Moonlight Fire GRAIP Watershed Roads Assessment

Lights Creek and Indian Creek

Plumas National Forest, California

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Table of Contents

List of Figures

List of Tables

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Executive Summary

This report presents results from a watershed-wide inventory and assessment of roads in Lights Creek and Indian Creek, and adjacent watersheds which encompass the Moonlight Fire area in the northern Sierra Nevada Mountains in California. The method used was the Geomorphic Road Analysis and Inventory Package (GRAIP), a field-based model developed by the Forest Service Rocky Mountain Research Station and Utah State University. The primary objectives of the project were to:

- Evaluate the types, and sources of road-related hydrologic risk in the watershed
- Locate and quantify sediment sources and contributions to streams
- Identify and prioritize future restoration actions
- Compare results from the GRAIP model to results from studies in the Sierra Nevada and other geologically similar areas.

Field inventory, modeling, and analysis were completed on 691 km (429 mi) of Forest Service and public roads. 616 km (383mi) were Forest Service or private, system roads existing on maps prior to the GRAIP survey. Approximately 98% of the 657 km (408 mi) mapped system roads in the 514 km^2 (199 mi^2) watershed were surveyed. 74 km (46 mi, 11%) of all roads surveyed were Forest Service non-system roads that were not mapped at time of GRAIP survey. A small amount of length surveyed was near, but outside the watershed boundary.

Observations of road surface erosion were made from sediment plots in the study area. Four plots were installed on roads in granitic geology types, and four on volcanic geology types.

The GRAIP model was used to predict risk and impacts from roads. The model predicts road to stream hydrologic connectivity, sediment delivery to streams, downstream sediment accumulation, risks of shallow landslides caused by roads, gully initiation risk below drain points, and risks to road-stream crossings. Inventory data are also used to locate and describe problems with existing drain points.

Hydrologic connectivity was found to be about 13% of all road length at 92 km out of 691 km (57 mi out of 429 mi). The model predicted 347 Mg/yr of delivered road surface fine sediment to stream channels, which is 12% of the 2,920 Mg produced annually. This sediment was delivered through 1,154 of 9,536 (12%) drain points. It was found that road surfaces that were rocky, rilled, and/or eroded are most likely to deliver sediment to streams. 9.8 km (6.1 mi), or 13% of non-system roads contribute about 47.6 Mg/yr of sediment to the stream network, which represents about 14% of all fine sediment delivered. Less than 5% of drain points deliver 90% of delivered sediment (Figure 13). This can help focus remediation efforts on a limited set of drain points in the area.

Specific sediment due to road surface-related sediment in some small catchments was as high as 27 Mg/km^2/yr. Specific sediment values range dramatically. Strahler order 1-3 streams ranged between 0-19 Mg/km^2/yr. Average for Strahler order 1 streams was 0.44 Mg/km^2/yr, and for Strahler order 2 and 3 streams was 0.70 Mg/km^2/yr in. Strahler order 4 and 5 streams ranged between 0.04-2.6Mg/km^2/yr with a mean of 0.68 Mg/km^2/yr. Accumulated and downstream specific sediment values include sediment that may be trapped by Antelope Lake Dam on Indian Creek as if it were routed through the system without the presence of the dam. The value of specific sediment in Indian Creek at the dam was 0.62 Mg/km^2/yr. Specific sediment production from all road related sources in this study was 91 Mg/km^2 yr, or about 17% of regional sediment production rate. Specific sediment delivery rate from all road related sediment sources for the entire study area was 8.1 Mg/km^2 yr, or about 2% of regional sediment delivery rate from all hillslope erosion sources. For subwatersheds contributing to Antelope Reservoir, specific sediment delivery rate in this study was 3.0 Mg/km^2 yr, or about 1.5% of reservoir deposition rate from all hillslope erosion sources.

Summary table of GRAIP road-related risk predictions in the Lights Creek and Indian Creek watersheds.

Impact/Risk Type	**GRAIP Predicted Risks**
Road-Stream Hydrologic Connectivity	92 km (57 mi), 13% of road length, and 1,154 (12%) drain points are stream connected
Fine Sediment Delivery	347 Mg/year, 12% of all fine sediment produced from road surfaces delivers to streams
Landslide Risk	Estimated 65,150 Mg (8% of all sediment produced), or estimated 3,260 Mg/yr delivered to streams; many slides are in deep seated terrain and are not shallow colluvial failures; 6% of watershed area with elevated landslide risk due to roads
Gully Risk	Estimated 418 Mg/yr of sediment delivered to streams, 18% of all drainage locations exceed ESI$_{crit}$ threshold
Stream Crossing Risk	
- plug potential	17 sites (5%) with elevated risk (SBI of 3)
- fill at risk	25,145 m^3, 40,230 Mg of fill
- diversion potential	115 sites (25%) with diversion potential
Drain Point Problems	2,508 drain points (26% of all) with problems; Road derived fill erosion delivered- 2,325 Mg (1,450 m^3, 5% of all drain points; 442 Mg were from gullies eroding along road surfaces to drain points), estimated 116 Mg/yr delivered to streams

There were 76 landslides observed by field crews in the course of the inventory, with a total volume of 538,080 m^3 (703,800 yd^3). Of those, 71 were observed as having direct interaction with the road prism. It was conservatively estimated that as much as 65,150 Mg of landslide derived sediment has been delivered to streams. If delivered over 20 years, an average annual rate can be estimated at 3,260 Mg/yr, or more than 9 times more than sediment from road surfaces. Calibrated stability index modeling with SINMAP showed that 32 km^2 (20 mi^2), or roughly 6%, of the watershed area was put at higher risk of shallow landslide initiation by road drainage. Given the magnitude of the observed landslide sediment delivery, future road construction and restoration work in the area should consider the shallow landslide potential of the site and the impact of adding additional road drainage to steep hillslopes.

Gullies were observed at 168 drain points by field crews, totaling 6,350 m^3 (8,300 yd^3) in volume. Of those, six occurred in a wet swale, and 27 had flow contributions from springs, seeps, and other flow diversions (e.g. from an overtopped stream crossing). It is estimated that these gullies delivered 8,365 Mg of fine sediment to the stream channel. If delivered over 20 years, an average annual rate can be estimated at 418 Mg/yr, or roughly 1.2 times more than sediment from road surfaces. Of 7,597 applicable drain points (those with contributing road length), 1,381 (18%) had an elevated risk of gullying. The critical gully initiation index (ESI_{crit}) was found to be 12. The average ESI for the points without gullies was 8, while it was 11 for the points with gullies. The gully occurrence rate for drain points that fell above the ESI threshold was 3% versus 1% for points that fell below the ESI threshold.

There were 352 stream crossings with culverts recorded. The average stream blocking index (SBI) for these points was low at 1.0. Seventeen crossings had an elevated SBI of 3. No crossings had an SBI of 4, which is the highest possible value. The total calculated volume of fill at risk in an overtopping type event was 25,145 m^3 (32,890 yd^3, or 40,230 Mg). There were 115 stream crossings with the potential to divert stream flow from a plugged culvert down the road and onto unchanneled hillslopes. There were 25 stream crossings with elevated risk in more than one area (SBI, fill at risk, diversion potential). There were five crossings with an SBI of 3 and more than 100 m^3 of fill at risk, but no diversion potential. There were two crossings with both a high SBI and the potential to divert streamflow. Both had more than 100 m^3 of fill at risk. These two crossings have the highest combined stream crossing risk and are good candidates for risk reduction treatments.

Non-system roads present similar risks as crossings in the entire study. Of 61 stream crossings, 12 have culverts in place. Of those with culverts, five had an SBI of 3, three had failing culverts in place, and five had diverted stream flow. Eleven had eroding stream crossings with a total of 614 Mg of past eroded fill, and are likely to produce more. Of 20 excavated stream crossings, two were actively eroding.

Of the 9,536 recorded drain points, 2,508 (26%) had one or more problems of some type (e.g. blocked or crushed culvert, excess puddling on the road surface). Non-engineered drains had the highest frequency of problems, with 1,243 of 2,146 (58%), followed by ditch relief culverts (912 of 2,289, 40%). Fill erosion was recorded at 470 drain points (5%), with a total volume of 1,970 m^3 (69,570 ft^3, 3,150 Mg). Estimated total fill erosion sediment delivery was 1,453 m^3 (51,310 ft^3, 2,325 Mg), or about 74% of total fill erosion mass produced. If delivered over 20 years, an average annual rate can be estimated at 116 Mg/yr, or roughly 0.3 times the sediment delivered from road surfaces.

