brooks et al., 2006; Wemple et al., 2017; Elliot et al., 2018b and 2019; Black, 2019). GIS processes were applied to divide the road network into segments and determine the topographic attributes of each segment and the associated flow path to the nearest channel. The road segmentation procedure assumed that runoff will leave road surface when there are low spots or runoff rates are large enough to spill off the road surface. In the first step of the analysis, the low points were identified by the "Focal Statistics" tool within a given radius along roads. The flow accumulation was calculated and overlaid with road network. Then roads were then split by the low points and flowpath-road intersections. Our calculations showed that the low points within a 50m radius along road combined with the flow path extracted by 3-ha Critical Source Area provide reasonable road segmentation. A Total of 645 road segments were delineated and the topographic factors

[2] http://geodjango.mtri.org/geowepp/
[3] https://forest.moscowfsl.wsu.edu/fswepp/

Table 2. Comparison between channel networks as delineated from different DEMs

Order	10 m LiDAR DEM			1 m LiDAR DEM			Outslope road modified 1 m LiDAR DEM			Inslope road modified 1 m LiDAR DEM		
	N	Total length (km)	Mean length (m)	N	Total length (km)	Mean length (m)	N	Total length (km)	Mean length (m)	N	Total length (km)	Mean length (m)
1	196	58.96	300.81	201	60.79	302.42	194	61.36	316.3	200	64.01	320.07
2	87	22.37	257.16	98	26.25	267.84	99	29.98	302.8	101	30.23	299.31
3	39	11.1	284.54	41	14.95	364.61	38	11.61	305.63	38	11.38	299.49
4	24	4.76	198.28	23	4.45	193.32	20	4.45	222.25	22	4.45	202.08
5	42	5.98	142.3	35	7.09	202.53	33	7.09	214.7	34	7.09	208.48
Total	388	103.2	265.9	398	113.5	285.2	384	114.5	298.1	395	117.2	296.6

were calculated for each road segment. Road segment length was determined by a geometric calculation function. Road segment gradient was calculated as the elevation difference between two ending points divided by road segment length. For each road segment, the lower end was selected to measure the forest buffer length, that is, the distance to downstream channel. ArcGIS does not have a function to calculate the distance directly. We flipped the DEM by subtracting the original DEM from a constant value. The upstream flow path distance with the flipped DEM served as an approximation of the flow distance from any point in a watershed to the nearest channel.

The climate data used for the WEPP:Road analysis was the same as that for GeoWEPP from the Tahoe City Cross Station. The soil textures in the Blackwood watershed are either sandy loam and silt loam. Soil textures for each road segment can be determined by overlying the road network layer with the soil map. Rock fragment content was quantified by the same method. Two road design conditions were considered: an outslope road surface or an insloped surface with vegetated ditches. For main roads that were assumed to be 6m wide, the traffic level was set as high and road surface was set as graveled. The other roads were set as low traffic level and surfaces were assumed to be native. The road fillslope gradient was assumed as 50% and fill length was 10m. The buffer gradient for all road segments was assumed as 34%. The topographic, soil and management attributes of each segment were use by the WEPP:Road batch processor to predict erosion from hundreds of road segments in a single run (Elliot et al, 2018b and 2019).

2.5 Data Analysis

Modeling results for the four different roads treatment conditions (non-road condition, current and two possible road opening conditions) were compared. A one-way analysis of variance (ANOVA) and Fishers Least Significant Difference (LSD) test were used to see if there were differences in the estimated runoff and sediment generation amounts. Regression analyses were conducted to determine of there was a relationship between the increased soil loss rate and the road buffer length. The correlation coefficient (R) was used to evaluate the relationships among sediment delivery and road attributes. All of the analyses and graphical displays were made using the IBM SPSS Statistics for Windows Version 19.0 (IBM Corp., Armonk, NY, USA) and ORIGIN 8.0 (OriginLab, Northampton, MA, USA) software packages, respectively.

3. Results and discussion

3.1 Road network influence on channel network structure

The stream channel network was delineated four times with a critical source area of 5 ha from the four DEMs that reflected the non-road scenario, current scenario, and reopening with an outslope road profile,

Table 3. Changed channel networks as influenced by road reopening

Order	Reopen outslope road		Reopen inslope road	
	Disappeared channel (m)	New channel (m)	Disappeared channel (m)	New channel (m)
1	4206.8	4704.4	7591.3	10442.1
2	1225.8	1131.5	1649.0	2510.3
3	0.0	0.0	9.9	12.6
Total	5432.6	5835.9	9250.2	12965.0

and reopening with an inslope road profile (Figure 4). Table 2 shows the number and length of channel segments of the watershed for each scenario. The 10m DEM (non road scenario) showed the lowest total channel length among the four scenarios. The non-road senario had 10 fewer channel segments and about 10 km less total channel length than the current scenario delineated channels. Most of the reduction in the number of channel segments are for segment orders lower than 3. The average channel length is 20m less for the unroaded scenario compared to the current scenario. The decrease in channel length is likely due to the removal of flow interception or generation by roads, concentration of surface runoff, and diverting runoff to channels (Gucinski et al., 2001). The 1m DEM resolution for the current condition may also contribute to the shorter channel lengths as the 10m DEM ignores terrain details and tends to delineate straight channels instead of the winding channels exacted from the 1m LiDAR DEM (Zhao et al., 2010). The 10m DEM will also have a minimum channel length of 10 m, with additional lengths in 10 or 14.4m increments, whereas the 1m DEM will allow all channel increments as low as 1 m once the minimum channel length is exceeded.

Overall, the two road-modified LiDAR DEMs that described the reopened road scenarios resulted in a little longer total channel length compared with the original 1-m LiDAR DEM. The inslope reopened road scenario resulted in more channels than the outslope scenario. Within the stream orders, the difference among each order was highly variable, as the channels of orders 1 and 2 are longer, the order 3 channels are shorter, and the 4 and 5 order channels are unchanged after road opening. Figure 4 shows some channels disappear (the purple dash lines) and some new channels are generated (the red solid lines) after road reopening. Figure 4b shows that the channel network for the inslope road reopening scenario resulted in more disappearing and new channels than the outslope road reopening scenario (Figure 4a).

