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# **Sediment-Related Road Effects on Stream Channel Networks in an Eastern Sierra Nevada Watershed**

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## **ABSTRACT**

Squaw Creek, a small (21.1 km<sup>2</sup>), subalpine watershed located approximately 9.6 kilometers northwest of Lake Tahoe, California between the towns of Tahoe City and Truckee, is listed as an impaired waterway for excessive non-point source sedimentation under section 303(d) of the Clean Water Act. The watershed was evaluated from a geomorphic perspective to identify and characterize sources of sediment, including impacts from road networks on sediment delivery to the stream network.

Roads in the watershed contribute to sediment production by concentrating runoff, thereby increasing sediment load to the stream network. Most unimproved (dirt) roads connect either directly or indirectly with streams and, therefore, act as extensions of stream networks by effectively increasing watershed drainage density and subsequently sediment loads to streams. In the South Fork subwatershed of Squaw Creek, road connectivity has resulted in an increase in effective drainage density of approximately 250%. Throughout the Squaw Creek watershed, it is estimated that dirt roads potentially contribute as much as 7,793 metric tons/year to the watershed sediment budget.

## **INTRODUCTION**

### **Project Purpose**

Squaw Creek has been listed as impaired by sedimentation under section 303(d) of the Federal Clean Water Act by the State of California because of its high sediment production and turbidity levels relative to other tributary watersheds to the Lower Truckee River. This study represents a portion of a sediment source assessment of the Squaw Creek watershed as part of a Master's thesis project.

The principal intent of the study was to gain a greater understanding of the geomorphic processes influencing sediment movement through a subalpine catchment by conducting a sediment source assessment that focused on three primary objectives:

- Conduct a watershed scale geomorphic process-response analysis.
- Qualitatively and quantitatively analyze hillslope and in-stream erosion and storage.
- Evaluate the influence of land use and cover on sediment supply and transport processes.

A qualitative and quantitative assessment of the spatial and temporal variability of sediment transport was completed. Historic and present-day erosion susceptibility models were then created by compiling field and morphometric data to aid in the assessment of land use and land cover influences on sediment sources. The models were developed utilizing a Geographic Information System (GIS), field investigations, and modified published methodologies to identify and characterize natural and anthropogenic influences on sediment production, transport, and storage in the watershed.

