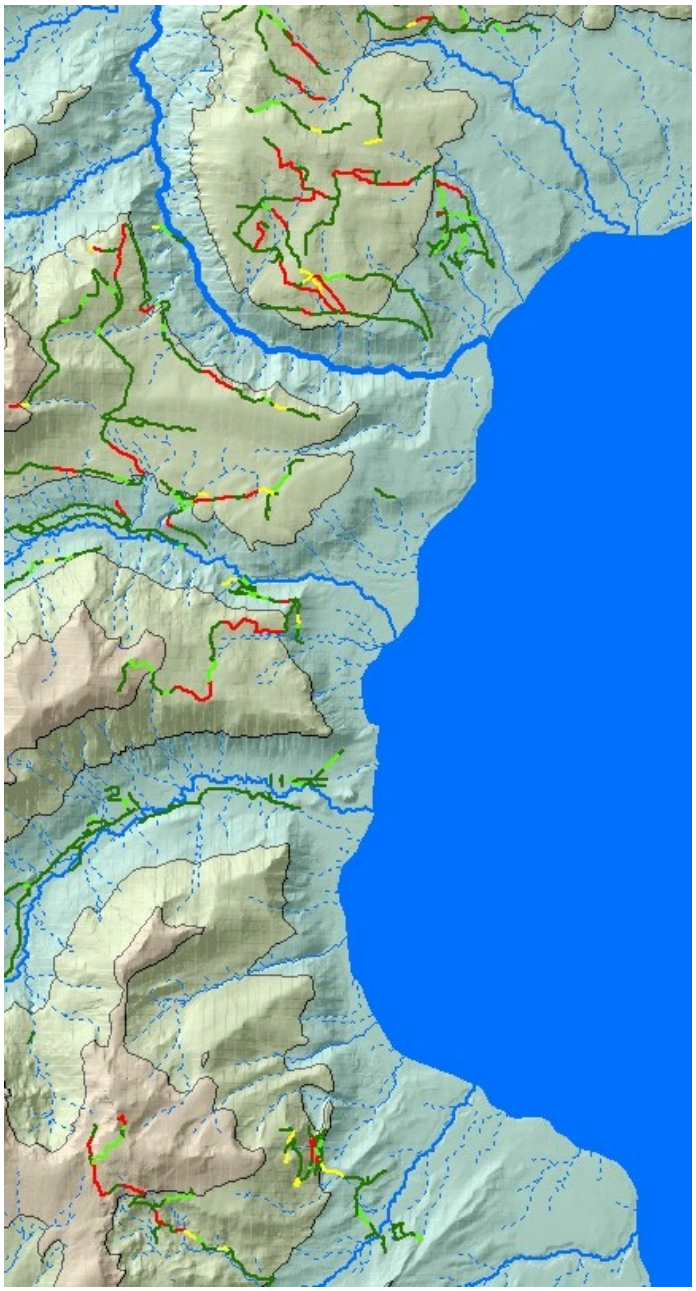

Final Report
Erosion Analysis of the Road Network
In the Lake Tahoe West Collaborative Restoration Project

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Abstract

The Lake Tahoe West Collaborative Restoration Project study area contains 181 km or roads, 33.5 km of which are paved. Many of the unpaved roads are closed and covered with vegetation. An analysis of road surface erosion and sediment delivery using GIS topographic tools and the Water Erosion Prediction Project WEPP:Road Batch interface estimated that the current road network was delivering 55 Mg of sediment per year. Closing unpaved roads that are currently trafficked will reduce erosion by 20 percent. Traffic supporting thinning operations will on the average, increase sediment delivery by 19

times on those road segments used for access, for the years in which the thinning operations are active. However, following active use for harvest, those estimated loads would rapidly return to the current values. Consequently, the increased sediment delivery associated with harvesting operations could be approximated by multiplying the estimated delivery by the fraction of time that the roads are actually used for harvest (for example, if the roads are likely to be opened for harvest 2 years out of 20, then the increase might double current loads from those road segments). These calculations do not account for potential sediment reduction benefits for harvest because of reduced impacts from wildfires, nor the reduction in erosion following wildfire because of the potential deposition of eroded sediments on the road surface. Furthermore, it is important to note that the sediment from the Lake Tahoe West road network is estimated to be less than 1% of that from the hillslopes.

Background

In the Lake Tahoe Basin, residents and public and private organizations are all agreed that maintaining the pristine quality of the lake's clarity is a priority (Waterboards and NDPE, 2008). In spite of decreases in clarity in recent years, there is considerable interest in minimizing sedimentation and associated nutrient delivery to the lake. Sediment sources include upland erosion from forests, roads, recreational areas and channel erosion. The greatest source of sediment in most forest watershed is from soil erosion following wildfire (Elliot, 2013). In the absence of wildfire, the road network is usually the greatest source of sediment (Elliot, 2013, Grace, 2017). In a report by the Waterboards and NDPE (2008), the Forest Uplands Sediment Category Group identified the road network as the primary source of sediment from forested areas. They suggested that improving sediment management from roads, or removing roads completely was the best way to reduce sediment from upland areas. The report noted that roads in steeper landscapes were likely contributing more sediment, but at the time, they were not able to delineate which road segments were generating the most sediment. Estimated sediment delivery from roads was adjusted by a scaling factor so that sediment delivered from roads accounted for all of the sediment observed leaving a given watershed. Scaling factors varied from 0.1 to 4 depending on watershed, with watersheds on volcanic soils generating more sediment. The report estimated that under current conditions, the subwatersheds on the west side of Lake Tahoe were generating 325 Mg y^{-1} from 170 km of road, or about 2 Mg km^{-1}.

In the Southern Nevada Public Land Management Act (SNPLMA) Round 7, Foltz (RMRS) and Chung (U MT) were funded to improve estimates of road sediment by focusing on individual road segments, using the Water Erosion Prediction Project (WEPP) technology. Foltz completed rainfall and runoff simulation studies on both volcanic and granitic soils, noting the same hydrologic differences as reported in the Waterboards and NDPE (2008) document. The results of this study showed that hydraulic conductivity was higher, and rill and interrill erodibility values were lower than the values that were in the WEPP:Road database (Foltz et al., 2011). With these lower erodiblity values, Foltz et al. (2011) reported that estimated sediment production from a typical road network could be 80 percent less than using the WEPP:Road interface. The erodibility values from the Foltz study were incorporated into a new online interface, the Tahoe Basin Sediment Model (TBSM)[1]. Efta (2009) applied the WEPP:Road interface to

[1] https://forest.moscowfsl.wsu.edu/fswepp/

roads in the Glenbrook Creek Watershed on Tahoe's East shore. In comparing existing conditions to the application of best management practices, he determined that sediment production could be reduced from 4 Mg km^{-1} to 1.2 Mg km^{-1}, a reduction of 73.4 percent.

In Efta's (2009) study, the length and steepness of each road segment was confirmed by a site visit. Such road topography surveys are commonly carried out to determine the sediment generated by a road network (Black, 2019). RMRS have recently developed GIS methods to estimate erosion by road segment to evaluate the risk of road erosion and sediment delivery from road network (Cao and Elliot, 2018), allowing for much quicker and less expensive analyses of road network erosion risks.

In 2015, a consortium of stakeholders, both public and private, began planning a major restoration project to improve forest health and decrease the risk of wildfire in the Lake Tahoe West study area, which encompasses 240 km^2 (100 mi^2) on the western side of the Lake Tahoe Basin. The University of Idaho (2018)[2] provided a detailed analysis estimating likely erosion from hillslopes in the proposed treatment areas for current, treated, and burned forest conditions, but not from the road network. Roads play a critical role in allowing access to the forest for the proposed treatments. The purpose of the study described in this report is to apply the Cao and Elliot (2018) method of road network erosion analysis to the forest roads described in a GIS road layer provided by the USDA Forest Service Lake Tahoe Basin Management Unit (LTBMU). The study builds on earlier work by the Lake Tahoe TMDL Pollutant Reduction Opportunity Report (Waterboards and NDPE, 2008) and Foltz's SNPLMA Round 7 studies (Efta, 2009, Foltz et al., 2011).