In general, chronic sedimentation risks such as road surface-derived fine sediment delivery in the Lights Creek and Indian Creek watersheds were found to be similar to, or lower than results from studies in regionally and geologically similar study areas, and high compared with studies across the western United States. However, episodic risks such as landslide risk, gully risk, stream crossing failure risk, and fill erosion risk, were found to be generally moderate across the watershed, but delivered a significant mass to streams totaling about 12 times the total road-surface fine sediment annually. This level of risk is consistent with other regional GRAIP studies. It is worth noting that these episodic risks are likely to have some potentially significant component of chronic sediment input after the initial event. Treatment recommendations include larger culverts and reduced fill volumes at stream crossings, additional drainage placed and spaced carefully on open roads, and decommissioning or long-term storage of unneeded roads. Road drainage locations that are actively delivering large amounts of sediment from road surfaces, gullies, and fill erosion to high priority streams are also prime restoration locations.

Overall, compared to other studies with similar geology types, Lights Creek and Indian Creek watersheds base erosion rates are similar to, or higher than other studies. Sediment production rates are similar to, or only slightly lower than other studies in similar geology, and high compared to rates across the western United States. Percent road to stream connectivity was generally lower than, or similar to other studies. The base erosion rates in Lights Creek and Indian Creek watersheds were higher than in areas with more stable geology. The base erosion rates in Lights Creek and Indian Creek watersheds were also higher than studies in areas where geology was similar but roads studied were older, more established, and experienced low traffic. Lights Creek and Indian Creek watersheds base erosion rates were very similar to studies in areas where geology was similar and roads were more established, but the study period was longer and included wetter years. The road stream connection and base erosion rates reported in this study may be lower than a true long term average because of the short term period of observation of this study during a period following three years of drought conditions prior to the onset of this study. This GRAIP study records a snapshot in time of existing geomorphic evidence observable in the field at the time of study, and therefore reflects a short term view of the geomorphic and hydrologic conditions. It may not represent long term, average sediment production and delivery rates, however, the rates do provide valuable relative comparisons within the study area and to other regional studies.

1.0 Background

The National Forest Transportation System represents a major public investment and provides many benefits to forest managers and the public. However, roads also have negative effects on water quality, aquatic ecosystems, and other resources. There is currently a large backlog of unfunded maintenance, improvement, and decommissioning work needed on National Forest roads. Critical components of the infrastructure (e.g., culverts) are nearing or have exceeded their life-expectancy, adding further risk and impacts to watershed and aquatic resources.

Lights Creek and Indian Creek, are some of the uppermost headwater tributaries to the North Fork Feather River, a 303(d) listed impaired water body under the federal Clean Water Act, California EPA, and California State Water Resources Control Board. They represent valuable, relatively clear, cold, uncontaminated water sources to water supplies along their entire length and ultimately to the major water supply of Lake Oroville (Mayes and Roby 2013, USDA 2013, SWRCB 2012). These streams may be adversely affected by sediment from roads in the watershed. In order to quantify the amount and location of sediment contributions from roads to streams, the Rocky Mountain Research Station designed a site-specific road sediment inventory, using the Geomorphic Road Analysis and Inventory Package (GRAIP, Prasad et al 2007, Cissel et al. 2012A, Black et al. 2012, http://www.fs.fed.us/GRAIP). Settlement funds generated from the 2007 Moonlight Fire that burned 263 km^2 (65,000 acres, 102 mi^2) within the study area were allotted to study fire effects and design restoration projects in the watersheds surrounding the fire, and provided the impetus for employing GRAIP.

The GRAIP data collection and analysis procedure provides land managers with field-based data that captures the extent to which roads interact with the stream channel. GRAIP identified precise locations where sediment delivery was occurring, where drainage features were compromised, and where road maintenance, restoration, or decommissioning could be recommended. This detailed information can be used to prioritize actions to minimize adverse watershed and aquatic impacts from roads.

All mapped roads that were managed by the Forest Service or were otherwise located on public lands were targeted for inventory. Roads on existing geographic information system layers (Plumas 2014), referred to as system roads, were targeted for inventory (657 km, 408 mi). Approximately 98% of these mapped system roads were surveyed. Because this study focused on roads within Forest Service management jurisdiction, some system roads were not surveyed. System roads not surveyed were major paved county roads, private roads with restricted access on timber or mining lands, and Forest Service campgrounds. However, several major access roads, though officially on private or Plumas County lands were surveyed because of their prominence in the road network. Total length of all road types surveyed (691 km, 429 mi) differs from Plumas GIS mapped length because of the addition of non-system roads surveyed, and because surveys of roads along the watershed boundary included lengths outside the watershed boundary that were not counted in the system road length, and some road routes varied greatly from their mapped routes.

Roads not mapped on existing GIS maps prior to commencing GRAIP survey, referred to as non-system roads, were also targeted for inventory. Length of all existing non-system roads is not known, because these roads can be difficult to locate, and time limitations prevented a more exhaustive survey. There were 74 km (46 mi) of non-system roads surveyed.

Elevations in the study area range between 1,070-2,385 m (3,520-7,820 ft, Figure 6). Precipitation occurs mostly in winter as rain below, or snow above 1,980 m (6,500 ft) in winter, and in summer as infrequent thunderstorms. Average annual precipitation for the study area is 82 cm/yr (32 in./yr). Snowfall typically occurs at elevations above 1,700-1,980 m (5,600-6,500 ft; USDA, 2007), but can fall as either rain or snow in that elevation range.

Field work began on June 3, 2014 and was completed on September 16, 2014. The survey was conducted during drought conditions and in a climatic context that reflects regional warming and drying trends (USDA 2013).The survey year was one of the six driest years since 1990, all of which occurred within seven years prior to the study. Data collection coincided with the dry season following a year of increasing drought from “Moderate” one year prior, to “Extreme” upon commencing field work (US Drought Monitor 2015).

Given the dry climate in which the survey was conducted, this study likely reflects a period of generally low erosion rates, though episodes of higher erosion generated by intense summer thunderstorms did occur during the study. The base erosion rates used to calculate sediment production and delivery were collected on newly disturbed study plots, and may therefore not reflect a long term average. Overall, compared to those of other road sediment studies conducted in the Sierra Nevada and geologically similar areas, GRAIP base erosion rates in Lights Creek and Indian Creek watersheds were higher or very similar. Sediment production and delivery rates in Lights Creek and Indian Creek watersheds were lower than or similar to other studies, and percent connectivity was lower. Specific sediment production from all road related sources in this study was about 17% of regional sediment production rate from all hillslope erosion sources estimated for the entire East Branch North Fork Feather River. Specific sediment delivery rate from all road related sources to Antelope Reservoir was about 1.5% of reservoir sediment deposition rate from all hillslope erosion sources.

2.0 Objectives and Methods

GRAIP is formulated to assess the geomorphic and hydrologic impacts of roads, their physical condition, and associated stream connections. It is a relatively intensive field-based method that provides detailed information designed to improve understanding of the overall effect of roads on key watershed processes. Specifically, the project was designed to address the following in the Lights Creek and Indian Creek watersheds:

- Identify the current level of fine sediment delivery from roads to streams in the Lights Creek and Indian Creek watersheds compared to background.
- Identify the types and sources of road-related hydrologic risk in the watershed.
- Locate and quantify sediment sources and contributions to streams.
- Select and prioritize future restoration actions to improve watershed conditions and move towards an ecologically and economically sustainable road system.
- Compare GRAIP results with other local and geologically similar sediment production and delivery rates.

GRAIP was used to inventory and model the risk profile of each of the road segments and drain point features included in the study. The GRAIP system consists of a detailed, field-based road inventory protocol combined with a suite of GIS models. The inventory was used to systematically describe the hydrology and condition of a road system with Geographic Positioning System (GPS) technology and automated data forms (Black et al. 2012). The GIS applications coupled field data with GIS terrain analysis tools to analyze road-stream hydrologic connectivity, fine sediment production and delivery, downstream sediment accumulation, stream sediment input, shallow landslide risk potential with and without road drainage, gully initiation risk, and the potential for and consequences of stream crossing failures. Detailed information about the performance and condition of the road drainage infrastructure was also collected.