## **Setting**

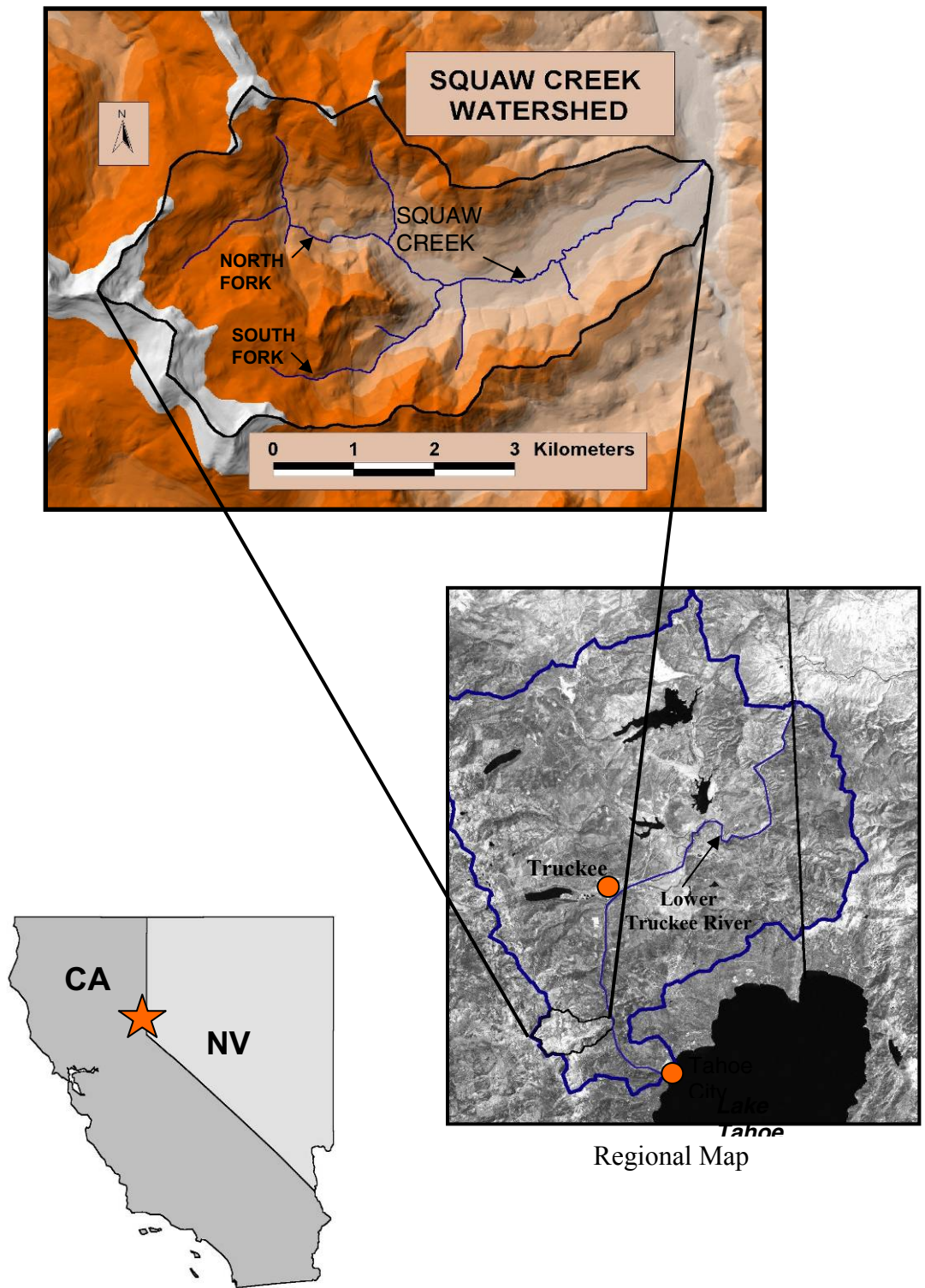
Squaw Creek, a tributary of the Lower Truckee River, is a small (21.1 km<sup>2</sup>), subalpine watershed located approximately 9.6 km northwest of Lake Tahoe in Placer County between the towns of Tahoe City and Truckee (Figure 1) on the Tahoe City and Granite Chief 7.5 Minute U.S. Geological Survey (USGS) Quadrangles (Maholland, 2002). Elevation of the watershed ranges from 2,745 m at the highest point to 1,865 m at the confluence of Squaw Creek and the Truckee River. Squaw Creek consists of a main, low-gradient trunk that is formed from the confluence of two primary forks in the north and south subwatersheds in the western portion of the watershed, as well as numerous first through third order streams feeding into the main channels. Current land uses include an expanded ski resort with year-round recreational opportunities, a golf course, commercial equestrian operations, sports fields, a network of hiking and bicycling trails, logging roads, residential development, and ski resort maintenance access roads.

The geology of the watershed is composed principally of Jurassic metasedimentary and metavolcanic rocks, Cretaceous intrusive granitic rocks of differing composition (mostly diorite and granite), and Pliocene basaltic andesite and pyroclastics. Quaternary age surficial geologic units are comprised of glacial deposits (lateral and terminal moraines), colluvial and alluvial fans at the intersection of the valley side slopes and the meadow, and fluvial deposits in meadow portions of the creek (Birkeland, 1961).

As is typical of many Sierra Nevada high altitude environments, precipitation in the Squaw Creek watershed is primarily in the form of snow, with some minor thunderstorm activity occurring during the summer and fall. Consequently, snowmelt runoff and rain-on-snow events are the primary climatic drivers of surface water hydrology (e.g., peak flows) and sediment movement within the watershed occur mostly during late spring and early summer. The main channels of the stream generally maintain baseflow throughout the year, although during dry years baseflow may be minimal.