The WEPP Model was used to predict erosion on and sediment delivery from the road network. The modeling approach is based on the template used in the WEPP:Road interface that estimates erosion on the road surface and sometimes the fillslope, and then sediment delivery from runoff that is routed

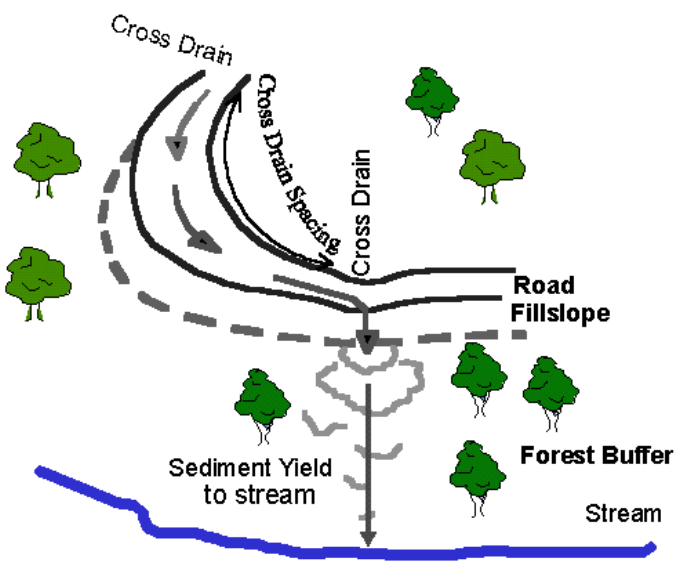

Figure 1. Template assumed for the WEPP:Road interface with sediment generated by the road surface routed over a fillslope and through a forest

[2] https://wepp1.nkn.uidaho.edu/weppcloud/lt/

from the road surface, over the fillslope, and through a forested buffer before reaching an ephemeral channel, or a seasonal or perennial stream (Figure 1[3]; Elliot, 2004). The WEPP model is a complex physically based computer program that models the processes that cause erosion, like runoff, sediment detachment, sediment transport and sediment delivery. It is run on a daily time step, and estimates the sediment delivery for each runoff event for a period of years ranging from a single storm to 999 years of daily climate. The WEPP:Road online interface is designed to allow users to easily describe the topography and road management practices for the elements shown in Figure 1. Management options include road traffic level (none, low or high), road surface design (insloped to bare or vegetated ditch, and outsloped with our without ruts) and road surface treatment (native, graveled or paved). Because most managers need to know the delivery from hundreds or even thousands of road segments, a batch interface (WEPP:Road Batch[4]) was developed to receive topographic input values from spreadsheets or databases and estimate the sediment delivery from hundreds of road segments at a time. Soil erodibility properties are highly variable with coefficients of variability (measured erodibility standard deviation divided by the erodibility mean) typically around 30 percent (Elliot et al., 1989). This means that at best, there is a 90 percent likelihood that an erosion value estimated by any model is within plus or minus 50 percent of the true value. No model can be any more accurate than the variability of the input data allows.

Methods

A GIS layer containing the Forest Service road network in the Tahoe Basin was provided by the LTBMU. The LTBMU road network data had six categories of road use (Table 1). LTBMU specialists were consulted to confirm the road attributes for each category. Each category was linked to road attributes required by the WEPP:Road interface. A cross walk spread sheet was developed with logistic functions to assign the WEPP:Road attributes to each LTBMU road segment category. For each LTBMU road category, we assigned a “design”, “surface”, “traffic level” and road width as required by the WEPP:Road Batch Interface (Table 1; Elliot, 2004; Brooks et al., 2006).

Using ArcMap 10.5.1, we adapted the topographic analysis methodology developed in Cao and Elliot (2018) to subdivide the LTBMU road network segments into hydrologic segments. The method identified cross drain outlet locations and determined the overland flow path from the cross drain outlet to the nearest likely cell with concentrated flow. The Cao and Elliot method then determined hydrologic segment lengths and gradients for each road segment, the length of each fill slope with a steepness of 50 %, and the length and steepness of each respective buffer. We assumed a maximum distance between cross drains to be 140 m (460 ft) as advised by the LTBMU

[3] https://forest.moscowfsl.wsu.edu/fswepp/docs/wepproaddoc.html
[4] https://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/wr/wepproadbat.pl

Table 1. Crosswalk between the LTBMU road category and the segment attributes for WEPP:Road.

LTBMU Road Category	WEPP:Road Attributes			
	Design	Surface	Traffic Level	Width (m)
0 – Not maintained	Outsloped Unrutted	Native	None	3.7
1 – Basic custodial care (closed)	Outsloped Unrutted	Native	None	3.7
2 – High clearance vehicles	Outsloped Unrutted	Native	Low	3.7
3 – Suitable for passenger cars	Outsloped Unrutted	Native	Low	5.5
4 – Moderate degree of user comfort	Outsloped Unrutted	Paved	Low	7.3
5 – High degree of user comfort	Outsloped Unrutted	Paved	Low	7.3

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The road segment topographic attribute table from ArcMap 10.5.1 was merged with WEPP:Road attributes from Table 1 in a spreadsheet, with one row for each hydrologic segment. From the merged data, columns in the spreadsheet were added to exactly match the WEPP:Road Batch input table. From this spreadsheet the columns intended for input to the WEPP:Road batch input were copied and pasted into the WEPP:Road Batch online interface in batches of about 800 segments to minimize the risk of "timing out" of the web browser during a batch run. We assumed a sandy loam soil category. Because of the variability in the climate, we divided the analysis into three elevation categories: 1800 – 2100 m, 2100 – 2400 m, and 2400-2700 m. We used weather statistics from the Rubicon Snotel station, located near the southern end of the management area combined with the PRISM 4-km monthly precipitation database to generate elevation-specific climates for each of the elevation categories (Scheele et al., 2001). Average annual precipitation depths of the stochastic climates are shown in Table 2. The average monthly maximum and minimum temperatures were also adjusted for each elevation category using the online "Rock Clime" climate builder tool[5] (Scheele et al., 2001). The WEPP model was run for 30 years of

[5] https://forest.moscowfsl.wsu.edu/fswepp/

stochastic climate for each road segment, the minimum suggested for climates with more than 500 mm of precipitation.

The output tables from each of the WEPP:Road Batch runs were copied and pasted back into the spreadsheet where the results could be summarized, and linked back to the original GIS attribute tables containing the road network. In the GIS, the stream order and road erosion, sediment delivery, and buffer deposition rates were classified to aid in visualizing where the segments with the greatest risk of erosion and sediment delivery were located. Additional summary calculations were carried out in the spreadsheet.

The analyses were carried out for three different conditions. The current condition where many of the roads were closed to traffic (Table 1), a future condition where all unpaved roads now open were assumed to be closed and overgrown, and a harvest condition where all unpaved roads were assumed to be rutted and free from vegetation with high traffic. The “Low Traffic” level was selected for the paved roads because this option assumes mature vegetation on the fill slope, which is the case on most of the Lake Tahoe West roads, whether they are paved or native. The LTBMU managers did not describe any of the roads as graveled, only native or paved.

Results

Summary

There were 1359 individual road segments identified in Lake Tahoe West in the GIS analysis (Table 2), totaling 181 km (112 miles) in length. 33.5 km (20.8 miles) were paved; the remainder were modeled as native surface (Table 2). Table 2 shows that road segment lengths averaged 84-101 m, with the shortest lengths in the highest elevation category. The average road gradients ranged from 4.7 to 9.1 %, increasing with elevation. The total estimated amount of sediment leaving the roads annually for the current condition was 108 Mg (118 tons, Table 3) and the estimated annual amount of sediment delivered to the stream system was 54 Mg (59 tons). 80% of this sediment was delivered from only 42% of the road network. At least 1 kg of sediment was delivered from 86 % of the road segments. Closing non-paved roads (so they revert to a revegetated condition) would reduce sediment delivery by about 20%. On the other hand, opening those roads for harvest traffic would increase sediment delivery on the average by 19 times. Such changes in sediment delivery are segment specific, and managers are advised to evaluate segments slated for closing or harvest on a segment-by-segment basis.