Table 3 summarizes the channel network changes for the two reopening scenarios. The results showed that more than 22km channels would be changed if all abandoned roads were reopened as inslope roads. On the other hand, only 12.6km channels would be changed if the roads were reopened as outslope roads. Nearly all the changed channels were low order channels with the orders of 1 and 2.

Figure 4b also shows that some new channels overlap with inslope roads and act as hydrological linkages between different road segments. This interaction between channels and insloping roads confirms that an inslope road surface can accumulate runoff and therefore develop channels that follow roads (Gucinski et al., 2001). Detailed analyses were conducted to examine the position between roads and channels of order lower than 3 by extracting road-channel intersections and calculating the length of channels which are close to roads (Table 4). Table 4 shows that channels of order lower than 2 are more likely intersect with roads and are to be found within 5m of roads after reopening roads with inslope surfaces. This result demonstrates the role of road-accumulated runoff in altering the watershed channel network (Wemple et al., 1996; Croke and Mockler, 2001). On the other hand, the road-channel intersections were changed little by outslope road reopening. The length of channels that are within 5m of an outslope road surfaces was almost half of the length of channels within 5m of inslope roads.

Table 4. Relative position between road and channel networks

Order	Road-channel intersections			Channel within 5m to road (m)		
	Current	Reopen outslope	Reopen inslope	Current	Reopen outslope	Reopen inslope
1	56	55	63	2443.72	3382.14	5639.03
2	19	19	23	742.55	1063.19	2220.27
3	4	4	4	109.99	129.00	99.13
Total	79	78	90	3296.26	4574.34	7958.49

3.2 Road influence on sub-watershed runoff and soil loss

The changes in runoff due to the finer resolution DEMs are likely due to the presence of the low conductivity road surfaces (Jones and Grant, 1996; Hubbart et al., 2007) and not the finer resolution (Zhang et al., 2009). Reopening of roads changes the underlying terrain and alters the channel network. The altered channel network in turn may alter runoff and other hydrologic processes, erosion and sediment delivery (Wemple et al. 1996 and 2017). The influence of road reopening on runoff and soil loss at a watershed scale was explored with the GeoWEPP model using the four different DEMs as input (10-m DEM for no roads; 2-m DEMs for current condition, reopening with an insloped surface and reopening with an outsloped surface). Table 5 shows the estimated average annual runoff and sediment delivery for the 10 sub-watersheds that were modeled. Estimated annual runoff increased slightly after road reopening and decreased if all roads were removed. The increase in runoff may be due to increased interception of lateral flow as well as the increase of road surface runoff (Jones and Grant, 1996; Hubbart et al., 2007).

Table 5 shows that channel erosion was the main source for soil loss for all scenarios. The increased runoff from the roads resulted in increased channel erosion (Croke and Mockler, 2001). The average annual sediment delivery at sub-watershed outlets was estimated as 0.84 t/ha, which is greater than the observed sediment delivery of 0.65 t/ha at the Blackwood Creek outlet, suggesting that the low gradient Blackwood Creek is likely dominated by sediment deposition in the channel.

Elliot (2013) hypothesized that within undisturbed forested watersheds, upland channels are the main source of sediment. As the sediment is depleted from these channels, sediment delivery decreases until a wildfire occurs on the landscape, resulting in major hillslope erosion and deposition in upland channels. The sediment deposited in those channels following wildfire will continue to bleed out in the interval between fires. The road network, however, complicates this natural sedimentation process, as the active roads themselves become a chronic source of sediment (Elliot, 2013). Both hillslope and channel soil loss are

Table 5. Output of sub-watershed modeling results under different conditions

	Annual runoff (mm)	Annual hillslope soil loss rate (t/ha)	Annual channel soil loss rate (t/ha)	Annual sediment delivery (t/ha)	Sediment delivery ratio*
Remove roads	9.05	0.10	0.96	0.68	0.73a
Current condition	11.04	0.20	1.81	0.84	0.48ab
Reopen outslope roads	12.79	0.15	2.06	0.89	0.48ab
Reopen inslope roads	11.15	0.29	2.44	0.97	0.45b

* Different letters identify values that are significantly different

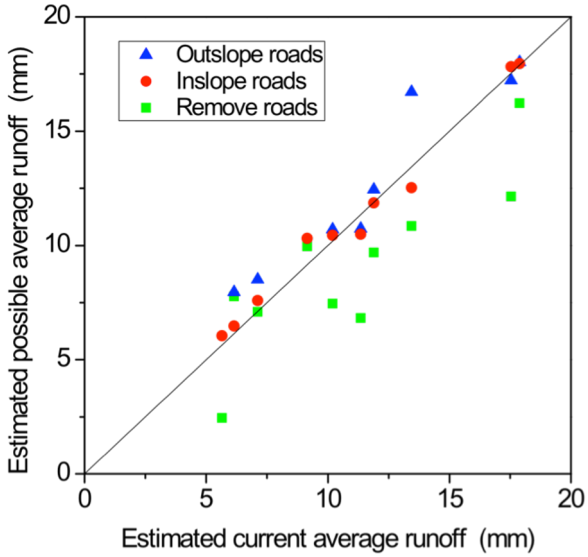

Figure 5. Estimated runoff for three possible road scenarios vs. the current condition scenario.

predicted to increase if roads are reopened with insloping surfaces, with the channel soil loss rate increasing more than the hillslope rate. If all roads are reopened using an insloping surface, the annual sediment delivery predicted at sub-watershed outlets was increased by 15.5% from the current roaded condition. If all roads are reopened with an outsloping surface road channel soil loss will also increase the annual sediment delivery slightly. If all roads are removed, both hillslope and channel soil loss are predicted to decrease, and the total sediment delivery from the subwatersheds is predicted to decrease by 20%.