## **Geomorphic Effect of Road Networks**

Road networks represent a mechanism for potentially significant increases in sediment delivery to streams (Grace and others, 1996; Sun and McNulty, 1997) and are considered to be more important than other disturbance effects such as deforestation (Swanson and Dyrness, 1975). The relative contribution from road networks to sediment production and delivery to drainages is considered in this paper as part of the larger Squaw Creek watershed sediment source assessment study.



**Figure 1.** Location map of the Squaw Creek watershed. Blue outline on regional map represents the California portion of the Lower Truckee River watershed boundary (Maholland, 2002).

The road corridor and associated features, such as drainage ditches, road surfaces, cut banks, fill slopes, stream crossings, and culverts, as well as sand applied during winter months, all contribute to stream sediment through two main mechanisms: (1) increased runoff, and; (2) increased sediment yield (Foreman and Alexander, 1998). The road surface and road corridors function both as sediment sources and as delivery mechanisms for runoff and sediment. Surface flow is concentrated and the networks of roads and road corridor attributes have the net effect of increasing overall watershed drainage density, which leads to higher watershed peak flows and, therefore, increased stream power. Roads disrupt other hydrologic processes including subsurface flow conversion to surface flow at road cuts, increased numbers and elongation of first order streams resulting from concentrated flows off of roads, engineered structure failure (e.g., culverts and bridges), and compaction and redistribution of the soil matrix through cut and fill construction techniques and use. These disruptions can lead to dramatic increases in landslide frequency and resulting in-stream sediment supply (Swanson and Dyrness, 1975; Foreman and Alexander, 1998; Jones and others, 2000). Research in the Victorian Highlands of Australia (Brown, 1994) has shown that the extent and degree of impacts from roads is related to vegetation and cover, soil types, topography, and the level and type of use associated with the road corridors. Differences in the degree and extent of effects related to these variables were also observed in the erosion data collected for the Squaw Creek watershed during the course of the sediment source assessment study.

Detrimental effects associated with road networks are controlled in part by the spatial relationship between the road corridors and hillslope position (ridges, mid-slope, valley bottom) and the connection of road segments to stream drainages. Road segments situated on high alpine ridges in upper watershed areas may experience significant erosion effects related to the deeper snowpacks that occur in these areas and, therefore, supply more available water for erosive impacts during melting periods. In the Squaw Creek watershed, precipitation as snow accounts for approximately 50% of the total winter precipitation at lower elevations (below 2,400 m) and 90% of the winter total for higher altitudes (above 2,400 m), with snow accumulations greatest on north-facing slopes. High elevation roads in most watersheds are generally not directly connected to streams by virtue of their high position in the watershed and, therefore, their contribution of sediment to streams is often limited. Roads located in mid- and lower portions of a watershed, however, typically have a greater frequency of stream crossings, creating a direct connection to the stream network (Jones and others, 2000). Roads located in these areas commonly are oriented parallel to the main reaches of the stream, allowing the associated rills, gullies, and culverts to transport sediment efficiently to the stream, as was observed in the Squaw Creek watershed (Figure 2). Road cuts located in the mid- to lower- portions of the watershed are also more likely to intercept and redirect shallow subsurface water flow to the surface where it may add to existing runoff from the road (Wemple and others, 1996) (Figure 3). Similarly, road drainage ditches function in the same connective capacity as road segments, transporting and generating sediment from road surfaces and associated ditches, cut banks, and debris slides directly to stream networks (Jones and others, 2000). In the Squaw Creek watershed, however, the majority of the roads are connected to stream networks due to the high density of roads, small watershed area and their close proximity to stream channels. This increases the effective drainage density, as discussed below.



**Figure 2.** Gully formed on road surface concentrates and directs runoff and sediment to an adjacent stream channel in upper area of the South Fork of Squaw Creek. Red arrow indicates direction of flow (Maholland, 2002).



**Figure 3.** Interception of shallow groundwater on hillslope cut to accommodate a maintenance road contributes to increased flow in ditches and road surfaces (Maholland, 2002).