Table 2. Summary of road network topographic characteristics and their distribution by elevation category.

	Metric	English
Average Annual Precipitation		
1800-2100 m	937 mm	36.89 in.
2100-2400 m	1338 mm	52.68 in.
2400-2700 m	1484 mm	58.43 in.
Length of road		
1800-2100 m	56.55 km	49.15 miles
2100-2400 m	85.72 km	60.04 miles
2400-2700 m	5.08 km	3.16 miles
Total	180.80 km	112.34 miles
Number of road segments		
1800-2100 m	632	
2100-2400 m	689	
2400-2700 m	38	
Total	1359	
Average segment length		
1800-2100 m	95 m	312 ft
2100-2400 m	101 m	332 ft
2400-2700 m	84 m	276 ft
Average segment gradient		
1800-2100 m	4.7 %	
2100-2400 m	6.0 %	
2400-2700 m	9.1 %	
Average buffer length		
1800-2100 m	43 m	140 ft
2100-2400 m	59 m	194 ft
2400-2700 m	63 m	206 ft
Average buffer steepness		
1800-2100 m	14.9 %	
2100-2400 m	23.5 %	
2400-2700 ml	26.1 %	
Road density for LTW study area	0.55 km km^{-2}	0.88 mi mi^{-2}

Online Data

The road network erosion analysis results are available at https://wepp1.nkn.uidaho.edu/weppcloud/lt/ From this link, scrolling down to **Lake Tahoe West Shore (LTWS) Road Analysis** section. The downloadable files include:

- LTWS_RoadAnalysis.zip – a single compressed file containing the two map packages, the three spreadsheets and the two *.pdf files from the analysis as a single download file as described below.
- LTWS_RoadAnalysis_README.pdf – a summary of the documents on this site.

Table 3. Summary of runoff, erosion and sediment delivery for the three elevations and the road network erosion analysis for the Tahoe West Restoration Project, current condition.

Result	Current Condition		Non Paved Roads Closed		Non Paved Roads Logged	
	Metric	English	Metric	English	Metric	English
Precipitation	mm	in.				
1800-2100 m	937	36.9				
2100-2400 m	1338	52.7				
2400-2700 m	1484	58.4				
Rainfall Runoff	mm	In.	mm	In.	mm	In.
1800-2100 m	12.5	0.49	7.4	0.29	14.3	0.56
2100-2400 m	9.8	0.39	22.3	0.88	14.1	0.56
2400-2700 m	5.4	0.21	5.4	0.21	8.79	0.35
Winter Runoff	mm	In.	mm	In.	mm	In.
1800-2100 m	41.2	1.62	14.6	0.57	39.6	1.56
2100-2400 m	35.2	1.39	57.0	2.24	66.05	2.60
2400-2700 m	34.9	1.37	34.7	1.37	81.42	3.21
Total Runoff	mm	In.	mm	In.	mm	In.
1800-2100 m	53.7	2.12	22.0	0.87	53.9	2.12
2100-2400 m	45.0	1.77	79.3	3.12	80.2	3.16
2400-2700 m	40.3	1.59	40.1	1.58	74.8	2.95
Sediment Leaving Road	Mg	Tons[a]	Mg	Tons	Mg	Tons
1800-2100 m	44.95	49.45	30.81	33.89	464.11	510.52
2100-2400 m	58.70	60.04	51.29	53.26	1378.60	1516.46
2400-2700 m	3.86	3.16	3.89	3.16	226.42	249.96
Sediment Delivered	Mg	Tons	Mg	Tons	Mg	Tons
1800-2100 m	17.99	19.79	11.55	12.71	157.96	173.76
2100-2400 m	33.95	37.35	26.78	29.46	627.40	690.14
2400-2700 m	1.74	1.91	1.59	1.75	88.93	97.82
Sediment Delivered	Mg/km	Tons/mile	Mg/km	Tons/mile	Mg/km	Tons/mile
1800-2100 m	0.23	0.40	0.20	0.36	2.79	4.94
2100-2400 m	0.35	0.62	0.31	0.55	7.32	12.96
2400-2700 m	0.34	0.61	0.31	0.55	17.51	30.99

[a] 1 Ton = 2,000 lbs

- 1811_FY19_Scope_of_Work_West_Shore_Water Quality.pdf – A description of the approach to the study and other activities associated with the Lake Tahoe West Water Quality group.
- LTWS_WEPP-Rd_CuttentCond.xlxs – a spreadsheet for the Lake Tahoe West road database provided by the LTBMU and broken down into individual road segments, and the WEPP:Road input data and modeling results for each segment for the current condition (Figure 2a).

- LTWS_WEPP-Rd_Logged.xlxs – a spreadsheet with the Lake Tahoe West road database for non paved roads only, provided by the LTBMU and broken down into individual road segments, and the WEPP:Road input data and modeling results for each segment were those segments opened for timber removal (Figure 2b).
- LTWS_WEPP-Rd_Closed.xlxs – a spreadsheet with the Lake Tahoe West road database for non paved roads only, provided by the LTBMU and broken down into individual road segments, and the WEPP:Road input data and modeling results for each segment were those segments closed and partially covered in vegetation (Figure 2c).
- LTWD_WEPP-Rd_MapPackage.zip – A compressed file containing three ArcMap 10.5 map packages:
    - BW-WS_RoadSedimentResults.mpk - A subset of the WEPP:Road results for the Blackwood Creek Watershed only;
    - LT_West_Shore_Road Sediment_Results.mpk - The results of the WEPP:Road analysis for each road segment, allowing the user to view the road erosion and sediment delivery results in space;
    - LT_West_Shore_Road_Sediment_Results.zip - A set of supporting files to complement the LT_West_Shore_Road Sediment_Results.mpk file;
    - LT_West_Shore_Road_Topo_Analysis.mpk - The topographic analysis containing all the GIS layers for applying the Cao et al. (2018) method to the LTBMU road database with a 10-m DEM.

There is one spreadsheet for each condition: current, logged and closed (Figures 2a, b and c). There is one line for each road topographic unit identified by the GIS topographic analysis of the road network. Most of the LTBMU road segments needed to be subdivided into several topographic lengths to correctly describe the road segment runoff hydrology (Cao et al., 2018). Each spreadsheet file has introductory sheets with general modeling information, and one sheet for each elevation with the segment-by-segment analysis. The elevation spreadsheets have four sets of columns. The first set of columns contains the information in the attribute table for the road layer that was provided by the LTBMU road database. The second set of columns contains the topographic information from the Cao et al. (2018) analysis. The third set of columns are the crosswalk from the LTBMU database and topographic analysis to the correct format to be copied and pasted into the WEPP:Road Batch input screen. The final set of columns contain the outputs from the WEPP:Road Batch run (Similar to Figure 6 in the Example section of this report). When the length of a road segment exceeded 140 m, the analysis was done for 140 m, but the results were adjusted proportionately to account for the additional length. The adjusted road erosion rates and sediment delivery rates are in the final two columns of the spreadsheet (Figure 6).

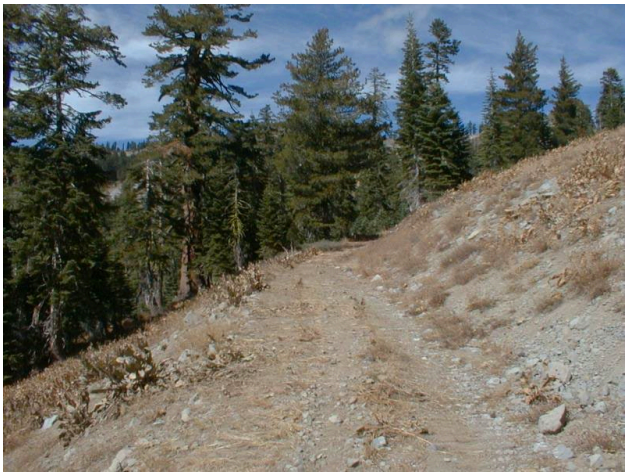


Figure 2a. Typical low use road in the Tahoe Basin. Note the existing ruts, negating the benefits of outsloping (Villanueva, 2013).