The sediment delivery ratio varied when comparing the scenarios. The ratio slightly decreased if roads were reopened but increased if the roads are removed. The decrease in watershed delivery ratio from the presence of roads may be explained by the effect that insloping roads act as low gradient channels causing sediment deposition rather than transporting all detached sediment to the watershed outlet, and not by the finer resolution DEM (Zhang et al., 2009). Outsloping road profiles provide low gradient barriers to overland sediment transport, and may become sites of deposition (Elliot et al., 2018a).

An alternative way to present the results to better reflect the variability in the modeling among the 10 subwatersheds is presented in Figure 5 for runoff and Figure 6 for erosion and sediment delivery. Figure 5 shows that average annual runoff amounts in both outslope and inslope scenarios were above the 1 to 1 line for most of the subwatersheds, meaning an increase in runoff. This may reflect the role of road networks in changing surface flow accumulation, and increasing runoff generation from decreased road infiltration and interception of subsurface flow by the road (Jones and Grant, 1996) and the increased channel network (Wemple et al., 1996). The road removal scenario estimated that 8 out of 10 sub-watersheds generated less runoff than the current condition scenario. This decrease in estimated runoff following road removal may be due to the increased infiltration from forests compared to roads, and the decrease in subsurface flow interception (Jones and Grant, 1996; Hubbart et al., 2007).

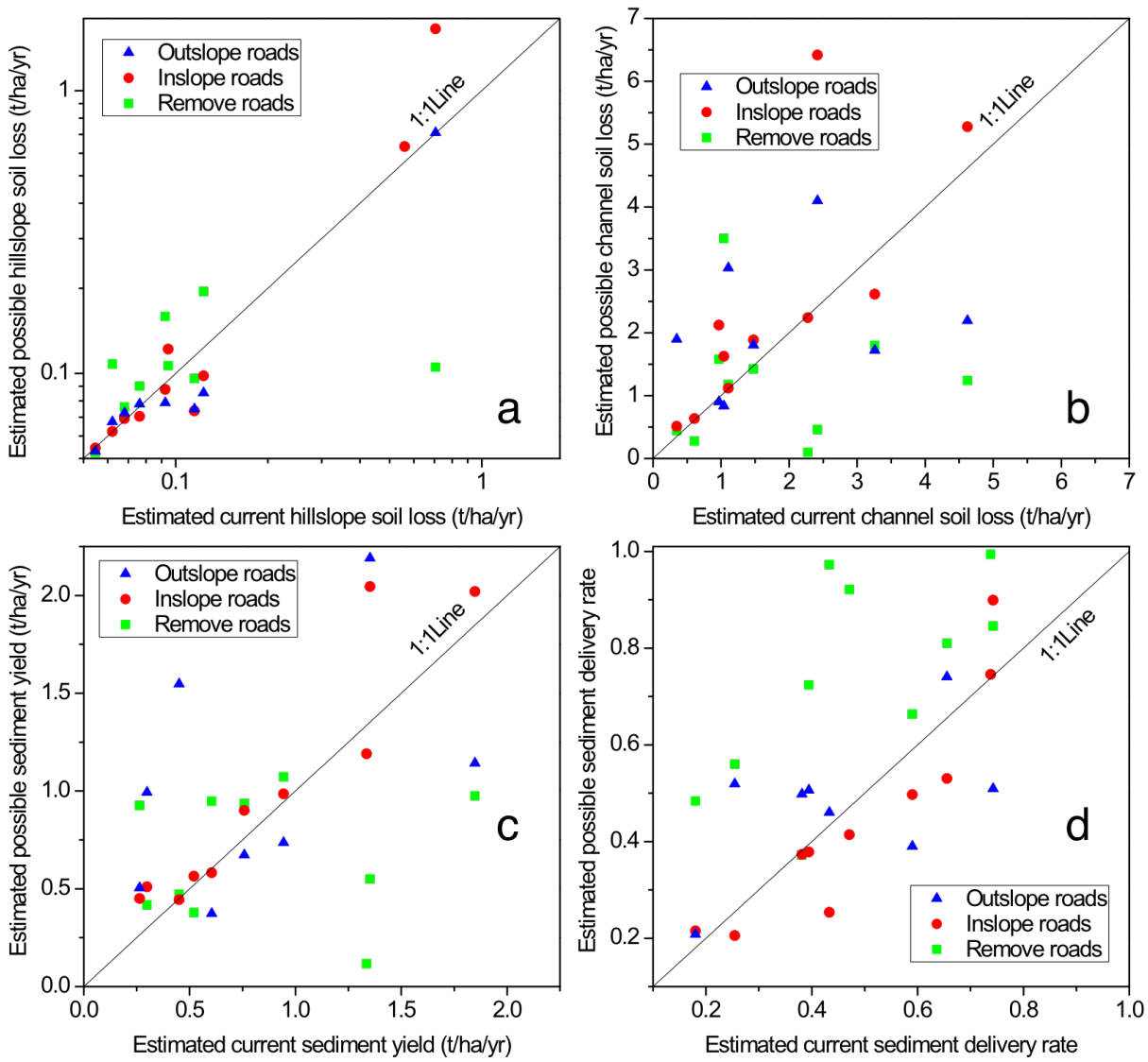

Figure 6. Estimated a) hillslope erosion, b) channel erosion, c) subwatershed sediment delivery and d) sediment delivery ratio for rebuilding closed roads and removing existing roads vs the sediment delivery for the current condition for the 10 subwatersheds modeled in the Blackwood Creek watershed.