## Road Density

Road density is frequently used as an overall index of road impacts in a watershed because the negative effects (e.g., higher runoff, increased sediment delivery to streams) tend to increase with increased density (Foreman and Alexander, 1998). Portions of the Squaw Creek watershed exhibit a high density of roads (Figure 4). The road density for the overall watershed is 3.62 km/km<sup>2</sup>, with the highest density occurring in the South Fork subwatershed: 10.03 km/km<sup>2</sup> (Table 1). Foreman and Alexander (1998) noted that increased peak flows in streams are evident at road densities of 2 to 3 km/km<sup>2</sup>. These figures would indicate that the road densities in the south fork of Squaw Creek and on the north-facing valley moraine wall are great enough to create a negative effect on the geomorphic and hydrologic character of stream networks. Using the logging road density for a northern California coastal watershed reported by Madej (2000), the 10.03 km/km<sup>2</sup> value for the south fork of Squaw Creek is approximately two times greater than the value of 5 to 7 km/km<sup>2</sup> for a typical managed (logged) watershed. To compare similar land uses, road density values for Heavenly Valley ski resort in the Lake Tahoe basin were calculated using a GIS. Heavenly Valley's road density values are estimated to be 3.75 km/km<sup>2</sup>, which is notably less than those found in the South Fork subwatershed of Squaw Creek where the majority of the ski area is located.

**Table 1.** Density of dirt roads by location in the watershed (Maholland, 2002).

Location	Road Density (km/km <sup>2</sup> )
South Fork Subwatershed	10.03 km/km <sup>2</sup>
North Fork Subwatershed	0.56 km/km <sup>2</sup>
North Facing Lateral Moraine	6.73 km/km <sup>2</sup>

## Effect of Roads on Drainage Density

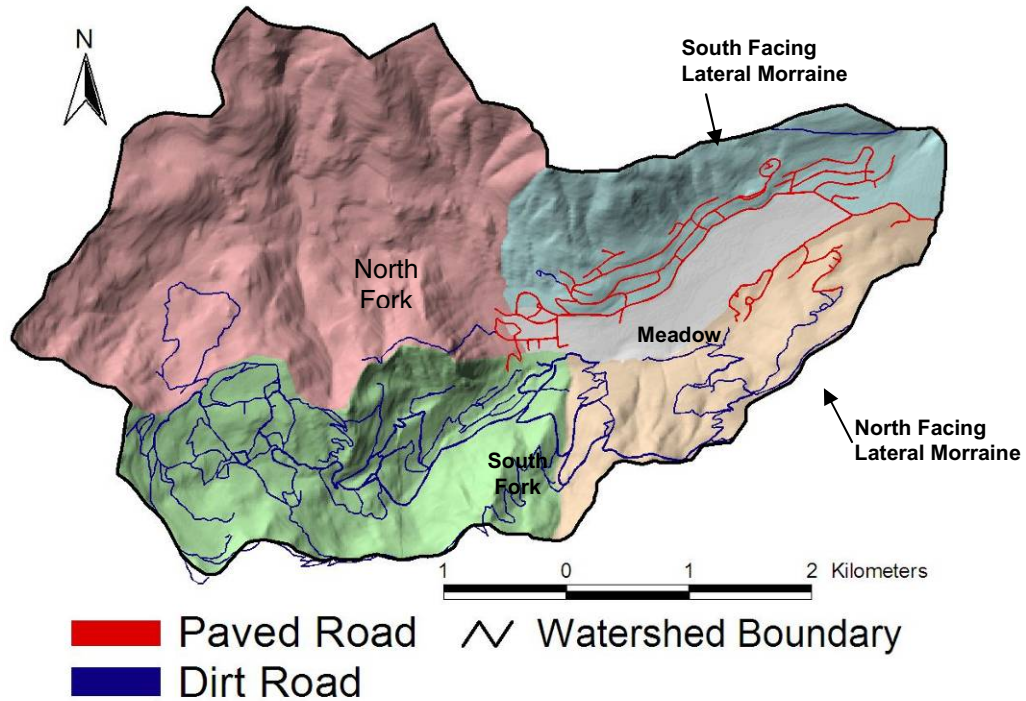
The drainage density ( $D_d$ ) of a watershed is defined as the summation of the stream lengths ( $\Sigma L_S$ ) divided by the watershed area ( $A$ ) (Equation 1),

$$D_d = \Sigma L_S / A \quad \text{Equation 1}$$

and is expressed as stream length per unit area (Wemple and others, 1996). Drainage density has been used as an indicator of the efficiency of a stream network such that higher drainage density values indicate greater discharges, erosive power, and sediment transport within the watershed.