The selection approach for surveying non-system roads was designed to target a sample in order to develop an understanding of the general character of non-system roads with the highest potential for sediment production and delivery. Locations of non-system roads were identified where they intersected with system roads. GPS points and notes on conditions of the road visible from the intersection were collected. Only some non-system roads were selected for focused GRAIP survey, so total length of all existing non-system roads is not known. Most were visible on LiDAR coverage of the area. Referencing the intersection notes, LiDAR, and data for surveyed system roads up and down slope of the non-system roads, non-system roads were selected for survey if they were likely to traverse near or cross drainages that would qualify to be collected as a stream crossing (rather than a ditch relief culvert) according to GRAIP definitions (wider than one foot with bed, banks, evidence of transport, and evidence of annual flow, Prasad et al, 2007; Cissel et al., 2012A; Black et al., 2012; http://www.fs.fed.us/GRAIP). It follows that if a channel was large enough to be collected as a stream crossing drain point where it was crossed by a system road upslope, then the channel would also be large enough to be a stream crossing on the non-system road lower on the slope, and the non-system road would be selected for survey. If a non-system road was above a system road that had no stream crossings it was not surveyed. If a non-system road was upslope of a system road that had stream crossings, the non-system road may or may not have been selected for survey depending on its relative slope position along its length. Non-system roads were selected for survey also if they were low in the watershed where they could possibly cross large streams, or paralleled streams closely. The entire length of each non-system road was not necessarily surveyed. The survey was concluded if, as judged by topographic map and field observation, the road trended away from channels with no chance of stream crossings further along the road. With this method many non-system roads were investigated in the field, but only some were surveyed with GRAIP. See Section 4.1 Road-stream Hydrologic Connectivity for a discussion of increase in probability of stream connectivity with decrease in drain point distance to stream. It is that concept which most directed the selection of non-system roads to be surveyed.

Of the roughly 440 non-system roads identified during the course of the study on public and private lands, 109 non-system roads on mostly Forest Service land were selected to receive a focused GRAIP survey. Length of non-system roads surveyed totaled 74 km (46 mi), or about 11% of all road length surveyed. 124 other non-system roads had only a very short length surveyed as contributing lengths to other major roads, for a total length of about 5.1 km (3.2 mi). 15.6 km (9.7 mi) of non-system roads surveyed are numbered Forest Service trails. Due to the focused selection method, results for non-system roads may over-estimate the non-system road fraction of the entire study area’s road related problems, sediment production, and delivery. The focused approach for non-system road survey succeeded at discovering a very useful data set of actual problems. Of the undiscovered problems on the non-system roads not surveyed, what likely exists are ditch relief culverts and more, but probably minor, stream connectivity.

The base erosion rate is the annual road surface sediment production rate that is derived directly from field measurement methods. Transported sediment discharged from distinct road plots on native surface roads was collected and measured over a unit of time from within the Lights Creek and Indian Creek watersheds. The base erosion rates were calculated after field data were collected using the mass collected, plot length, and plot slope (Black and Luce, 2013). The units are in kilograms of mass produced per year, per vertical meter of elevation (kg/yr/m). The base erosion rates were then multiplied by the vertical meter of elevation along each of the two flow paths per road segment surveyed in the study to calculate annual sediment production mass for each road segment in kilograms per year. Vegetation in the flow path, and paved or rocked surface types are also accounted for by the model.

Field measurements for use in calculating the base erosion rates were from sediment collected from eight study plots throughout the study area. Four were located on road segments in granitic geology, and four in volcanic geology so that a unique base erosion rate could be calculated for each geology type. Plots were constrained upslope and downslope by constructed waterbars, and all surface and ditch flow was directed via a culvert into collection tanks. Plot construction and data processing methods are well documented (Black and Luce, 2013). Plots were installed in June 2014 and the first set of data was collected in late September, 2014, so base rates for Lights Creek and Indian Creek watersheds in this report are derived from measurements taken during one summer season, and will change as more data are collected. Rates may adjust upwards if production during winter and spring seasons plays a larger roll than summer thunderstorms. They may adjust downwards as road surface armoring increases over time, because the data collected at the time of this writing were from newly disturbed study plots. (Coe 2006, Megahan and Kidd 1972, NCASI 2003, Stafford 2011).

The base rates derived in Lights and Indian Creeks were 78 kg/yr/m for volcanic geology, and 30 kg/m yr for granitic geology. The base rates were applied to each road segment based on the underlying geology type. The volcanics base erosion rate was applied to 128 km (80 mi, 18%) of road length, and the granitics base erosion rate was applied to 563 km (350 mi, 82%) of road length. Geology type was determined using a GIS geology shapefile (Plumas 2014) and observations in the field. Roads mapped as underlain by granitic rock types (granodiorite, gabbro, diorite, quartz diorite, and quartz monzonite) or volcanic rock types (basalt, rhyolite, andesite, breccia volcanic, pyroclastic, volcanic, and subvolcanic) were easily assigned. Roads underlain by minor geology types were assigned based on the similarity of weathered road surface fine sediment to the fine road sediment from roads on either granitic or volcanic types. Properties of weathered road surface fine sediment assessed were texture and grain size composition. Volcanic road sediment composition generally had a visibly lower coarse grain size fraction. Relative cohesion was higher as observed by greater stickiness and plasticity, as well as lower coarse grain size fraction in hand samples. Fine road surface sediment composition from roads in granitics had visibly higher coarse grain size content, mostly as sand, as was reflected by little plasticity and stickiness in hand samples. Fine sediment on granitics did not form wheel ruts deeply or as easily as volcanic based surfaces. Using these observations, roads underlain by metamorphic, metasedimentary, metavolcanic, and chert geology types were assigned the granitic base rate, and those underlain by sedimentary, or conglomerate rock types were assigned the volcanic base rate. Quaternary alluvium, colluvium, and landslide deposits were assigned the surrounding geology type. For roads underlain by minor geology types, there were 64 km (40 mi, 11%) of road length assigned the granitics base erosion rate, and 45 km (28 mi, 35%) of road length assigned the volcanics base erosion rate. Some geologic contacts were modified based on field observations and GRAIP geologic assignments may not perfectly align with the GIS mapped contacts.

3.0 Study Area

Lights Creek and Indian Creek watersheds comprise some of the upper headwater reaches of the North Fork Feather River, a major system of economic and water resource significance in northeastern California. Lying in the northeast portion of Plumas county, and Plumas National Forest, the two watersheds drain 514 km^2 (199 mi^2, 127,000 acres). From their headwaters they flow from north to south to meet in Genessee Valley near Taylorsville, CA. From their confluence, Indian Creek flows to Spanish Creek. In turn Spanish Creek meets East Branch North Fork Feather River which flows into North Fork Feather River. 45 miles downstream from the study area, the North Fork Feather River below Lake Almanor, as well as the Middle Fork and South Fork Feather Rivers above Lake Oroville, are 303(d) listed water bodies (SWRCB 2012). Other major tributaries to Indian Creek are Pierce, Willow, Boulder, Lone Rock, and Hungry Creeks. Major tributaries to Lights Creek are East Lights, West Lights, Upper Lights, Morton, Smith, Bear Valley, Moonlight, Cooks, and Peters Creeks. Antelope Dam forms Antelope Reservoir at the confluence of Indian, Boulder, and Lone Rock Creeks, which is important for regulating flows to habitat in Indian Creek below the dam, (USDA 2013, Boles 1980), and provides water supply, storage, and recreation in the local area (Figures 1 and 4).

The Lights and Indian Creeks study is the first watershed-scale GRAIP inventory to be completed in the USDA Forest Service Pacific Southwest Region (Figure 1, Region 5). The Legacy Roads project conducted GRAIP monitoring at 6 sites in multiple National Forests in Northern California (Cissel et al. 2011A, 2011B, 2011C, 2011D, 2012B). One other GRAIP watershed study is in progress in the North Fork Mokelumne River watershed in Eldorado National Forest.