Figure 2b. Road condition that would likely be associated with harvesting, with wheel ruts and a large fraction of fines on the surface that will easily be detached by runoff (Villanueva, 2013).

Figure 2c. Example of an overgrown road with no traffic in the Nez Perce NF (Elliot et al., 2018)

Figure 2d. Recontoured Road (Villanueva, 2013).

There are two *.zip files with map packages on the web site. The LTWS_RoadAnalysis.zip contains all of the files described at the start of this section including the spreadsheets, the map packages, and the *.pdf files. The LTWS_WEPP-Rd_MapPackage.zip, contains three ArcMap 10.5 map packages and supporting GIS data for the LT_WEST_Shore_Road_Sediment_Results.mpk file. The LT_West_Shore_Topo_Analysis.mpk file contains all of the layers that were developed for the topographic analysis starting with the LTBMU road network file and a 10-m DEM. Details of how these layers were developed are described in Cao et al. (2018) and further step by step instructions for applying the method to this or other road network analyses can be provided by Sue Miller[6]. The second

[6] sue.miller3@usda.gov

map package, LT_West_Shore_Sediment Results.mpk contains the maps of the results of the erosion analysis for all three elevations and all three conditions. Users can select the layers or segments of interest from this file, and adjust the ArcMap symbology colors and categories to suit their needs in the ArcMap Table of Contents screen. The attribute table with this map contains much of the same information as the three spreadsheets. Users with GIS skills may prefer to work with the map package and attribute table, while users with limited GIS skills may prefer to work with the same information in the spreadsheets. The orders of the columns in the GIS sediment results attribute tables are that same as in the spreadsheets. The first set of columns contain the LTBMU road network broken down into segments from the Cao et al. (2018) topographic analysis. The second set of columns contain the input data for the WEPP:Road Batch input screen, and the third set of columns contain the WEPP:Road Batch output road runoff, surface erosion and sediment delivery estimates for each road segment. The BW-WS_RoadSedimentResults.mpk contains a subset of the LT_West_Shore_Sediment Results.mpk file, containing only the road segments within the Blackwood Creek Watershed.

Figures 3a – 3c provide an example of the information on the Sediment Results map package. The figures show the current (3a), closed (3b) and harvest (3c), for the Blackwood Creek Watershed only. GIS tools can be used with the Map Packages to zoom in on any watershed or road segment of interest. Figure 3a shows the current condition, which includes both the paved road that runs near Blackwood Creek, but turns to gravel about ¾ of the way up the watershed. The three elevation zones are noted by different shading. The maximum sediment delivered from any single road segment for the entire Lake Tahoe West analysis for the current condition was only 0.1 Mg, and that was from a paved road segment.

Figure 3b shows only the non-paved roads, and the estimated sediment delivery if they were closed and allowed to revegetate. Many of the roads in the current condition were already closed, so there is not much difference between Figures 3a and 3b for many of the non-paved roads.

Figure 3c shows the distribution of the non-paved roads if they were logged. Only a small number of the non-paved road segments will be disturbed for harvest in any given season. The modeling assumed that harvest roads would experience high traffic and be rutted. As soon as the harvest operation ends, it is likely that the road will be regraded and possibly closed, reverting to the current or closed condition within a year.

Larger maps can be viewed and printed from the Road Sediment Map Package.

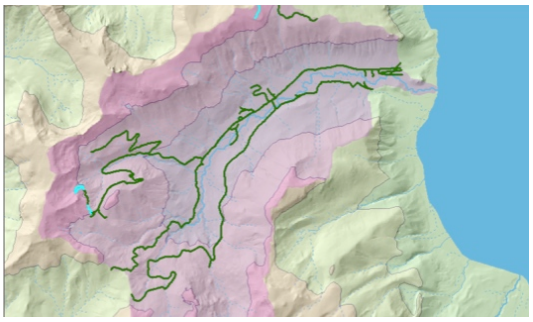


Figure 3a. Sediment delivery from the buffer to a channel for current conditions in Blackwood Creek Watershed.

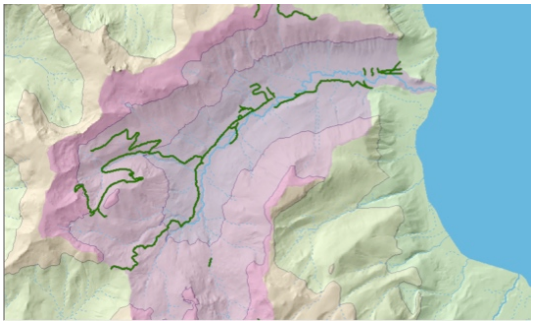


Figure 3b. Sediment delivery from the buffer to channel for closed conditions of non-paved roads. Maximum sediment delivery is 0.43 Mg, but most vales are less than 0.1 Mg per segment in Blackwood Creek Watershed.

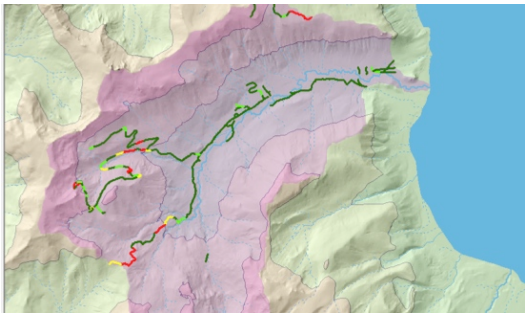


Figure 3c. Sediment delivery from non-paved roads if used for harvest. Maximum value is 21 Mg, and black segments are delivering less than 1 Mg to the stream. Green segments delivery 1-2 Mg, Yellow 2-3 Mg, and Red delivering greater than 3 Mg sediment per segment.

Discussion

Completeness of Road Layer

The LTBMU GIS road layer did not include all of the roads in Lake Tahoe West. In a recent remote sensing study (O'Neil-Dunne et al., 2014), impervious areas were identified by their reflectance, and some of those areas were roads. Figure 4 shows the results of that study where potential road segments not in the LTBMU database can be seen, within the vicinity of the Blackwood Creek Watershed. Impervious areas include roads, building roofs, and non-vegetated areas like screes and rock outcrops (Figure 4). It is readily apparent that the LTBMU road layer did not include all of the roads in Lake Tahoe West, but likely included most of the roads that will be used for fuel management activities.

In a related study, Cao et al. (2019) evaluated the effects of "ghost roads" in forested landscapes, focusing on the Blackwood Creek Watershed. Ghost roads are roads that are not part of the current road network, but at one time were used for harvest or other uses. Cao et al. identified these roads manually, using LIDAR images and historic air photo images (Figure 5). The Cao et al. study identified a large number of road segments that were neither on the LTBMU database (Figure 3a), nor identified by the impervious area study (Figure 4). Some of those road segments may likely extend to meet other partial segments, but vegetation and perhaps erosion make it difficult to discern without a field survey.

Figure 4. LTBMU road layer as shown in Figure 3a, plus the layer of impervious areas determined by remote sensing showing additional roads and urban roofs, and in Upper Blackwood, some bare rock outcrops shaded in yellow.