Figure 6 shows the estimated hillslope erosion, channel erosion, subwatershed sediment yield and sediment delivery ratios verse the estimated current watershed predictions. Predicted hillslope soil loss in most sub-watersheds was lower than 0.2 t/ha and close to the 1:1 line (Figure 6a). This implies that road networks generally do not greatly increased hillslope soil loss. The channel soil loss estimates with 10m DEM for the road removal scenario were generally below the 1:1 line and most of the two reopened road results are above that line (Figure 6b). This suggests that removing roads will reduce channel erosion, and reopening roads will likely increase watershed sediment delivery by increasing channel erosion. This result is consistence with the predicted change for flow accumulation and increase channel density as described previously. Wemple et al. (1996, 2001) reported this finding from field data.

Because of the increased channel soil loss, the estimated sediment delivery rates at sub-watershed outlets are also increased with road reopening (Figure 6c) for most of the subwatersheds. For the nonroaded

scenario, sediment delivery from some sub-watersheds are above the 1:1 line and some below, although the overall average sediment delivery for the road removal scenario was lower than for the current scenario in Table 5. This mixed result might be due to the difference between DEM cell sizes in delineating channel networks. With the 10m DEM there are more straight channels in some sub-watersheds than with the 2m DEM. Straighter, shorter channels can lead to more sediment delivered to the watershed outlets. This fact may explain the trend of sediment delivery ratios in Figure 6d, which shows that the 10m non-road DEM estimated a higher sediment delivery ratio than the other DEMs with road terrain. Furthermore, the sediment delivery rate would generally decrease with the inslope road reopening scenario compared to the current conditions because the channel extensions associated with road ditches will likely result in more deposition for both road surface and hillslope sources of sediment. These results are consistent with the road network effect in blocking sediment transport efficiency as explained previously. Zhang et al. (2009) also hypothesized that finer resolution DEMs may tend to incorporate more low gradient segments at the bottom of hillslopes, leading to estimated higher deposition rates of upland erosion in riparian areas.

3.3 Estimated erosion risk from reopened roads segments

The previous analyses were all conducted with the GeoWEPP wizard with details of the road topography and soils incorporated into the analyses. The approach is useful for understanding the role of roads in watershed hydrology and sedimentation, but is less useful for evaluating hydrologic and erosion processes on individual road segments. The WEPP-Road interface is a better tool for evaluating erosion from individual road segments, and the effects of road management practices on road runoff and sediment delivery (Elliot, 2004). The WEPP:Road Batch interface was used to estimate erosion from individual road segments to provide a detailed evaluation of road reopening effects on road network soil loss risk. Table 6 shows the estimated runoff and soil loss from 191 sandy loam road segments (granitic soils) and 454 silt loam segments (volcanic soils). Table 6 shows that runoff and soil loss from silt loam road segments are generally higher than from the sandy loam segments. The hydraulic conductivity for sandy loam roads (3.8 mm h^{-1}) is greater than for silt loam (0.27 mm h^{-1}) in the WEPP:Road database, and therefore result in lower runoff and sediment delivery estimates (Table 6). Road surface design and topographical factors result in high variability among the road segments in estimated runoff and soil loss. Road design plays an important role in determining runoff and soil loss. The inslope road design shows significantly greater (ANOVA, $p<0.001$) runoff and soil loss than the outslope road design for the reopened roads. When considering the entire watershed, overall estimated soil loss is greater than the hillslope or "background" rate for either outslope or inslope road designs. Table 6 shows that the average annual soil loss rates for outslope road segments (3.0 – 4.7 Mg ha^{-1} y^{-1}) nearly 5 times higher than the background sediment delivery rate listed in Table 5 (0.7 – 1 Mg ha^{-1} y^{-1}). Soil loss rates at road buffer outlets, which illustrated the estimated sediment contribution from roads to channels (0.9 – 2.0 Mg ha^{-1} y^{-1}), were lower than the road soil loss rates due to deposition along buffers (Elliot and Tysdal, 1999; Brooks et al., 2006; Elliot et al., 2018b and 2019). Nevertheless, the average buffer outlet rates for inslope roads were still nearly double the sediment delivery rate for the watershed as a whole. It is possible that the estimated road sediment that is delivered to the upland channels may deposited in those channels making the overall channel sediment delivery from the surfaces less than the amount leaving the buffer, especially after the road has recovered from the initial reconstruction (Karwan et al., 2007).

The predicted annual soil loss rates of both reopened outslope and inslope road segments were spatially plotted with the background soil loss that was estimated using the GeoWEPP model with a 2m DEM describing the current condition (Figure 7). The modeling results for reopened road network and watershed were color classified at the same erosion rates for comparison purpose. Figure 7 shows that most of the predicted reopened road soil loss rates are higher than the background rates, especially for the insloped design. A large number of road segments resulted in the predicted soil loss rate greater than 10 Mg ha^{-1} y^{-1}. The outslope roads that zigzagged uphill with steep gradients on the northern part of the watershed also showed soil loss rates higher than 10 Mg ha^{-1} y^{-1} compared to the background rates that were

Table 6. Statistics for predictions of runoff and soil loss from road segments using the WEPP:Road interface

Road design	Indexes	Sandy loam road segments			Silt loam road segments		
		Annual runoff (mm)	Soil loss from road (t/ha/yr)	Soil loss at road buffer outlet (t/ha/yr)	Annual runoff (mm)	Soil loss from road (t/ha/yr)	Soil loss at road buffer outlet (t/ha/yr)
Outslope	Minimum	0	0.37	0.11	2	0.48	0.39
	Maximum	62	23.01	19.12	199	45.19	30.15
	Mean	5.93	3.07	0.94	22.19	4.74	2.09
	STD	10.02	3.89	1.83	26.82	7.07	3.15
Inslope	Minimum	1	0.20	0.13	3	0	0.22
	Maximum	84	37.50	28.02	386	78.70	77.73
	Mean	16.18	5.89	2.06	76.69	10.30	5.11
	STD	22.04	5.72	3.33	89.81	11.06	7.08

less than 3 Mg ha^{-1} y^{-1}. Figure 7 shows that eroding roads are a much greater risk to watershed health than eroding hillslopes.