Wemple and others (1996) and Jones and others (2000) have shown that the overall drainage density of a watershed or subwatershed is increased via road network connectivity with the stream network because roads function as extensions of the drainage network. This increase in drainage density, termed "effective drainage density", results in higher peak flows, increased delivery of runoff to streams, and in-stream

erosion. Drainage density increases ranging from 21% to 50% were reported for several study areas in the Western Cascades of Oregon with dirt road networks (Wemple and others, 1996). A comparison of drainage densities for subwatershed in the Squaw Creek watershed and drainage densities adjusted for road connectivity (effective drainage density) is represented in Table 2. The effective increases in drainage density, particularly in the South Fork subwatershed, have resulted in observable impacts to the stream network, including increased rill and gully formation from roads.



**Figure 4.** Distribution of primary and secondary dirt and paved roads in the Squaw Creek watershed overlain on study area map (Maholland, 2002).

**Table 2.** Stream network drainage density and effective drainage density adjusted for dirt road connectivity to streams in the Squaw Creek watershed (Maholland, 2002).

Location	Drainage Density: km/km <sup>2</sup>	Effective Drainage Density: km/km <sup>2</sup>	Increase in Drainage Density
South Fork Subwatershed	2.93 km/km <sup>2</sup>	10.24 km/km <sup>2</sup>	250%
North Fork Subwatershed	4.58 km/km <sup>2</sup>	5.06 km/km <sup>2</sup>	10%
North Facing Lateral Moraine	5.01 km/km <sup>2</sup>	8.61 km/km <sup>2</sup>	70%
Squaw Creek Watershed	4.02 km/km <sup>2</sup>	7.6 km/km <sup>2</sup>	90%

## **Other Effects Related to Unimproved Road Networks in Mountainous Regions**

Studies conducted in steep forest landscapes have shown an increase in the frequency of debris slides, debris flows, and landslides associated with road networks located within the watershed when compared to similar forested and undisturbed (roadless) watersheds (Jones and others, 2000; Wemple and others, 1996). These types of mass movements are considered to be the major source of sediment in some mountain streams (Fredricksen, 1970; Madej, 2000). Varnes (1978) found that small-scale, shallow translational slides are associated with roadcuts and steep slopes having thin mantles of colluvium. Natural processes, such as frost heaving or the differential expansion of clay minerals, may further enhance translational slides. Minor occurrences of debris splays were identified in the study area related to the presence of roads, but were not directly quantified.

Increases in the peak flow, or peak discharge, defined as the maximum volume flow rate passing by a particular location in a stream during a precipitation event or specified timeframe can cause hydrologic and geomorphic adjustments in stream channels, such as channel width enlargement, channel incisement, rapid soil movement, bed and bank erosion, and bank failure (Foreman and Alexander, 1998; Hancock and others, 1998; Jones and others, 2000; Madej, 2000). Increases in peak flow are accomplished by road network connectivity through roadside drainage ditches that reroute precipitation runoff generated from compacted road surfaces and intercepted shallow subsurface water from roadcuts and are frequently observed in portions of the study area containing roads (Figure 2). Compacted road surfaces cause a decrease in infiltration capacity and soil permeability and an increase in surface runoff resulting in accelerated water erosion, removal of vegetation, and increases in the production of fine sediment (Brown, 1994; Foreman and Alexander, 1998; Jones and others, 2000; Lahde, 2003). Drainage water may then be rapidly delivered to stream networks, causing not only increases in magnitude, but increases in the frequency of peak discharge as well (Wemple and others, 1996; Jones and others, 2000; Madej, 2000). Paired watershed studies in the Idaho Batholith (Wemple and others, 1996) strongly support these observations by showing a statistically significant increase in peak flows as a direct result of road networks. Increases in peak discharge were not recorded in the study area, since Squaw Creek is not a gaged stream, but may be inferred by the documentation of frequent rill and gully occurrence leading directly to stream networks from roads.