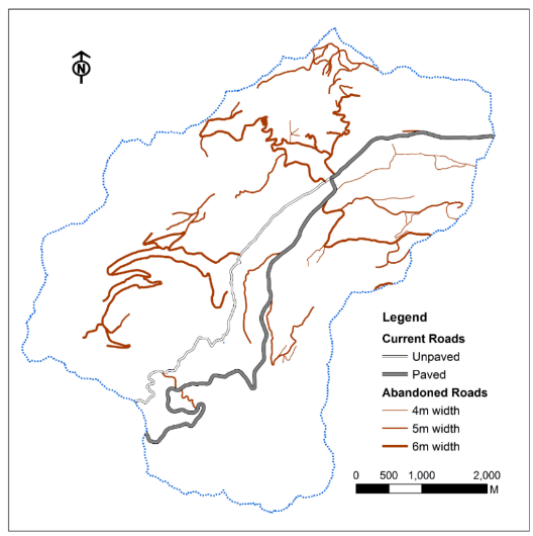


Figure 5. LTBMU Road layer, and abandoned roads identified with the aid of LIDAR and historic satellite imagery (Cao et al. 2019)

In a similar road network study (Elliot et al., 2018) in the Clear Creek Watershed in the Nez Perce National Forest, Elliot, Miller and Cao visited several road segments and confirmed that the segment gradients and lengths observed with a site survey were similar to the values estimated from the GIS analysis. At the completion of the Clear Creek erosion study, Elliot and Miller visited the watershed to see some of the segments that were predicted to be delivering large amounts of sediment (Elliot et al., 2018). They found that those road segments were either grassed over (Figure 2c) or covered in young trees, and no longer generating sediment (Foltz et al., 2009). One of the segments had even been recontoured (Figure 2d). The runoff diverted by the roads that have not been recontoured, however, may still be causing off-road erosion as noted in the Cao et al. (2019) study (Figure 5). Local specialists may wish to visit Lake Tahoe West segments predicted to be delivering the greatest amount of sediment to determine if mitigation measures should be considered for current conditions, or if the road is opened up to allow access for thinning; or if the road is not generating sediment either from the road or downslope.

Accuracy of Predictions

This study used the WEPP:Road soil database. Rainfall simulations on roads within the Tahoe Basin by Foltz et al. (2011) found that the hydraulic conductivity of Tahoe roads was higher, and the interrill erodibility was lower than the values in the WEPP:Road database for the sandy loams soils that were assumed for this study. It is likely that if the Foltz et al. (2011) values had been used in the modeling rather than the generic database, that the predicted sediment delivery would have been less. Foltz et al. (2011) estimated road surface runoff and sediment delivery to be 80% less using the locally observed erodibility values. They also suggested that time since last traffic may have a greater effect on sediment delivery than soil properties, as the Tahoe sites were all low traffic sites on native surface roads. However, a study of sediment generated by roads in the nearby King's River Experimental Forest found that WEPP:Road was underestimating sediment leaving the road (Stafford, 2011). Details of the analysis, however, were not sufficient to determine if the modeling had been correctly applied in the study, in particular, the climate and the buffer lengths. Also, the soils in the Stafford (2011) study on the western slopes of the Sierras were finer-textured than the LTW soils. So the Foltz et al. (2011) study suggested WEPP:Road may be over predicting sediment, whereas the Stafford (2011) study suggests that the WEPP:Road erosion estimates may be under predicted. The high variability of soils and year-to-year climate always challenge validation comparisons. Even though the absolute predicted values may be over or under estimated, those road segments that are predicted to have the highest sediment delivery rates will remain the same (Foltz et al., 2011).

The erodiblity values used for WEPP:Road were developed from rainfall simulation studies. The plot-to-plot variability for the erodibility values is such that the coefficient of variation (the standard deviation divided by the mean) is generally around 30 percent for rainfall simulation studies, regardless of who is doing the studies. With a coefficient of variation of 30 percent, there is a 90 percent confidence interval that the observed sediment delivery from a replicated study is, at best, plus or minus 50 percent of the mean. With such a large variation in observed data, it is not possible for any predicted value based on those data to be any more accurate. This means that there is a 90 percent probability that the accuracy of a predicted sediment delivery value, is at best, plus or minus 50 percent. Such is the nature of all soil erosion prediction technology, regardless of what model is used.

Sediment Delivery

The WEPP technology does not use a "sediment delivery ratio" to determine sediment delivery, but rather estimates each run individually, estimating runoff and sediment generated by the road, and then runoff changes over the fillslope and forested buffer. As the runoff and slope steepness change on the fillslope and the buffer, WEPP calculates the sediment transport capacity, and sediment detachment or deposition for 100 points on the fillslope and the buffer. For most scenarios, infiltration on the buffer limits sediment delivery from the buffer. The overall ratio of the sediment delivered to the bottom of he hill compared to the sediment leaving the road is 0.5 in this study. This value, however, varies considerably, with no sediment leaving paved roads, so all sediment is from the fillslope and the forest buffer, to some scenarios where no sediment is delivered from a buffer even though there was sediment generated from the road surface. As shown in the examples, the road segment generating the greatest amount of sediment is paved, with all sediment coming from an eroding buffer from the excess runoff generated by the paved road surface. In the Waterboards and NDEP (2008) report, the authors had assumed that all upland sediment was from roads, and then estimated a delivery ratio for each watershed by dividing the observed sediment leaving the watershed by the estimated road surface erosion rate and found ratios varying from 0.1 from granitic watersheds where buffer infiltration rates were high to 4 on watersheds dominated by lower infiltration volcanic watersheds. The report did not discuss the likely erosion occurring in the buffers as determined by the WEPP:Road analysis procedure, nor the hillslope and channel erosion estimated in the LTW watershed study.

Road Sediment vs. Hillslope Sediment

The total estimated sediment leaving the LTW Road Network is 108 Mg, and the delivery from the LTW road network to nearby channels for the current condition is 55 Mg (Table 3), for an average of 0.3 Mg y^{-1} km^{-1}. To put this in context with hillslope erosion, the total sediment delivery estimated for LTW from hillslope and channel erosion for the current condition was estimated to be 6905 Mg, with 35 percent of the sediment coming from Blackwood Creek[7]. These estimates are similar to the estimated sediment yields for current conditions in the report by the Water Boards and NDEP (2008), that estimated the forested landscape to generate 7671 Mg/y and the road network 325 Mg/y or about 1.9 Mg y^{-1} km^{-1}. The Water Boards and NDEP (2008) report attributed the relatively low amount of sediment from the current road network to the low surface area covered by roads in Lake Tahoe West, only 0.2% of the area. Elliot (2013) stated that in forest watersheds, roads tend to be the second greatest source of sediment, after wildfire. The results on the West Shore do not support this assertion, but as noted in the Water Boards and NDEP (2008) report, the low values for road sediment is likely due to the relatively low road density of only 0.55 km km^{-2}, compared to 2.4 km km^{-2} in many forested watersheds.

The large difference in estimates between the Water Boards and NDEP (2008) and this study is likely due to the very different methods of analysis. The Water Boards and NDEP (2008) approach measured the sediment concentration leaving a 1-m^2 plot from rainfall simulation, and then adjusted that concentration by the sediment concentration observed in channels leaving each of the watersheds. The study did not consider road segment lengths or gradients, or the location of the road on the landscape. It also made assumptions about the fraction of delivery of sediment from forests and roads. The

[7] https://wepp1.nkn.uidaho.edu/weppcloud/static/mods/lt/results/lt9_sed_del_summary.csv

approach then adjusted the delivery ratio by watershed to determine the total amount of sediment from roads and from forests. The Water Boards and NDEP study failed to consider channel erosion when evaluating sediment from forest watersheds, but addressed channel sediment sources in another chapter. In some watersheds, the Water Boards and NDEP (2008) increased the sediment delivered from the roads by up to a factor of 4 because of the observed sediment concentration in the channel. With their approach, the Water Boards and NDEP authors assumed that the roads must be generating greater amounts of sediment than predicted by the runoff and sediment deliveries observed from the rainfall simulation plots. Hence the greater estimate of road sediment in the Water Boards and NDEP report of 325 Mg on the West Shore than the estimate of 55 Mg from this analysis.