Some outslope road segments that follow the contour lines predict similar or even lower erosion rates than the background rate. This is likely because those roads decreased the slope gradient and reduced the original slope length, therefore reducing the erosion to be less than the background hillslopes.

Connectivity of road segments to the stream system is a critical factor influencing sediment delivery. Table 6 shows that only about half of the sediment generated by the road surface is delivered to the bottom of the buffer. It is likely that not all of the delivered sediment from the buffer will be routed through the stream system. Table 5 suggests that the stream network delivery ratio is likely around 0.5, suggesting that sediment from roads entering the upland channels will likely be further reduced because of downstream deposition.

Many of the hillslopes in Figure 7 that are predicted to have high erosion rates are likely rock outcrops that are common in the upper parts of the basin, and the erosion rates are likely over predicted. Enhanced modeling methods are needed to address rock outcrops that are beyond the scope of this study (Elliot et al., 2016).

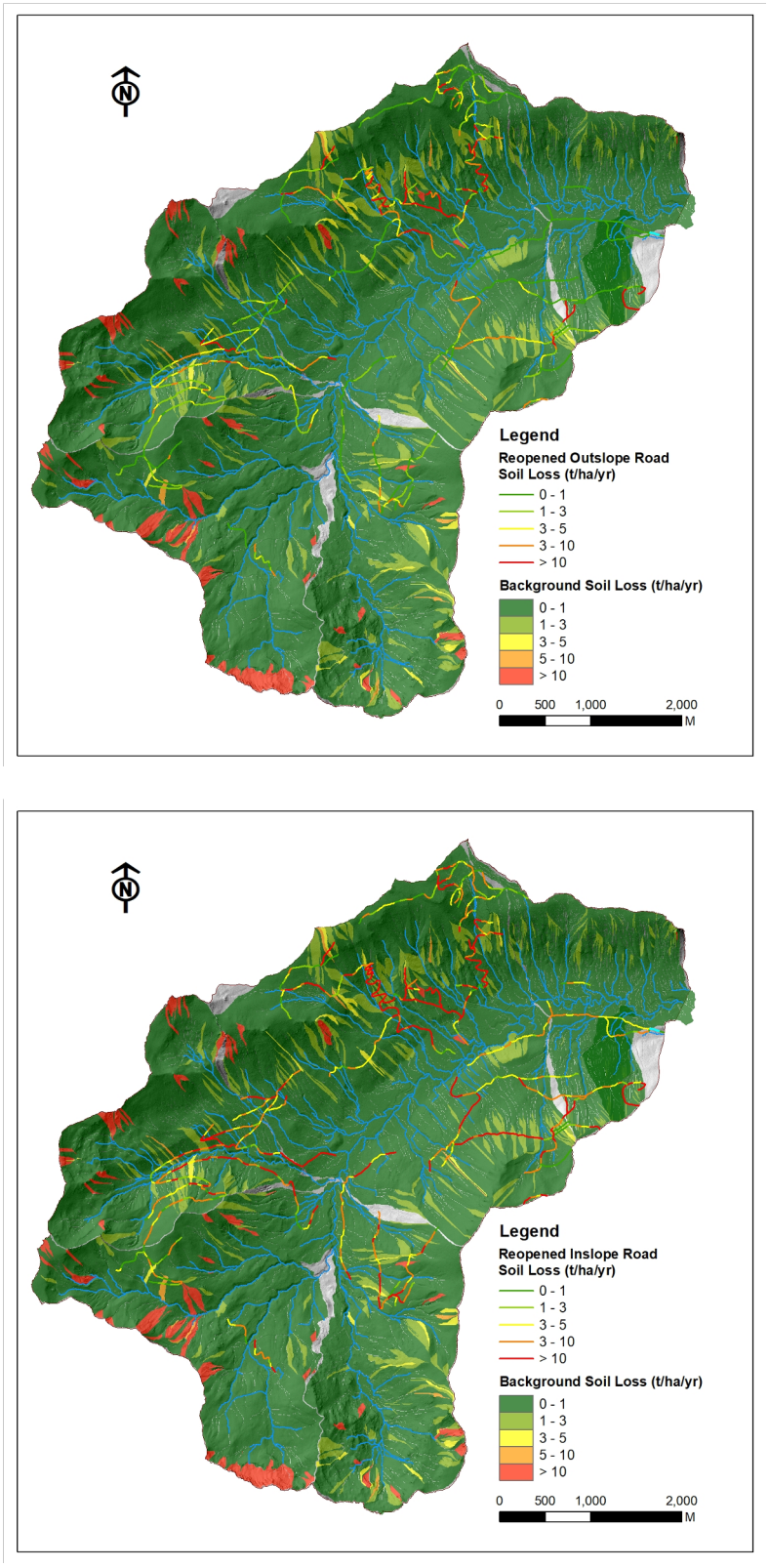

Figure 7. Estimated soil loss if all roads are reopened from road surfaces and hillslopes; top: outslope road reopening, bottom: inslope road reopening