Fire

In September, 2007, the Moonlight Fire burned about 263 km^2 (65,000 acres), the majority of the northwest portion of the study area, leaving a radically changed landscape of greatly reduced wood and vegetation. 258 km (160 mi) of Forest Service roads, 40 km (25 mi) of 4-wheel drive trails, 30 km (18 mi) of non-motorized trails, and 764 km (475 mi) of streams were affected (Figure 5. Geology of the Lights Creek and Indian Creek watersheds., USDA 2013). Along with roads, high intensity fires result in the highest erosion rates among any other land use impacts in the Sierra Nevada (Coe 2006), and the Moonlight Fire is noted as an exceptionally large and intense fire (USDA 2013). Reaching its full extent in 13 days it burned 58% of its area at high severity, and 17% at moderate severity. Moonlight Fire did not burn the entire watershed area, though other overlapping fires significantly increase total burned area, and extent of high burn intensity area in these watersheds (USDA 2013). In the east, the Stream Fire in 2001, and Antelope Complex in 2007 burned lower Indian Creek. The area east of Boulder Creek and north of Antelope Lake was burned in the 2006 Boulder Fire. And a small area west of Hungry Creek burned in the 2006 Hungry Fire. Boulder Creek, and most of the highest elevations in the north, south, and southwest have not burned in recent time. Some of the higher elevations may have escaped burning due to less dense forest cover around Kettle Rock and Red Mountain, but other high elevation areas are densely forested including a fine area of old growth on the southwest ridge above Cook’s Creek.

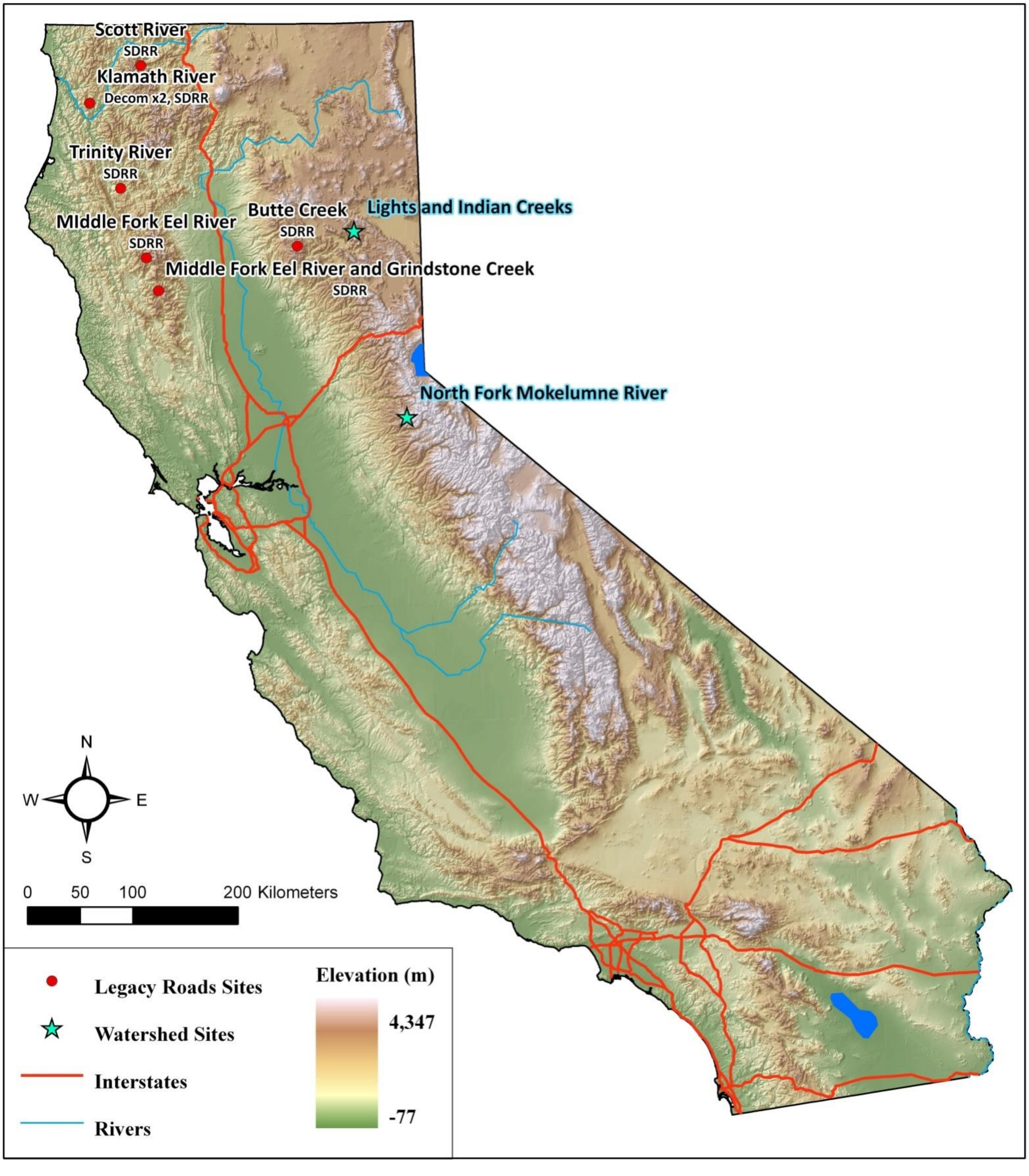

Figure 1. Location of watershed inventories and Legacy Roads Monitoring Project sites in the California section of the Pacific Southwest Region.

Fire effects in the Lights Creek and Indian Creek watersheds have been studied for a wide variety of impacts to vegetation, soils, and hydrologic conditions. Soils prior to the fire had high percent vegetation cover, down wood, and organic content, and had low compaction. The fire radically reduced riparian vegetation in over 60% of the fire area.

Impacts to stream conditions began in the early 1900s with historical mining and grazing causing increases in runoff, fine sediment in pool tails of lower gradient streams, bank erosion, headcutting in meadows, and decreases in vegetation cover and water table depth (USDA 2013, USDA 1989). Following these early impacts, stream conditions began to improve around 1940 (USDA 1989). While most tributaries were shown to be generally improving by 2005, two years prior to the Moonlight Fire, Upper Indian, Pierce, Boulder, and Hungry Creeks were cited as highest in pool tail fines, risk for cumulative impacts, or for stream bank erosion among the watersheds in the study area (USDA 2013). Each of those streams were among watersheds with the highest sediment delivery rates of all subwatersheds studied in the entire East Branch North Fork Feather River watershed (USDA 1989). Wood in streams was rated good or fair in 90% of streams prior to the fire. Nearly all wood in 1st and 2nd order streams, and partially in larger streams, was removed by the fire causing release of in-stream sediment and formation of prominent terraces upstream of the confluence area of East, West, and Upper Lights Creeks in the first two years post fire. Pool tail fines increased, and stream shade and pool depth decreased in the first two years post fire, but then returned to pre-fire levels within 2-4 years post fire in Moonlight Creek, the only channel monitored for these metrics post-fire. Though vegetation has returned, soil cover and organic content recovery has not recovered as well (USDA 2013).

Post fire surveys of upland erosion showed that a predicted increase in post fire soil erosion rate of 10,200 Mg/km^2 yr (46 tons/acre yr) was not fully realized due to a lack of large storm-events and spring runoff following the fire (USDA 2013). Notable erosion and gully formation persists in West Lights Creek on old mining features which experienced high burn severity and are still nearly bare of vegetation (**Error! Reference source not found.** and **Error! Reference source not found.**). Other comparisons of sediment production rates in the study area are discussed in Section 5.0 Comparison to Other Studies.

Road density increased dramatically during and after the fire due to fire suppression activities and post-fire salvage logging. The resulting road densities ranged between 0.78-1.83 km/km^2 (1.25 to 2.94 mi/mi^2), or an average of 1.36 km/km^2 (2.18 mi/mi^2). The average for Plumas National Forest is 1.83 km/km^2 (2.94 mi/mi^2, USDA 2013). Although soil erosion rates were not as extreme as predicted post-fire, mass failures in road prisms increased in some areas, especially within areas of high burn severity, possibly due more to loss of root structure than saturation from precipitation (USDA 2013).

Figure 2. Photo showing red oxidized soil with lack of vegetation from severe burn intensity on old mining features along 28N30 in West Lights Creek.

Figure 3. Close up of same area in Figure 2. Note gullying is active in these bare areas.