Culverts present unique and potentially serious issues related to watershed erosion. Runoff from road surfaces, ditches, and cutslopes is concentrated by rerouting through culverts, thus increasing its erosive power. This can lead to increases in delivery of sediment to the stream network where culverts are directly discharging into streams, as well as gully formation and incision that can occur below culvert outlets, which in turn deliver additional sediment and flow (Megahan and others, 1986). The amount of sediment increase can be significant from these gullies. Megahan and others (1986) report deposition quantities of up to 15 times greater from gullies resulting from culvert discharge than runoff solely from the road surface. Steep slopes (>40%) are prone to gullying and may thereby add sediment and create another mechanism by which roads

are connected to the stream network (Wemple and others, 1996). In addition to the physical effects of hydrologic rerouting, sediment delivery increases can result from culvert failure. Plugged or undersized culverts can cause stream flow to divert around the structure and erode road fill material and cause rilling or gullying. Similarly, failed culverts above stream networks may divert and discharge flow onto unprotected hillslopes causing rilling and gullying (Megahan and others, 1986; Madej, 2000), as was observed in portions of the Squaw Creek study area (Figure 5).



**Figure 5.** Failed culvert in South Fork subwatershed of Squaw Creek showing evidence of increased sediment and discharge to stream network.

### **Sediment Yield from Road Corridors**

With consideration of the preceding factors, quantification of sediment yields from road corridors can be problematic despite their importance as a primary source of eroded material to stream networks, particularly in high-traffic watersheds such as Squaw Creek (Table 3). However, several sources provide comparisons of sediment load in disturbed (established road corridors) and undisturbed systems that can be used as guides in assessing the relative contributions of sediment from roads. In a study of logging roads constructed in a forested watershed, Fredrickson (1970) reported that sediment output was 250 times that of the undisturbed condition following road construction, decreasing to two or three times during subsequent years. Logging road construction in the Idaho Batholith, consisting of steep granitic terrain and shallow coarse-textured soils similar to portions of the Squaw Creek watershed, resulted in accelerated surface erosion and sedimentation hundreds of times greater than undisturbed watershed rates (Megahan and others, 1986). The same study also reported road erosion rates of  $50 \text{ m}^3 \text{ ha}^{-1}$  for

constructed logging roads in the No Name Creek watershed in Idaho. Using the Universal Soil Loss Equation (USLE), Sun and McNulty (1997) predicted a loss of 1 to 50 metric tons/ha/year from managed roads. Swanson and Dyrness (1975), in a study of right-of-way slide erosion along roads, found that right-of-ways associated with roads eroded thirty times faster than comparable forested sites. Data collected from sediment fence traps in the Squaw Creek watershed support the observations of increased levels of sedimentation from roads.

**Table 3.** Total road length and road surface area in Squaw Creek watershed by road type (Maholland, 2002).

Road Type	Length	Road Surface Area (km <sup>2</sup> )		
		Squaw Creek	North Fork	South Fork
Dirt – Single Track	41.9 km	0.255 *[1.2]	0.082 *[0.3]	0.187 *[3.4]
Dirt – Double Track	13.2 km	0.161 *[0.8]	0 *[0.0]	0.114 *[2.4]
Total Dirt Roads	55.1 km	0.416 *[2.0]	0.082 *[0.3]	0.301 *[5.8]
Paved – Primary	6.9 km	0.063 *[0.3]	0 *[0.0]	0 *[0.0]
Paved – Secondary	14.3 km	0.114 *[0.5]	0.001 *[0.9]	0.003 *[0.1]

\*Road surface area expressed as a percent of watershed area is shown in brackets.