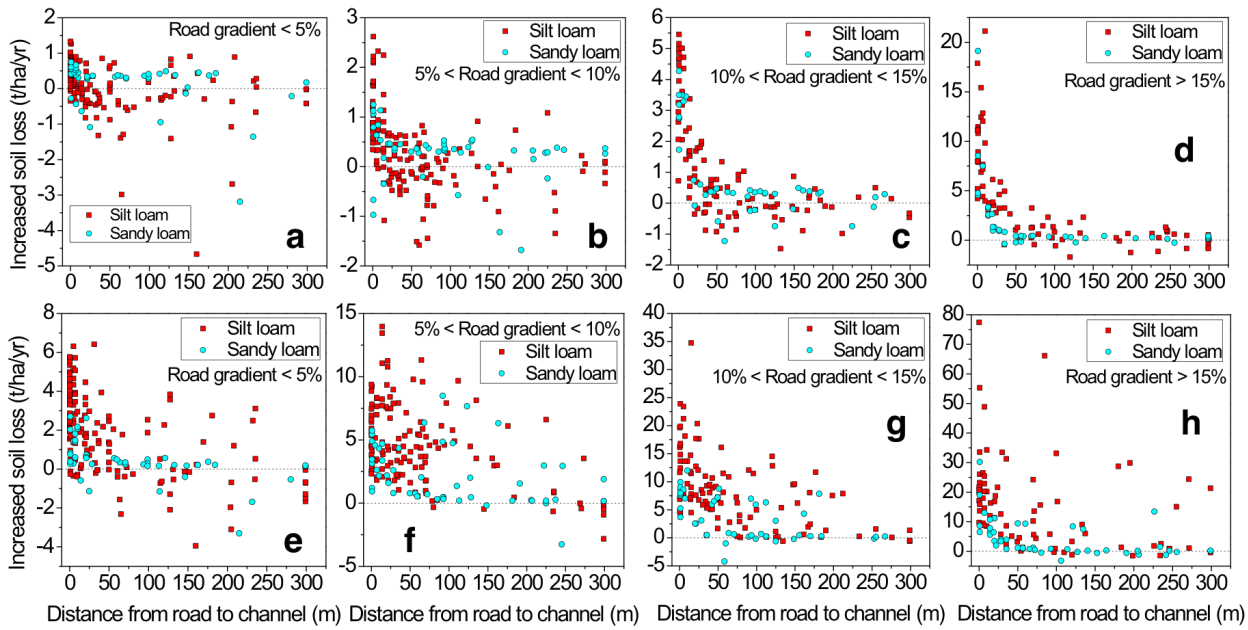

Figure 8. The relationship between the increased soil loss rate from roads compared to the hillslope erosion, and road buffer length for four road gradient categories and two soil textures; Figures 8a to 8d for outslope road segments, figure 8e to 8h for inslope road segments

Four of the main factors that influence sediment delivery to stream channels in this analysis are: the road gradient; the distance from the road to the channel; the soil texture; and the road design (Elliot et al., 1999). A sensitivity analysis was carried out with these four factors on the ***difference*** between hillslope erosion rate and road sediment delivery rate, and the results are presented in Figure 8. Some of the scatter in Figure 8 is due to different road segment lengths. Note the difference in the vertical scales in Figure 8, showing that insloped roads generate more sediment than outslope roads, and higher gradient roads generate more sediment than lower gradient roads. Figure 8 shows that the increase in soil loss generally declines with road buffer length, especially for shorter distances, reflecting the likely deposition of sediment in the buffer. For short buffers, the results vary widely as in some cases, there was likely net erosion in the buffer, whereas in others, there was likely net deposition (Elliot and Tysdal, 1999). In general, road segments that are close to channels result in a greater increase in sediment above the hillslope rate than segments further away. With longer buffers, soil loss above the background are generally much lower, and may even be zero for many segments. Road segment gradient also plays an important role in the increase of soil loss rate above background, with higher gradients generating more sediment. The increase in sediment delivery was not sensitive to soil texture when road gradients are lower than 15%. The silt loam segments resulted in more soil loss than the sandy loam segments when road gradients were greater than 15%. On the whole, inslope road segments (Figure 8e to h) resulted in an increase in sediment delivery several times higher of soil loss and with fewer increases at or below zero than the outslope segments (Figure 8a to d) for the same slope gradient.

All 8 graphs in Figure 8 show some negative values, for the "increase" in erosion. In these cases, the presence of road segments are decreasing hillslope erosion rates. This occurs for lower gradient segments, and does not appear to vary with texture. The magnitudes of the negative values do not appear to depend on road design, with values ranging down to 4 Mg ha^{-1} y^{-1} decrease in soil loss. This finding is consistent with anecdotal observations of sediment deposition on lower gradient roads, and with the post wildfire study by Elliot et al. (2018a).

Table 7. Regression relationship between increased soil loss rate and road buffer length

Road design	Road gradient (%)	Sandy loam road segments			Silt loam road segments		
		Equation	R	N	Equation	R	N
Outslope	0-5	E = -0.003D + 0.370	-0.381*	44	E = -0.004D + 0.268	-0.338***	134
	5-10	E = -0.004D + 0.569	-0.410**	51	E = -0.004D + 0.523	-0.415***	138
	10-15	E = -0.011D + 1.782	-0.602***	42	E = -0.013D + 1.934	-0.560***	99
	>15	E = -0.015D + 2.852	-0.440**	48	E = -0.036D + 7.685	-0.570***	78
Inslope	0-5	E = -0.006D + 0.932	-0.514***	49	E = -0.014D + 2.574	-0.525***	137
	5-10	E = -0.010D + 3.272	-0.396**	53	E = -0.017D + 5.666	-0.410***	136
	10-15	E = -0.027D + 5.948	-0.532***	44	E = -0.046D + 11.78	-0.544***	101
	>15	E = -0.031D + 7.365	-0.469***	47	E = -0.059D + 20.37	-0.342**	74

E is the increased soil loss rate after road reopening (Mg ha^{-1} y^{-1}), D, is the flow length from roads to streams (m)

Linear regression relationships were developed for the results in Figure 8 between the increase in sediment and the buffer length, and the results are summarized in Table 7. The negative values on all coefficients reflect the decrease in sediment delivery with increasing buffer length (Figure 8, Table 7). The more negative the equation slope coefficient, the greater the decrease in sediment delivery with buffer length should the road be reopened. The constant of each equation is an estimate of the maximum soil loss increase estimated for segments that have a minimal buffer distance between the road and the nearest channel. Results in Table 7 showed similar trends for both outslope and inslope road segments for all road gradients. The intercept is generally greater and the slope is more negative for silt loam road segments than that for the sandy loam segments. For the same road gradient category and soil texture, the inslope segments had greater intercept value and more negative slope values than outsloped segments. These findings suggest that the shorter the buffer, the greater the benefit from an outsloping road design for limiting sediment delivery.