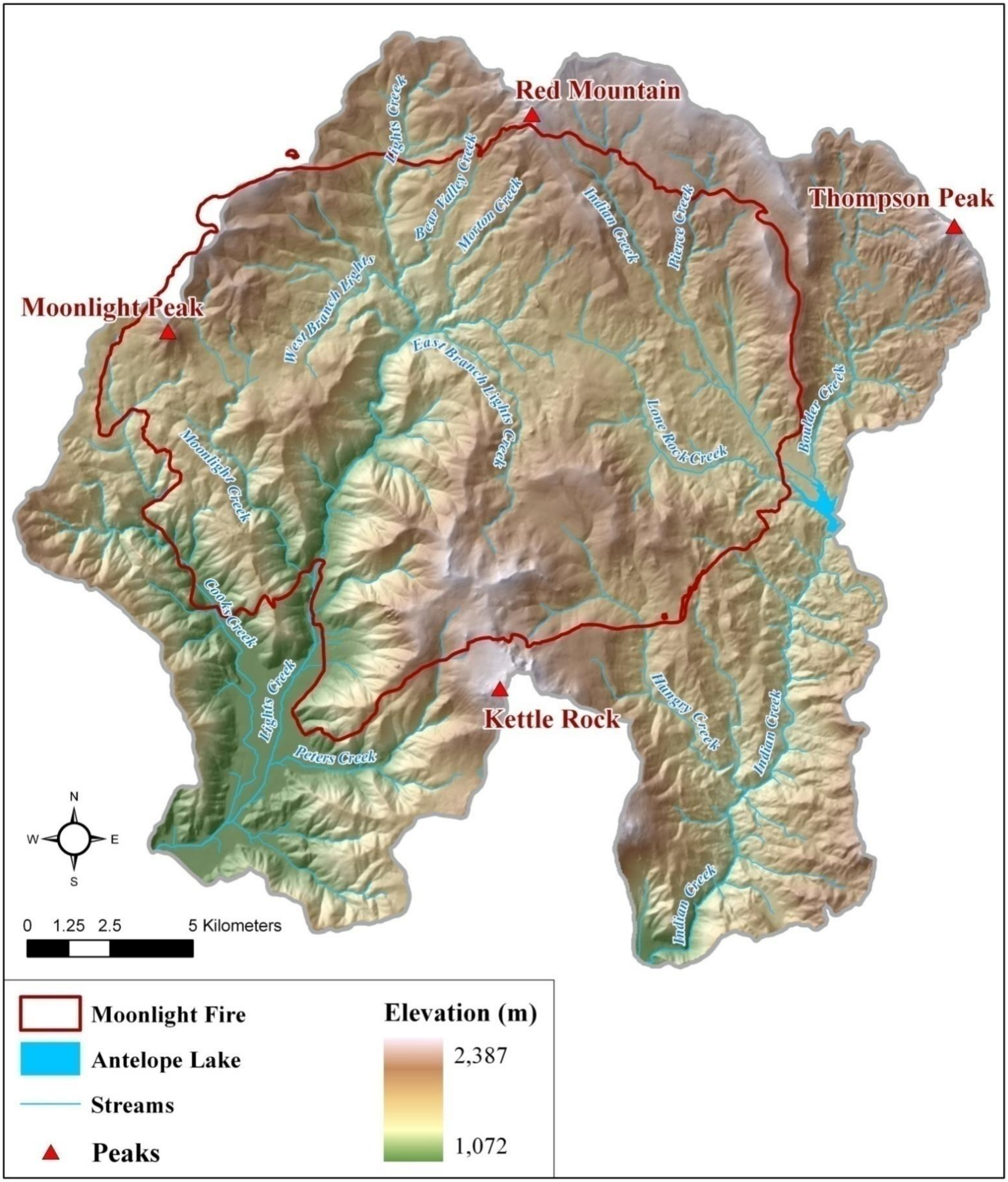

Figure 4. Study area showing Lights Creek and Indian Creek watersheds, major tributaries, prominent peaks, and Moonlight Fire area.

Geology

Geology in the study area is an interesting contact of several geologic provinces (Figure 5, CGS 2013). The oldest are deformed Jurassic (150–400 million years old) rocks of the older metamorphic, metasedimentary, and metavolcanic belts of the Sierra Nevada Province in the southwest section of the study area. They lie west of, and on the upthrown block of the major northwest-southeast trending thrust faults that separate them from the younger Cretaceous (200–65 million years old), intruding granodiorite rocks of the Sierra Nevada pluton. The granodiorite, in the south and eastern portion of the study area, is the northern most exposure of the Sierra Nevada Province, which has a vague margin to the north where it is overlain by the youngest rock units of Tertiary age (2.6–65 million years old). These Tertiary units are composed of sedimentary and volcanic rocks of the Cascade Range and Modoc Plateau Provinces. The eastern margin of the pluton is an abrupt, sharp mountain front that rises 610-1520 m (2,000–5,000) foot along the Honey Lake Fault Zone from Honey Lake Basin. West of the fault zone are a series of parallel normal faults that break up the pluton as it rises from east to west. One of these major faults lies along the Indian Creek valley. East of Honey Lake Fault Zone is the Basin and Range Province.

Climate and Elevation

Elevations in the study area range between 1,070-2,385 m (3,520-7,820 ft, Figure 4). The low point is in the southwest of the study area where Lights Creek confluences with Indian Creek in Genesee Valley, and the highest point is in the south at Kettle Rock. Other prominent locations around the study area perimeter are Moonlight Peak to the west at 2,070 m (6,800 ft), Red Mountain in the north at 2,310 m (7,570 ft), and Thompson Peak in the east at 2,350 m (7,720 ft).

Climatic data in the area are measured at three California Department of Water Resources (CDWR 2015) gages. The lowest is at 1,090 m (3,570 ft) in Greenville west of the study area. The highest is on Kettle Rock at 2,225 m (7,300 ft) on the southern boundary of the study area. The Antelope Lake gage lies on the east boundary of the study area at 1,511 m (4,960ft).

Mean daily air temperature at Antelope Lake gage since 2007 is 8.3 °C (47 °F). Maximum temperature during this period was 37 °C (98 °F) in July 2013, and minimum was -27 °C (-17 °F) in January 2013. Mean daily temperature in summer months (May-Oct) is 14 °C(58 °F, ranging 8.3-20 °C (47-68 °F)), and in winter months (Nov-April) is 1.7 °C (35 °F, ranging -1.1-6.1 °C (30-43 °F)). Mean daytime (8 am-7pm) temperature in summer is 17 °C (63 °F), and in winter, 3.3 °C (38°F), with ranges between 11-23 °C (51-73 °F) in summer and 6.1-17 °C (43-62 °F) in winter. Mean nighttime temperature in summer is 12 °C (53 °F), and in winter, 0.56 °C (33°F), with ranges between 6.1-17 °C (43-62 °F) in summer, and -2.2-3.9 °C (28-39 °F) in winter. Kettle peak experiences much colder temperatures with a mean daily temperature of 5.6 °C (42 °F), a maximum of 33 °C (91 °F), and minimum of -18 °C (0 °F) from 2007 to April 2015. (CDWR 2015).