The draft Ghost Road analysis for the Blackwood Creek watershed (Cao et al., 2019) approached sediment prediction in several ways. Erosion from the existing network and from ghost roads should they be reopened was estimated with WEPP:Road Batch, assuming that granitic soils were best described as sandy loam in the WEPP:Road soils database, and volcanic soils as silt loam in the database. They also used a LIDAR DEM to evaluate the impact of the roads on overland flow and stream channel erosion. In a third analysis, they used a 30-m DEM to estimate hillslope and channel erosion if there was no road network, as the effect of roads on topography would be masked in a 30-m DEM. They estimated that the erosion rate for granitic soils, using the sandy loam soil, was 376 kg/km, compared to an estimate of 329 kg/km from this study for the Blackwood Creek Watershed. The Cao et al. study only applied the sandy loam texture to granitic soils and the silt loam texture to volcanic soils in the Blackwood watershed, whereas this study used the sandy loam classification for both granitic and volcanic soils, as both parent materials resulted in soils that would be classified as sandy loam. Estimated sediment delivery rates are higher from silt loam soils (Cao et al., 2019). One of the interesting outcomes in the Cao et al. study is that the presence roads changes the first order channel networks, extending the length of some of the existing first order channels, and shortening the length of others. The net effect was a net increase in channel lengths from 103 km with the 30-m DEM that ignored road topography to 114 km using a 1-m LIDAR assuming roads were outsloped. This increase in channel length resulted in an increase in channel erosion from 1 Mg/ha for watersheds if roads were removed to 2 Mg/ha for watersheds if roads were all reopened as outsloped roads, doubling the sediment delivery from upland watersheds. This increase in upland channel erosion did not result in as great an increase at the watershed outlet however, as some of the sediment detached in steep upland channels was predicted to be deposited downstream in the lower-gradient higher-order stream channels. In this study, those road segments that had sediment delivery from the buffer greater than sediment delivery from the roads, is also an indication of the increased offsite erosion associated with some road segments.

The Lake Tahoe West hillslope study estimated that sediment delivery were all hillslopes logged would increase to 9,370 Mg/y, whereas the road network erosion would increase to 874 Mg, now about 9 percent of the total sediment in the stream system. Compared to many western forested watersheds, where road densities can exceed 2.4 km km^{-2} (4 miles $mile^{-2}$) the roads in Lake Tahoe West with a density of 0.55 km km^{-2} will play a lesser role in the overall sediment budget than in many watersheds, similar to the findings of the Water Boards and NDEP Report (2008).

Were a wildfire to occur on the study area, a study by Elliot et al. (2018) reported that 227 Mg of sediment were deposited on Highway 89 from an upslope area of less than 50 ha. Anecdotal accounts following other fires have also reported sediment deposition on forest road surfaces within the fire

perimeter. This suggests that should a wildfire occur following road reconstruction on this project, that upland sediment yields may be reduced because of the presence of those roads.

Fine Sediment

The main concern related to sediment in the Tahoe Basin is "Fine Sediment." Fine sediments tend to stay suspended in the lake indefinitely, riding on the internal vertical water fluxes driven by wind shear and wave dynamics on the lake surface (Luettich et al., 1990). Fine sediments are also more easily re-entrained into suspension due to wave action near the shores (Adams, 2004). These suspended sediment particles reduce the clarity of the clarity of the lake's water. Two different definitions of "fine sediment" are common in the Tahoe literature. The USGS and a report based mainly on the USGS monitoring data by Simon et al. (2006) define "fine sediment" as clay and silt size particles under 63 µm. The Water Boards and NDEP report (2008) also defined fine sediment as particles less than 63 µm. Water quality literature associated with the TMDL for Lake Tahoe, however, typically defines "fine sediment" as mineral particles less than 16 µm (California Regional Water Quality Control Board, 2010).

One of the outputs from the WEPP model is a table showing the distribution of primary particles (sand, silt, and clay), small aggregates made up of silt and clay particles and organic matter, and large aggregates made of up all particle sizes and organic matter. From this table, it is possible to estimate the mass of particles smaller than any desired cutoff value, as demonstrated by the online Tahoe Basin Sediment Model[8] Interface.

For this study, a number of WEPP Runs were carried out with the WEPP:Road interface for a number of different buffer lengths for native and paved outsloping roads with the Rubicon Climate to see the predicted particle size distribution of the delivered sediment. In all but one case, the particle size distribution of the delivered sediment was the same of the distribution of the upland sandy loam soil. Thus, on native surface roads, the sediment from the road is predicted to be similar to the soil on the hillslope. On paved roads, the sediment is eroded from the fillslope and forested hillslope below the road, and will also be similar to the surface soil.

The results of the concurrent Lake Tahoe West hillslope and watershed erosion analysis included a summary of the particle size distribution on the hillslopes and in the sediment delivered from the watershed[1]. Table 4 presents a summary of the particle size distribution from the Blackwood Creek watershed analysis for hillslopes and sediment delivered by Blackwood Creek, and the sandy loam soil in WEPP:Road. Similar analyses can be carried out for the other watersheds in Lake Tahoe West and would yield similar results, although watershed sediment loads will be lower. The watershed erosion analysis for current conditions for Blackwood Creek resulted in an estimated total sediment delivery of 2433 Mg. Table 4 shows that 72.2 percent of the delivered sediment is less than 63 µm . Combining these two numbers results in an estimated "fine sediment delivery" for Blackwood Creek of 1756 Mg/y. Simon et al. (2008) reported that their estimate for this number, based on USGS monitoring data was 1347 Mg/y, confirming the reasonableness of the WEPP analyses.

[8] https://forest.moscowfsl.wsu.edu/fswepp/

Table 4. Particle size fractions on the Blackwood Creek Watershed hillslopes and estimated from the channel, and the Sandy Loam soil in the WEPP:Road

Particle	WEPP:Road Sandy Loam	Blackwood Hillslopes	Blackwood Channel
Clay	0.05	0.0768	0.268
Silt	0.35	0.2799	0.454
Sand	0.60	0.6433	0.278
Fraction < 16 µm	0.121	0.134	0.360
Fraction < 63 µm	0.40	0.357	0.722

As the total sediment from the Lake Tahoe West road network (54 Mg) is only a fraction of that delivered from the Lake Tahoe West hillslopes (6900 Mg), the road sediment is unlikely to alter the predicted watershed sediment delivery results.