The negative correlation coefficients (R) between the increase in sediment delivery and the distance from the road to the stream in Table 7 confirm the effectiveness of buffers. The modest values between -0.34 to -0.60 suggest that there are factors other than road design, soil category, road gradient and distance to stream that influence sediment delivery. Some other factors not considered in this analysis that contribute to the variability in sediment delivery reduction are the amount of sediment and runoff generated by the road, the road segment length and the buffer gradient (Elliot et al, 1999).

The equations in Table 7 can used by planners to evaluate risks of reopening roads in this or other nearby watersheds based on the texture, road gradient, and distance to the nearest channel. They can be particularly useful for prioritizing which roads to open, which to remove, and where to construct new or temporary roads. Figure 8 plots these equations and shows how a critical distance can be estimated from the equations by defining an acceptable increased rate of soil loss (E), a practice often used by watershed planners when considering management alternatives. The intercepts of equations with the X-axes are an estimate of the minimum buffer lengths needed so that road soil losses are similar to the hillslope rates. Road segments further from the streams than this intercept value will not increase soil loss risk after reopening. The results show that the critical distances generally increase with road segment gradients. This is likely because higher gradient road segments generate more soil loss and hence need a greater distance for deposition before sediment reaches streams. Road segments that are insloped have a relatively higher soil loss and accumulate a greater volume of runoff, so the critical distances for no soil loss increase are greater for insloping road segments (Figures 8c and d) than outsloping segments (Figures 8a and b). This

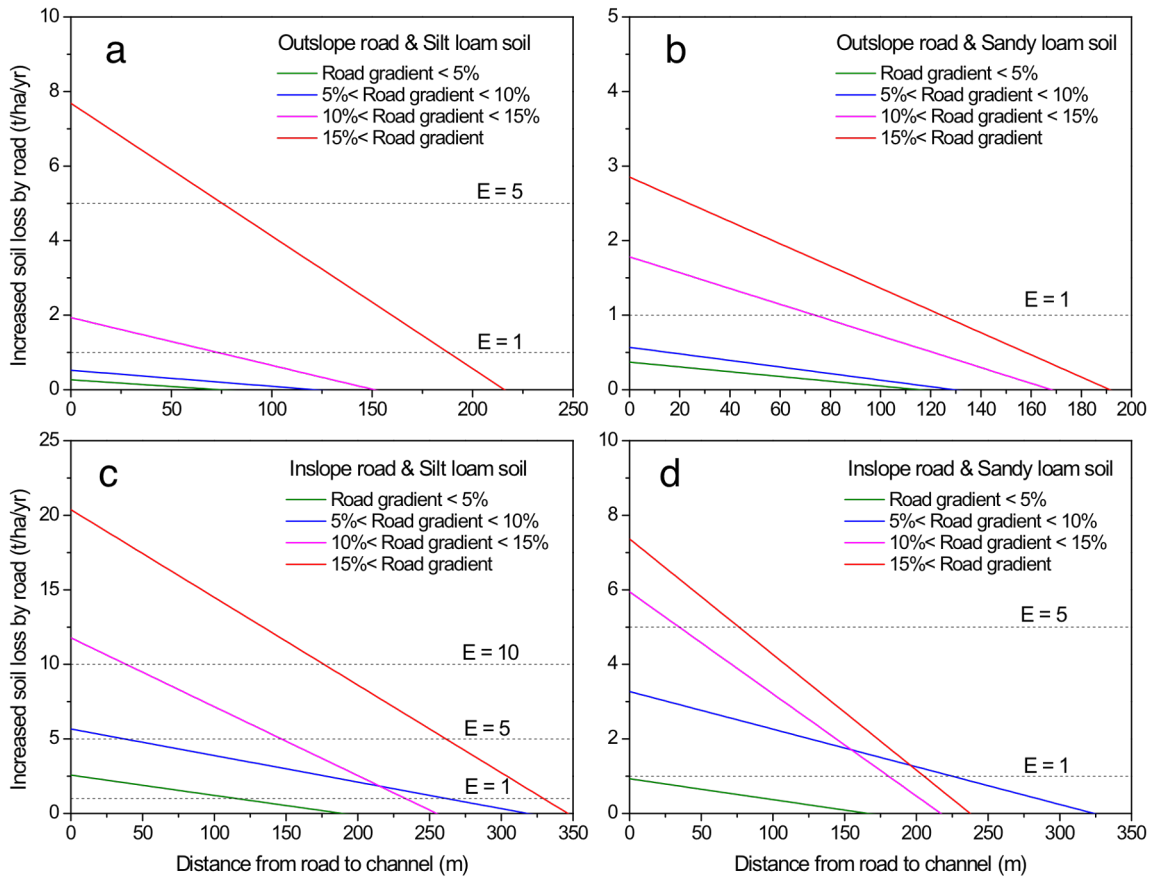

Figure 9. The critical distance for road segments in affecting soil loss

analysis determined the length of road segments from the underlying topography. One mitigation method to reduce sediment from critical road segments is to shorten those segments by installing surface cross drains or ditch relief culverts on insloping roads, shortening the road segments (Copstead et al., 1998). To reduce sediment from critical outsloping road segments, slash windrow filters can be installed along critical road segments (Foltz and Elliot, 2001) using slash from either road reconstruction, or thinning operations.