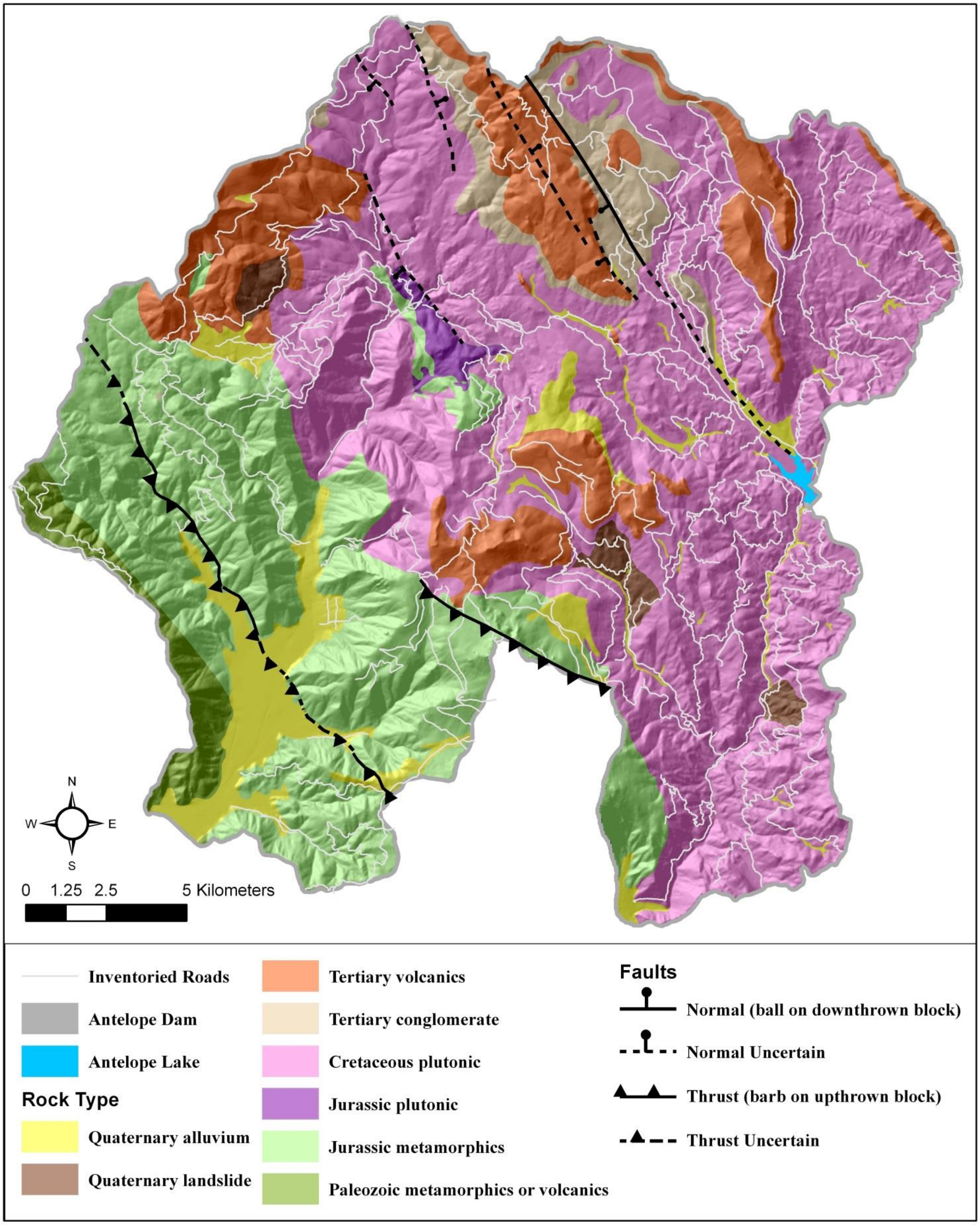

Figure 5. Geology of the Lights Creek and Indian Creek watersheds.

The study area is generally drier than the greater northern California mountainous region (CDWR 2015). Because the study area lies east of the Sierra Nevada crest, the area is in a rain shadow and precipitation is lower than that in the western Sierra Nevada. Within the study area precipitation is generally higher in the west, and lower in the east (USDA 2013, USDA 1989). Precipitation occurs mostly in winter as rain below, or snow above 1,980 m (6,500 ft), and in summer as infrequent thunderstorms. Average annual precipitation for the study area is 100 cm/yr (39 in./yr) at Greenville, 60 cm/yr (24 in./yr) at Antelope Lake, and 84 cm/yr (33 in./yr) at Kettle Rock. Average monthly precipitation varies widely from 0.5 cm (0.2 in.) in July to 22 cm (8.7 in.) in January at Antelope Lake. Snowfall typically occurs at elevations above 1,700-1,980 m (5,600-6,500 ft, USDA, 2007), but can fall as either rain or snow in that elevation range. Kettle Rock reports a snow water content high of 138 cm (54 in.) in early 1998, and its lowest at 16 cm (6.4 in.) in early 2014 (CDWR 2015), which is just prior to the onset of this study.

The survey was conducted in a climatic context that reflects regional warming and drying trends (USDA 2013). Data collection coincided with the dry season following a year of increasing drought from “Moderate” one year prior, to “Extreme” upon commencing field work (US Drought Monitor 2015). The larger regional trends show there has been a significant decrease in total annual precipitation at nearby Susanville of nine inches since 1893, an increase of mean annual temperature of 0.94 °C (1.7 °F), and a decline in total annual snowfall from 168 cm (66 in.) in 1894 to 10 cm (4 in.) in 2009. Spring snowpack has decreased 70-100%. Spring thaw occurs 10-15 days earlier than in the mid 1900s. In Sierra Nevada streams, peak stream flows occur 5-15 days earlier (USDA 2013). Water years with high total annual precipitation greater than 130% of average at Antelope gage since 1990 were all more than 10 years prior to the start of the study (1995-97, 2003, 2006; 140-79 cm, 55-31 inches). The late 1990s years were wet in winter and summer, whereas the years in the early 2000s were wet only in winter. Since 1990, five of the six driest years at Antelope Lake were within the 7 years prior to the study season (2007-08, 2012-14; 28-41 cm, 11-16 in), including the 2014 study year. Only 2011 had normal total annual precipitation.

Large storm events, including winter rains and summer thunderstorms, can produce locally heavy precipitation intensities, and runoff, which may represent an increasing fraction of available erosional force as annual snowpack declines and precipitation falls more as rain (USDA 1989). Erosional force for particle detachment and transport increases in part as a function of storm intensity and rainfall total (Black and Luce 1999, Wischmeier and Smith 1978), so it is valuable to examine patterns of large storm events in the study area. Even though large storms can produce high daily precipitation, they may not add up to high seasonal or annual total precipitation. Storm intensity can be examined by looking at daily total precipitation. Based on watershed monitoring reports for East Branch North Fork Feather River for water years 7 years prior to this study (2008-2013), high daily total precipitation days occur mostly October through May with few days in summer. The highest winter daily total was greater than 15 cm (6 in.) in November 2012 (Plumas Corporation 2009-2014), only two winters prior to the start of this study, but the total winter precipitation was normal for that year (CDWR 2015). Typically there are 2-4 winter days in the season with high daily precipitation totals in the 4.5-8.9 cm (1.75-3.5 in.) range, but the most frequent winter daily totals are 0.64-3.8 cm (0.25-1.5 in.). Precipitation is infrequent in summer months with only a few days with any precipitation after May, usually less than 1.3 cm (0.5 in.) per day. Notable is summer 2011, an above average summer with 8 days of precipitation, one of which had a total of about 1.5 cm (1.75 in., Plumas Corporation, 2009-2014). For comparison, during this study, the highest daily totals at the Antelope Lake gage were 1.2 cm (0.48 in.) on July 19, 2.1 cm (0.84 in.) on August 5, and 1.3 cm (0.52 in.) on August 11. These two months were typical for event frequency, but had above average total precipitation (240%, and 700% of normal, respectively). However, precipitation for the entire 2014 summer was only 71% of average for summers 1990-2014 (CDWR 2015). Given the dry climate in which the survey was conducted, the landscape at time of study likely reflects a period of seasonally average or low erosion rates, but with episodic high pulses of erosion during summer storms. During the summer storms, rapid, widespread expansion of rills, small gullies in road surfaces and cutslopes, and expansion of flow paths below roads were observed. Some of this water was intercepted or originated by roads.

Land Ownership

The Lights Creek and Indian Creek watersheds are comprised of primarily federally owned and managed land (Figure 7). The Forest Service manages 406 km^2 (157 mi^2, 100,325 acres, 79%). Private land comprises 107 km^2 (41 mi^2, 26,440 acres, 21%) of the watershed area.

There were 565 km (351 mi) of system road length on Forest Service lands within the watershed boundary mapped prior to survey. 96% (544 km, 338 mi), were surveyed. Including non-system roads and road segments longer than mapped or outside the watershed boundary, a total of 641 km (398 mi) were surveyed on Forest Service lands (Figure 7).

There were 92 km (57 mi) of system road length on private lands within the watershed boundary mapped prior to survey. 47% (44 km, 27 mi), were surveyed. Including non-system roads and road segments longer than mapped or outside the watershed boundary, a total of 50 km (31 mi) were surveyed on private lands (Figure 7). Many roads that exist on private land do not appear in Figure 7, nor on the Plumas GIS roads map. Most existing roads in private lands were not surveyed and may represent some portion of road sediment production and delivery not accounted for in some of the subwatersheds within the study area, especially Upper Lights, East Lights, West Lights, Cook’s, Lower Lights, and Lone Rock Creeks.