Contributions of sediment from dirt roads in the Squaw Creek watershed were estimated from sediment collected at an erosion fence sample site below a waterbar that conveyed runoff from a road surface segment (Maholland, 2002). The amount of sediment collected during the study period is assumed to estimate the amount of sediment from a dirt road surface, specifically because the sample site is situated near the top of a ridge and, therefore, any sediment being transported by runoff would come only from the road surface. However, the effect of roads on erosion rates in other areas is not reflected in this calculation. The road surface contributing areas (Table 3) were derived from the Tahoe National Forest roads database that was mapped using 1986 U.S.G.S. quadrangles and digitized into a GIS. This layer was then revised using recent (1997) stereo aerial photographs, 1998 digital orthophoto quadrangles (DOQs), and verified through field reconnaissance. Measurements were then calculated in ArcView after applying a width buffer along digitized road networks (Maholland, 2002). Using the soil bulk density to convert the volume of sediment to sediment mass and dividing that value by the contributing dirt road surface area, a mass per unit area value was computed. This value was then multiplied by the total dirt road surface area in the watershed to estimate that dirt roads have the potential to contribute approximately 7,793 metric tons/year to the watershed sediment budget (Maholland, 2002).

## **Paved Roads**

Discussions related to the effects of road networks in forested settings generally focus on unimproved (dirt) roads. However, paved roads also have the potential to contribute to accelerated levels of erosion in a watershed. A number of paved roads are located within the Squaw Creek watershed, primarily the main roads leading to commercial areas and in the residential subdivisions. Paved roads comprise approximately 21.2 km of the road network in the Squaw Creek watershed and nearly 1% of the total surface area of the watershed. Paved roads do not themselves contribute to erosion, but rather provide impervious cover that restricts infiltration and concentrates runoff and associated sediment transport. The runoff may then increase erosion in roadside ditches and adjacent unpaved surfaces, such as road shoulders. Field observations indicate that nearly all paved road runoff is collected in ditches and directed through culverts into the meadow or directly into Squaw Creek itself. In particular, fine-grained material appears to be frequently transported into Squaw Creek utilizing remnant ditches created to drain the meadow for parking during the 1960 Winter Olympics. Paved roads also represent a source of sediment due to road sanding operations during winter months, with approximately 327 metric tons of sand per year being used in the Squaw Creek watershed. Some sand applied in winter is mechanically removed through sweeping, although records are not maintained.

## **SEDIMENT LOAD REDUCTION**

A number of management activities and Best Management Practices (BMP's) could be implemented within the watershed to reduce road related impacts to the stream network from increased sediment loading. These could potentially include:

- Reducing the overall number of dirt roads within the watershed through decommissioning. Increased benefits will be realized if decommissioning efforts include topographic restoration (restoring the contour of the hillslope), targeting roads that cross channels, armoring roadside ditches with rock and revegetation efforts, and stabilizing roadcuts with rock rip-rap and vegetation to stabilize the soil.
- Outsloping of flat grade maintenance roads, where topography allows, to reduce the potential for rill and gully development and to disperse runoff.
- Improving revegetation efforts on ski slopes and decommissioned roads by emphasizing native plant use, breaking up compacted topsoil to allow for infiltration, mulching with pine needles, and cross-contour ripping.
- Decreasing or eliminating the number of culverts that daylight directly into stream channels, and instead utilize sediment detention basins, dispersing runoff in low erosion areas (e.g., flat, forested areas), and other similar BMP's.

- Residential areas would benefit from the installation of curb and gutters to collect urban runoff and dispersing runoff in the meadow through the construction of micro-topographic ridges, instead of remnant Olympic-era channels.

## **CONCLUSION**

Within watersheds, multiple mechanisms operate to cumulatively affect sediment production, transport, and storage in the watersheds. Road corridors serve to generate and deliver increased runoff and sediment to the stream network and play a significant role in the sediment yield of a watershed and in channel processes. This is accomplished through the concentration of flow from an increase in the overall watershed drainage density, which leads to higher peak flows and subsequently, increased stream erosive power. Downstream, increased stream erosive power results in accelerated bank erosion and incision, affecting both fluvial processes and the stream environment zone. In most watersheds, the spatial relationship between the road corridors and hillslope position is important relative to the potential for roads to be connected to the drainage network. However, most roads in the Squaw Creek watershed are connected to stream networks due to the high density of roads, small watershed area and their close proximity to stream channels.