The example E values of 1, 5 and 10 in Figure 9 show that the predicted reopened road soil loss rate are 1, 5 and 10 Mg ha^{-1} y^{-1} higher than the background rate respectively. The corresponding distance in the X-axis for certain E value implies that soil loss rate will exceed the E value if reopened road segments are within that distance from streams. If the reopened road segments are outsloped and gradients are lower than 10%, the increased soil loss rate is less than 1 Mg ha^{-1} y^{-1} even for segments that are very close to channels (Figures 9a and 9b). However, if road segments are steep or reopened as inslope surfaces, the increased soil loss could exceed 5 Mg ha^{-1} y^{-1} and even 10 Mg ha^{-1} y^{-1} (Figures 9c and 9d). The distance is affected by both road gradient and soil texture. In the case of the inslope road and silt loam soil scenario, segments with gradients between 10% and 15% need to keep at least 147m away from streams to avoid increasing soil loss by more than 5 Mg ha^{-1} y^{-1}. For road segments with gradients higher than 15%, that distance is increased to 261m from streams. In the case of the less erodible sandy loam soil, an inslope road segment gradient higher than 15% need only be 76m away from streams to avoid increasing such soil loss. The buffer distances suggested in Figure 9 can be compared to the 30 m buffers for intermittent streams and 90 m buffers

for fish-bearing streams that were recommended by the USDA Forest Service (1995) for Pacific Northwest Forests in the Inland Native Fish Strategy (InFish) guidelines. These guidelines were intended to improve fish habitat by reducing stream sedimentation associated with forest practices.

3.4 Implications of this study

The effect of forest roads on the watershed channel network, runoff and sediment generation were explored by spatial analysis and modeling technology. The GIS-based stream delineation showed that reopening abandoned roads may alter the location and increase the density of low-gradient channels. With an increase in channels, the sub-watershed erosion modeling results predicted that road reopening may generally increase channel soil loss rate. This suggests that more attention should be paid to low-grade channels that are close to reopened roads rather than the main channels or hillslopes. Because road reopening may alter adjacent channels by intercepting upstream runoff, culverts should be located to drain the accumulated flow from road segments at locations that are less likely to result in increased channel erosion, such as on convex hillslopes or wetland areas.

Soil loss modeling on the road segment scale provided detailed information about how road gradient and distance to stream influence soil loss rate after road reopening. According to the results in Figure 9, steep road segments that are close to streams are at the greatest risk for increasing soil loss within the watershed. Therefore it is not advisable to open such segments if possible. If risky segments are to be reopened, treatments such as sediment basins or flow diversion structures should be considered to minimize sediment from entering streams.

Both watershed and segment scale modeling results indicated that more soil loss would be caused if abandoned roads were reopened as insloped than as outsloped surfaces. The California Forest Practice of requiring all forest roads to be outsloped is justified. It is important, however, that the outslope profile is maintained during and after logging or other heavy trafficking with timely road grading to minimize rutting effects on runoff flow paths (Foltz, 1996). When evaluating sediment delivery from the forest road network on the Lake Tahoe west shore Elliot et al. (2019) were informed by forest managers that all maintained forest roads in the study area are outsloped.

Watershed scale channel delineation and soil loss prediction showed that removing roads would decrease channel density and reduce soil loss risk. The more erodible silt loam (volcanic) steep road segments that close to streams are at greatest risk for erosion, making their removal a priority. The equations in Table 7 and Figure 9 can be used by local watershed managers to make decisions based on site-specific conditions.

This study showed that the high resolution LiDAR DEM based terrain and hydrology analysis can provide a reasonable evaluation of road influence on surface flow accumulation and channel delineation. The method can be used for watershed hydrological simulation or environment assessment. The road segmentation method used in this analysis could also be enhance other LiDAR-based hydrological analyses that generally treated roads as barriers and force overland runoff through them with hydro-enforce technologies (Poppenga et al., 2014). In this study, we applied two WEPP based erosion models, GeoWEPP and WEPP-Road, for road erosion prediction. The results in this study illustrated that the GeoWEPP wizard could be used to evaluate the influence of road hydrology at a watershed scale. The WEPP-Road model has been shown to be effective in estimating soil loss at a road segment scale (Brooks et al., 2006; Elliot et al., 2018b and 2019). The two models were combined in this study to give different perspectives in forest road network soil loss prediction, but the results are comparable as they are sharing the same core algorithms well as soil and topography data sources. The modeling methods in this study can be useful in guiding similar road influence studies in other regions.

4. Conclusion

Based on GIS technology and soil erosion models, the effects of forest roads on hydrology and soil loss were estimated in a typical forest watershed on the western side of the Lake Tahoe Basin. The results showed that opening unused roads would likely alter surface flow paths and change channel structure and erosion. Channel density will generally decrease after road removal and increase if abandoned roads are reopened. Reopening roads would eliminate some channels by intercepting upstream runoff, but would also generate new channels by changing surface flow accumulation. These new channels are likely to intersect or form within 5m of reopened roads. Roads reopened with an insloped template will tend to influence channel network structure and erosion more profoundly than if using an outsloped template. The GeoWEPP modeling results showed that the average annual sediment deliveries from selected sub-watersheds were increased over the current condition by 15.5% if reopening roads using an inslope road template or 6% if reopening with an outsloping template. The predicted channel erosion contributed more to increasing subwatershed sediment delivery than the hillslope or road surface erosion. On the other hand, the predicted sediment delivery at sub-watershed outlets would be reduced by 20% if all roads in the watershed were removed. The sediment delivery ratio would likely rise after road removing as the road's effect in intercepting sediment would be eliminated. Road segment modeling results showed that the estimated annual soil loss rates for reopened road surfaces could be as high as 7 times the background sediment delivery rate. Reopened inslope road segments will likely cause more soil loss than outsloped segments. The increase in soil loss from reopening roads is dependent on both road gradient and flow length from road segments to streams. Reopened insloped roads near streams or with steep road gradients are predicted to be a high risk for soil loss. On the other hand, outsloped road segments that follow the contour with low gradients are predicted to have similar or even lower soil loss rate than the background rate. Roads that pass through silt loam (volcanic) soils are predicted to result in higher soil loss compare to roads in sandy loam (granitic) soils. Regression equations were derived predicting the increase in soil loss rate compared to the background rate as a function of road buffer length and gradient. The equations can be used to quickly identify road segments that will result in high soil loss rates if reopened, without the need for complex topographic analyses.

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