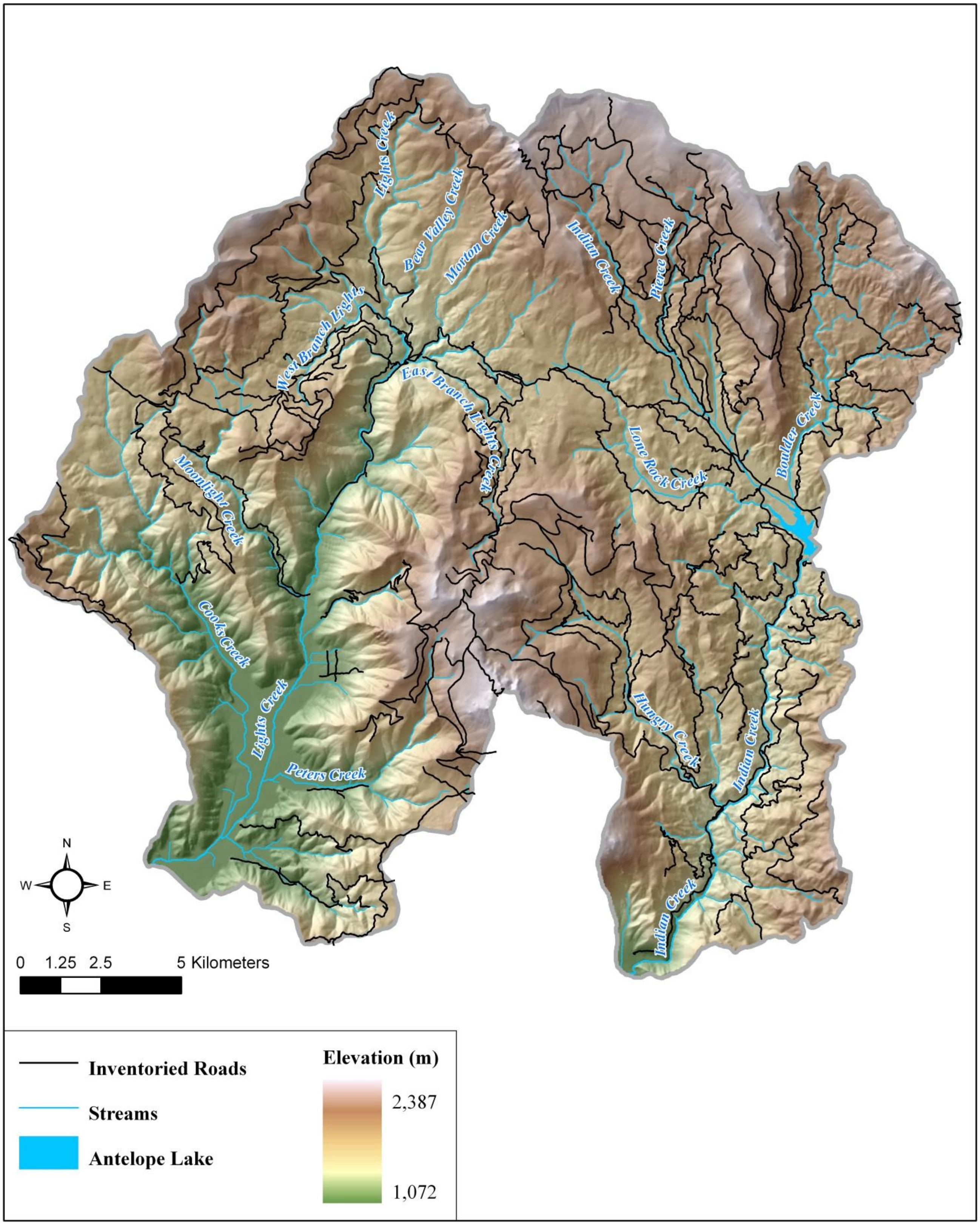

Figure 6. Elevation and location of inventoried roads within the Lights Creek and Indian Creek watersheds.

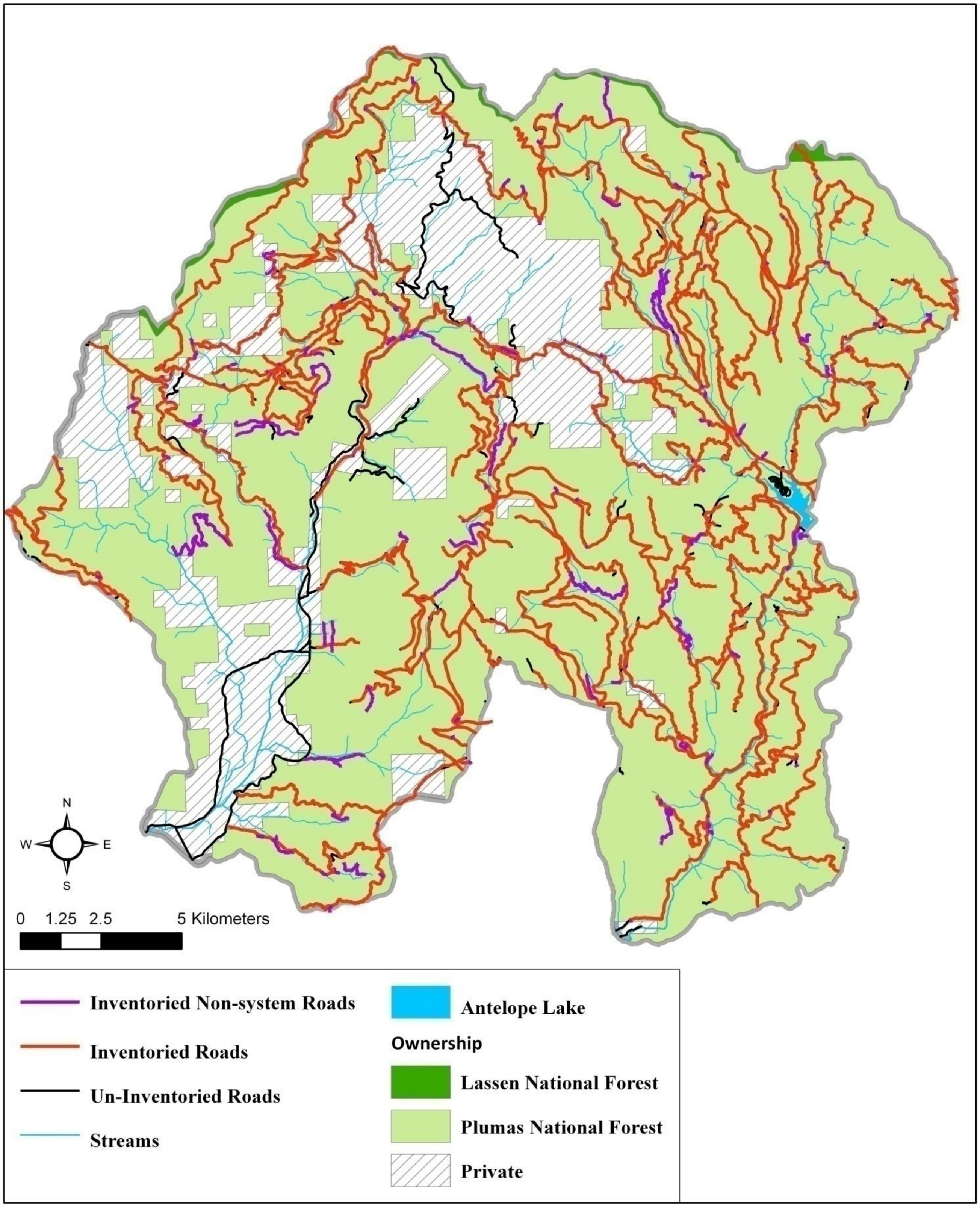

Figure 7. Land ownership and all roads within the Lights Creek and Indian Creek watersheds.

4.0 Results

A total of 9,536 drain points, 11,540 road segments, and 1,860 other associated features (including 168 gullies, 76 landslides, and 1,068 photo points) were inventoried in three and a half months of field work by four field crews. Each crew collected an average of 2–3 km (1–2 mi) of road per day. Data analyses provide specific information on the condition and function of 691 km (429 mi) of roads (Figure 6). GRAIP inventory and data modeling tools were used to characterize the following types of impacts and risks:

- Road-stream hydrologic connectivity
- Fine sediment production and delivery
- Downstream sediment accumulation
- Shallow landslide risk
- Gully initiation risk
- Stream crossing failure risk
- Drain point condition

4.1 Road-Stream Hydrologic Connectivity

Roads can intercept shallow groundwater and convert it to surface runoff, resulting in local hydrologic impacts when that water is discharged directly to channels (Wemple et al. 1996). Additional runoff is also produced from the compacted road surface. Basin-scale studies in the Oregon Cascades suggest that a high degree of integration between the road drainage system and the channel network can increase peak flows (Jones and Grant 1996).