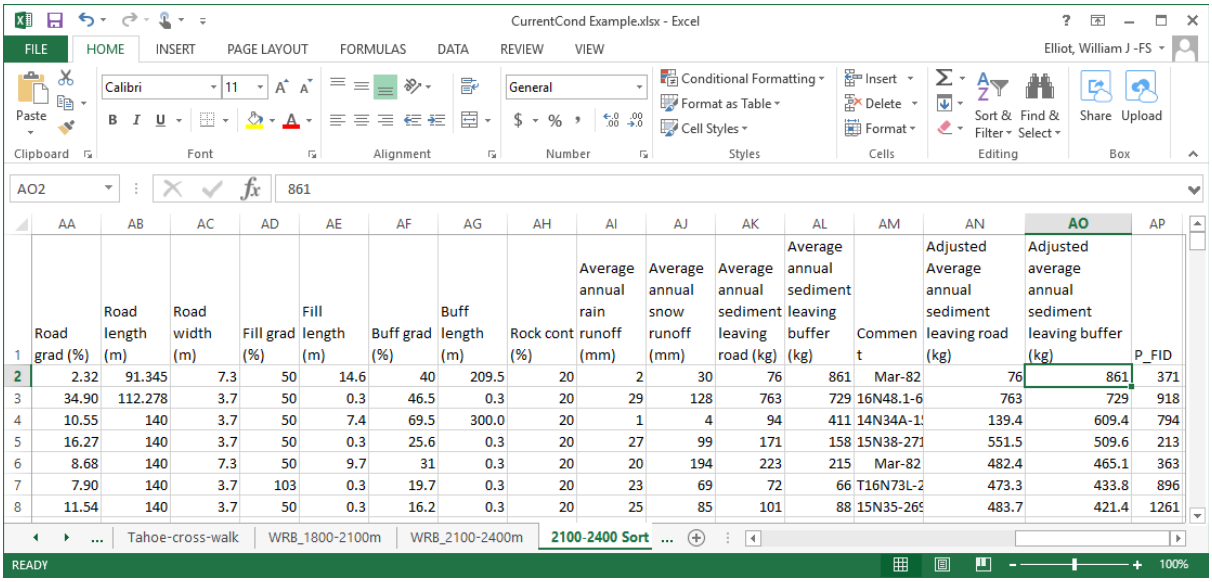
Management Implications

Numerous practices are available for reducing erosion risks during harvest operations. One practice is to put gravel or rock in ditches. Non-paved harvest roads, however, are outsloped and should not have any ditches that can be rocked. This practice would be limited to paved roads with ditches. Another practice is to add additional surface cross drains such as water bars during active harvest when roads become rutted. Where there are ditch relief culverts, a common practice in the Tahoe Basin is to install sediment traps downstream from ditch relief culverts. For nonpaved roads that are subject to high traffic, an effective practice is to install water bars about 15 m (50 ft) either side of every stream crossing, and then graveling or otherwise armoring roads between the waterbars as the road crosses the stream to minimize surface erosion in the vicinity of the stream crossing. When roads are not needed for harvest, ensuring an outsloping surface with waterbars, and removing culverts will minimize road impacts on runoff and erosion processes. During harvest, road erosion can be minimized by blading the road prior to the onset of wet weather to minimize the increased erosion associated with rutting, or winter harvest. Water Boards and NDEP (2008) listed a similar set of practices to minimize sediment from forest roads.

Managers also need to be aware that any reconstructed roads will only be generating the estimated increase in sediment during the years that the roads are being use for logging. Simply stopping the logging truck traffic and restoring the road outslope by blading will likely reduce the sediment generation by 80 percent (Foltz, 1996). Sediment generation will be reduced further in the following years as the road surface is revegetated (Foltz et al., 2009).

Future Climates

Future climates in the Tahoe Basin are projected to be warmer and slightly wetter. This means that there will likely be more wet days with rain in the fall and spring rather than snow. It also means there will be more days for potential evapotranspiration, leading to drier soils in the fall. There will also be less snow accumulation in the winter. The net effect of these changes is hard to generalize. Erosion may be greater because rainfall intensity and subsequent runoff are at a higher rate that normally associated with snowmelt. Erosion may be less because erosion may be driven by rain-on-snow events, and with less of a snowpack, runoff amounts associated with rain-on-snow events may be less. Runoff and sediment delivery may be less because the buffer element has generally lower water content because of



	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
1	Road grad (%)	Road length (m)	Road width (m)	Fill grad (%)	Fill length (m)	Buff grad (%)	Buff length (m)	Rock cont (%)	Average annual rain runoff (mm)	Average annual snow runoff (mm)	Average annual sediment leaving road (kg)	Average annual sediment leaving buffer (kg)	Comment	Adjusted Average annual sediment leaving road (kg)	Adjusted average annual sediment leaving buffer (kg)	P_FID
2	2.32	91.345	7.3	50	14.6	40	209.5	20	2	30	76	861	Mar-82	76	861	371
3	34.90	112.278	3.7	50	0.3	46.5	0.3	20	29	128	763	729	16N48.1-6	763	729	918
4	10.55	140	3.7	50	7.4	69.5	300.0	20	1	4	94	411	14N34A-1	139.4	609.4	794
5	16.27	140	3.7	50	0.3	25.6	0.3	20	27	99	171	158	15N38-271	551.5	509.6	213
6	8.68	140	7.3	50	9.7	31	0.3	20	20	194	223	215	Mar-82	482.4	465.1	363
7	7.90	140	3.7	103	0.3	19.7	0.3	20	23	69	72	66	T16N73L-2	473.3	433.8	896
8	11.54	140	3.7	50	0.3	16.2	0.3	20	25	85	101	88	15N35-269	483.7	421.4	1261

Figure 6. Screen shot of the 2100-2400 m elevation Current Condition sorted by sediment leaving the buffer, showing the road segments delivering the greatest amount of sediment.

increased evapotranspiration, resulting in greater infiltration and reduced runoff from the buffer. Warmer weather may result in more rain-on-snow events at higher elevations, increasing erosion for those locations.

Future climates are also predicted to have an increased “intensification” of precipitation, with longer dry spells, and greater amounts of rainfall on days when it does rain. Such an increase may increase erosion unless the intensification is mainly associated with winter snowfall. Past studies have shown that erosion may be increased or decreased with future climates, depending on how these various climate factors interact. Although not the focus of this study, future climates will likely result in more frequent wildfire in the Basin (Trotochaud, 2015), which will very likely increase total watershed sediment loads in the coming decades.

Future climate files for predicting road erosion within the Tahoe Basin are currently available with the online Tahoe Basin Sediment Model (TBSM) interface. Future climate characteristics can also be described in terms of warmer temperatures and altered precipitation patterns with the RMRS Rock:Clime program, and the generated future climate file used for estimating erosion from the entire road network from this study, or just selected road segments for a sensitivity study. Alternatively, a detailed analysis for a set of typical road segments using the Tahoe future climate files on the TBSM interface can be carried out if the stakeholders are interested in funding such studies.

Examples of Applying the Results

Determining the Road Segments with the Greatest Sediment Delivery

The spreadsheet for the current condition was downloaded, and saved as “Current_Condition_Example.xlxs” in a working directory. The entire sheet for the 2100-2400 m elevation was copied and pasted into a new sheet for sorting. The columns of the pasted sheet were formatted for convenience. Column AO, the “Adjusted average annual sediment leaving buffer (kg)” is selected. Under the Excel Data Tab, “Sort Largest to Smallest” was selected, and the “O Expand the

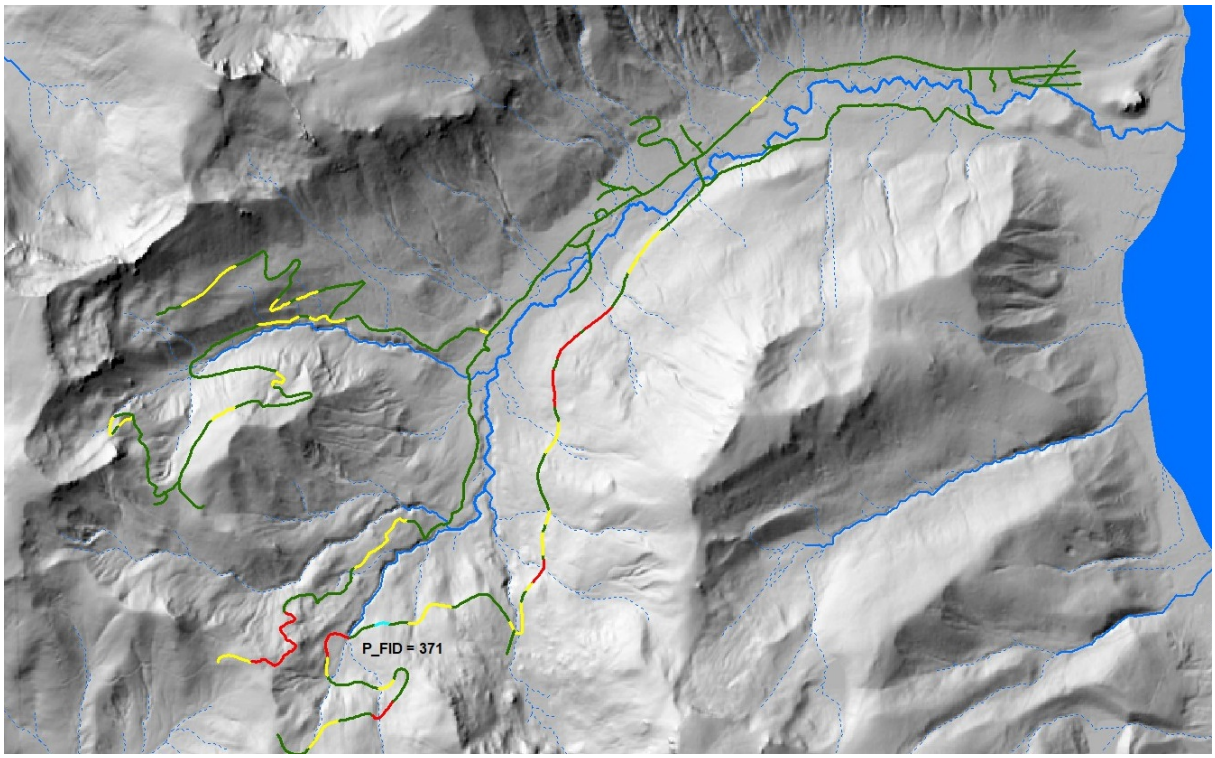


Figure 7. Screen shot from ArcMap with the road network current condition for the Blackwood Watershed. The highest sediment generating segment from the West Shore Road Network Analysis, P_FID=371, is highlighted in light green, delivering 861 kg. The sediment delivery for the dark green segments is 0 - 75 kg, the yellow segments 75 - 240 kg, and the red segments 248 - 861 kg.