In the south fork of Squaw Creek, road connectivity has resulted in an increase in effective drainage density from 2.93 km/km<sup>2</sup> to 10.24 km/km<sup>2</sup>, which represents an increase of approximately 250% that greatly enhances the effectiveness of the fluvial system to transport sediment and water, commonly with adverse effects to the stream channel form and function. Additionally, it is estimated that dirt roads contribute approximately 7,793 metric tons/year to the Squaw Creek watershed sediment yield, which has the potential to negatively affect local and downstream water quality and aquatic habitat.

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## REFERENCES

- Birkeland, P.W., 1961, Pleistocene history of the Truckee Area, North of Lake Tahoe, California [Ph.D. Dissertation]: Palo Alto, CA, Stanford University, 126 p. (includes Plate 1, Geologic map of the Truckee area, California, scale 1:62,500).
- Brown, K.J., 1994, River-bed sedimentation caused by off-road vehicles in the Victorian Highlands, Australia: *Water Resources Bulletin*, v. 30, no. 2, p. 239-250.
- Foreman, R.T. and Alexander, L.E., 1998, Roads and Their Major Ecological Effects: *Annual Review, Ecological Systems*, v. 29, p. 207-232.
- Fredricksen, R.L., 1970, Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds: PNW-RP-104, Pacific Northwest Forest and Range Experiment Station, United States Forest Service, Portland, OR, 15 p.
- Grace, J.M., Wilboit, J., Rummer, R., and Stokes, B., 1996, Surface erosion control techniques on newly constructed forest roads. In: 1996 ASAE Annual International Meeting, ASAE, Phoenix Civic Plaza, Phoenix, AZ, 14 p.
- Hancock, G.S., Anderson, R.S., and Whipple, K.X., 1998, Beyond power: bedrock river incision process and form. In: K.J. Tinkler and E.E. Wohl (Editors), *Rivers over rock: Fluvial processes in bedrock channels*, American Geophysical Union, Washington, DC, p.35-60.
- Jones, J.A., Swanson, F.J., Wemple, B.C., and Snyder, K.U., 2000, Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks: *Conservation Biology*, v. 14, no. 1, p. 76-85.
- Lahde, D. B., 2003, Relationships between low-standard roads and stream incision in Central Nevada [M.S. thesis]: Reno, University of Nevada, 106 p.
- Madej, M.A., 2000, Erosion and sediment delivery following removal of forest roads: U.S. Geological Survey Western Ecological Research Center, Aracta, CA, 22 p.
- Megahan, W.F., Seyedbagheri, K.A., and Mosko, T.L., 1986, Construction phase sediment budget for forest roads on granitic slopes in Idaho. In: R.F. Hadley (Editor), *Drainage Basin Sediment Delivery*, IAHS Press, Oxfordshire, UK, p. 31-39.
- Maholland, B., 2002, Geomorphic assessment of natural and anthropogenic sediment sources in an Eastern Sierra Nevada watershed [M.S. thesis]: Reno, University of Nevada, 178 p.
- Ritter, D.F., Kochel, R.C., and Miller, J.R., 2002. *Process Geomorphology*, 4<sup>th</sup> Edition: WCB/McGraw-Hill, New York, NY, 560 p.

Sun, G. and McNulty, S.G., 1997, Modeling Soil Erosion and Transport on Forest Landscape: Southern Global Change Program, USDA Forest Service, Raleigh, NC, p.189-198.

Swanson, F.J. and Dyrness, C.T., 1975, Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon: *Geology*, p. 393-396.

Varnes, D., 1978, Slope movement types and processes. In: Schuster, R.L., and Krizek R.J. (Editors) *Landslides: analysis and control*, National Academy Sciences, Transportation Research Board Special Report No. 176, 234 p.

Wemple, B.C., Jones, J.A., and Grant, G.E., 1996, Channel network extension by logging roads in two basins, Western Cascades, Oregon: *Water Resources Bulletin*, v. 32 no. 6, p. 1195-1207.