Selection" box was ticked. Figure 6 shows a part of the resulting spreadsheet. Road segment P_FID 371 caused the greatest sediment delivery in Lake Tahoe West, delivering an average annual amount of 861 kg. The road segment length of 91 m was less than the maximum value of 140 m, confirming that this segment was not truncated in the analysis. Thus the offending segment has a road segment length of 91 m and a road grade of 2.3 percent (Figure 6). The amount of sediment estimated leaving the road was 76 kg, and the amount of sediment leaving the buffer was 861 kg. Thus an eroding buffer was the main source of sediment. Further inspection of this segment's line in the spreadsheet reveals that this road segment is paved, so the "sediment leaving the road" is due to erosion in the fillslope, but the majority of erosion is occurring on the buffer. This suggests that this segment should be inspected to determine if the buffer showed signs of erosion. If it does, then practices to reduce erosion in this steep buffer should be considered, such as diverting runoff to sediment basins, or installing rocked channels. As the road is paved, it is also possible that there is an inside ditch. When modeling an inside ditch with a crowned road, the recommended analysis is to consider the two parts of the road separately, with half the road runoff contributing to an inside ditch, and the other half an outsloped road delivering a reduced runoff amount to the fill slope and buffer, reducing the erosion risk.

Locating the Road Segments with the Greatest Sediment Risk

To find this the road segment (P_FID = 317) in Lake Tahoe West, the map packages were extracted from the "LT_West_Shore_Sediment_Results.zip" file. The "LT_West_Shore_Sediment_Results.mpk" was then opened with ArcMap. In the ArcMap Table of Contents, the 2100-2400 Elevation, Current Condition Layer was found. A right click on this layer allowed the user to select the "View Attribute Table". This

table was opened, and scrolling to the right until the found the "P_FID" Column. The table was sorted on the P_FID column in ascending order, and the row for P_FID = 371 was selected. By clicking the cursor on the left hand column, and selecting "Zoom to Selected", the road segment was highlighted on the map. Zoom out on the map to see where the segment was located in Lake Tahoe West. The segment was located on an upper road near the top of the Blackwood Watershed (Figure 7). The "Identify" tool in ArcMap confirmed that this is an asphalt section on the main Barker Pass Road in Upper Blackwood.

The maps of the road network erosion can be saved as geo referenced pdf documents, and then used with a georeferencing map program, such as Avenza's PDF Maps software on a smart device. This will allow the user to locate the segment of interest in the field using the smart device's GPS capabilities.

Evaluating the Effect of Site-specific Factors on Sediment Delivery

The spreadsheets of the results contain all the information that was derived from the GIS topographic analysis linked to the LTBMU database and the WEPP:Road Batch input and output files. This means that users can use the sorting capabilities of the spreadsheets to evaluate the interrelationships of the input factors and output results for a very wide range of comparisons. For example, stakeholders have been concerned that increased forest activities on steep slopes will result in a greater risk of sediment delivery than on flatter slopes. As part of this analysis, the steepness of the buffer was determined from the underlying slope steepness layer, and is recorded in the buffer steepness column (column AF in Figure 6). By graphing the sediment delivery vs. the buffer steepness, the managers can quickly evaluate whether roads on steeper terrain generate more sediment than on flatter terrains (Figure 8). The coefficient of determination (r^2) for this analysis was only 0.13, indicating that the slope steepness only explains 13 percent of the variability in sediment delivery. Slope steepness alone does not explain the magnitude of sediment delivery. Similar analyses for other factors can also be carried out. Because of the number of factors contributing to road sediment delivery, however, no single factor is likely to be identified. Figure 8 also shows that there are a small number of road segments with high sediment delivery rates, and as shown in the first example, these segments can be readily identified.

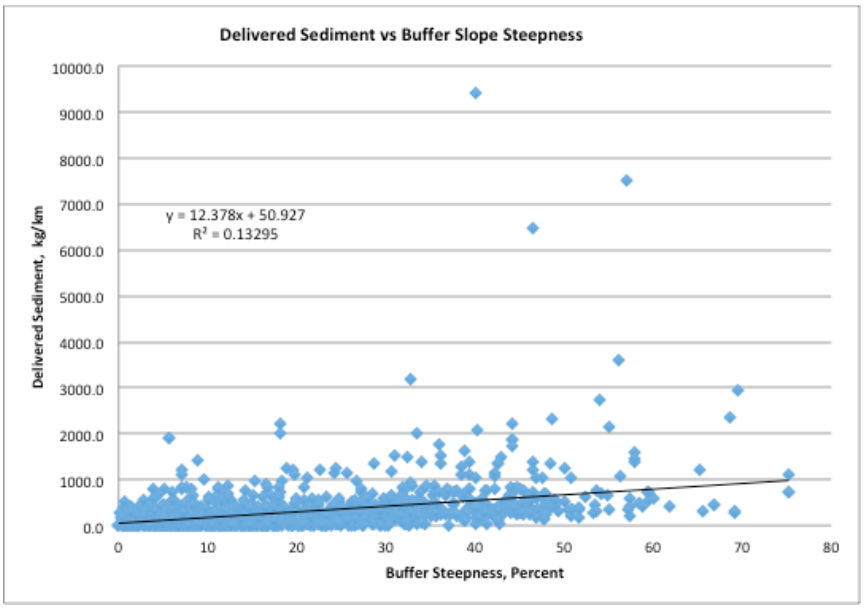


Figure 8. Example of using results in spreadsheets for further analysis. Sediment delivery vs. buffer steepness

Summary and Conclusions

The Lake Tahoe West Restoration Project contains 181 km of roads, 33.5 km of which are paved. Many of the unpaved roads are closed and covered with vegetation. An analysis of road surface erosion and sediment delivery estimated that the current road network was delivering 54 Mg of sediment per year. Closing unpaved roads that are currently trafficked will reduce erosion by 20 percent. Running harvest traffic on particular road segments will on the average, increase sediment delivery by 19 times for those segments during the years in which the harvest operations are active. However, following active use for harvest, those estimated loads would rapidly return to the current values. Consequently, the increased sediment delivery associated with harvesting operations could be approximated by multiplying the estimated delivery by the fraction of time that the roads are actually used for harvest. These calculations do not account for potential sediment reduction benefits for harvest because of reduced impacts from wildfires, nor the reduction in erosion following wildfire because of the potential deposition of eroded sediments on the road surface. Furthermore, it is important to note that the sediment from the Lake Tahoe West road network is estimated to be less than 1% from the hillslopes. Watershed managers are encouraged to visit the current roads predicted to deliver large amounts of sediment to determine if the segments or downslope runoff from those segments are the sources of sediment, or if those segments are now covered in vegetation and no longer an erosion risk. If the field survey of high-risk segments confirms road or downslope erosion, then appropriate management practices can be applied to mitigate that erosion.

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