The hydrologically connected portion of the road system is calculated in GRAIP using field observations of connection at each drain point and a road segment flow routing system. The flow path below each drain point is followed until evidence of overland flow ceases or the flow path reaches a channel. In the Lights Creek and Indian Creek watersheds, a total of 92 km (57 mi) out of 691 km (429 mi) of inventoried road (13%) were hydrologically connected to the stream network. Non-system roads had 13% percent connectivity by road length; 9.8 km (6.1 mi) out of 74 km (46 mi). While not all connected, 32 km (20 mi) of road length was within 50 ft (15 m) of the stream channel (Figure 9; Appendix B, Maps 1a and 1b).

Road-stream hydrologic connectivity represents the maximum extent that roads are integrated with streams, and is controlled by the pattern and distribution of runoff, slope length, slope distance from discharge point to stream, vegetation, and delivery paths, among other factors (Bracken and Crocke 2007). Maximum connectivity in the Lights Creek and Indian Creek watersheds observed during the duration of study was during summer convective storm events. In July and August 2014 (240% and 700% of normal rainfall for each month respectively), rapid and widespread expansion of rills and small gullies in road surfaces and cutslopes, and expansion of flow paths below roads were observed (Figure 8).
Some of this water was intercepted by or originated on roads.

Figure 8. Cutslope rills and road surface gullies that increased and expanded during summer thunderstorms.

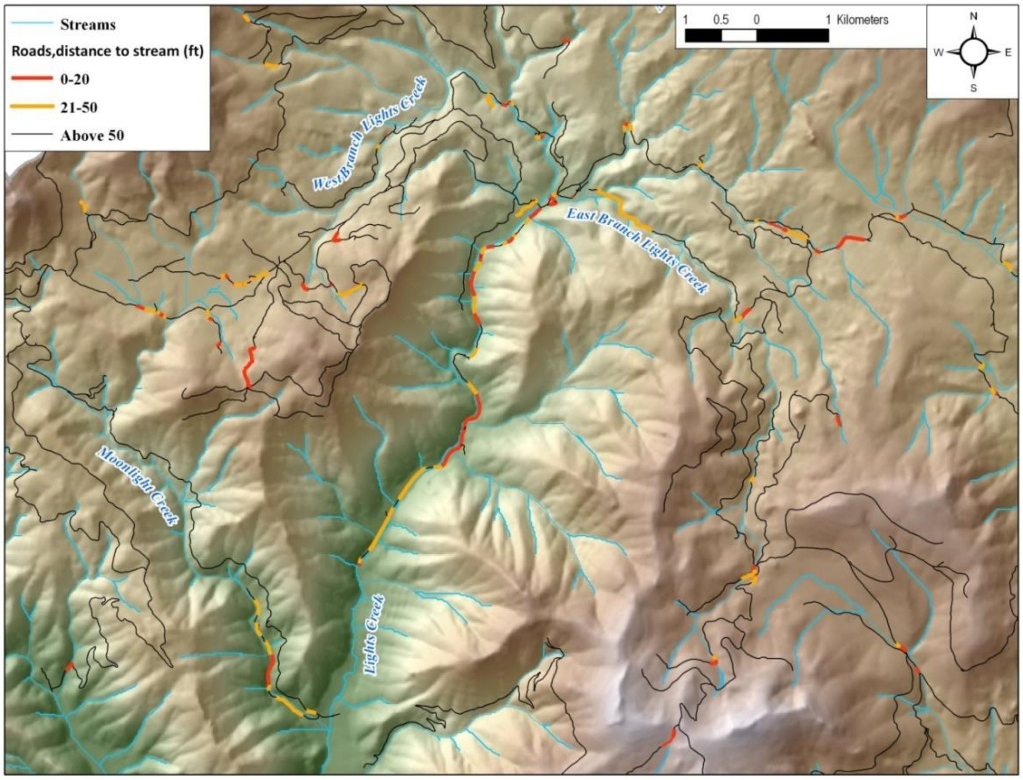

Figure 9. Road segments within 50 feet of stream channels in the east central portion of the study area.

Broad based dips, ditch relief culverts, and non-engineered drain points were the most common types of drainage features (2,598, 2,289, and 2,156 features, respectively), and, along with waterbars (1,074 features) drained 85% (304 km, 189 mi) of the road network (Table 1). The bulk of the hydrologic connectivity occurred at stream crossings (3.8 km, 2.4 mi, 41%), and along with broad based dips, ditch relief culverts, and non-engineered drain points, 94% (8.6 km, 5.3 mi). There were 469 stream crossings, and they drained 3.8 km (2.4 mi) of the road network, all of which was connected. The ditch relief culverts drained 17 km (11 mi) of the road network, 1.7 km (1 mi) of which was connected to the stream network.

Table 1. *Summary of effective road lengths by drain point type. Sumps cannot be stream connected, while stream crossings are connected by definition.*

DrainType	All Drain Points			Connected Drain Points			Not Connected Drain Points			% Length Connected
	Count	Average Effective Length (m)	Σ Effective Length (m)	Count	Average Effective Length (m)	Σ Effective Length (m)	Count	Average Effective Length (m)	Σ Effective Length (m)	
Broad Based Dip	2,598	85	219,600	166	100	17,080	2,432	80	202,530	7.8%
Diffuse Drain	554	110	62,040	19	100	1,870	535	110	60,170	3.0%
Ditch Relief Culvert	2,289	75	174,370	233	70	16,650	2,056	80	157,710	9.6%
Lead Off Ditch	349	60	21,530	16	80	1,260	333	60	20,270	5.9%
Non-Engineered	2,156	60	129,490	188	80	15,040	1,968	60	114,460	11.6%
Stream Crossing	469[1]	80	37,480	377[2]	100	37,480	92	0	0	80%
Sump	20	65	1,330	0	0	0	20	65	1,330	0.0%
Waterbar	1,074	40	44,490	36	45	1,640	1,038	40	42,840	3.7%
Excavated Stream Crossing	27	20	560	27	20	560	0	0	0	100%
All Drains	**9,536**	**70**	**690,890**	**1,154**	**80**	**91,580**	**8,382**	**70**	**599,310**	**13%**

[1] All stream crossings.

[2] Non-orphan stream crossings, where contributing road length is not zero.

The idea that road distance from streams has a large effect on the likelihood that a road is stream connected is not new (Croke et al. 2005, Ketcheson and Megahan 1996, Packer 1967). There is a relationship between drain point or road distance from streams and sediment delivery likelihood in Lights Creek and Indian Creek watersheds. The distance from drain point to streams modeled by TauDEM was graphed against observations of stream connectivity to generate a probability versus distance function (Figure 10). For drain points that discharge at a distance within a 30 m grid cell that contains a modeled stream, there is a 45% chance that the drain point will be stream connected. As drain point distance gets further from the modeled stream, probability of connection decreases sharply from about 25% at 50 m (160 ft) to about 5% at 150 m (490 ft).

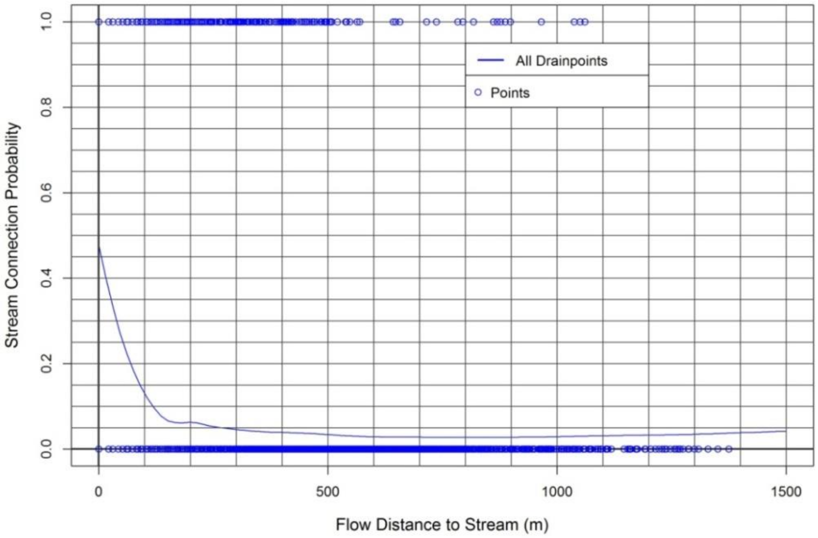

Figure 11. Probability of stream connection decreased with increasing drain point distance to a TauDEM modeled stream.

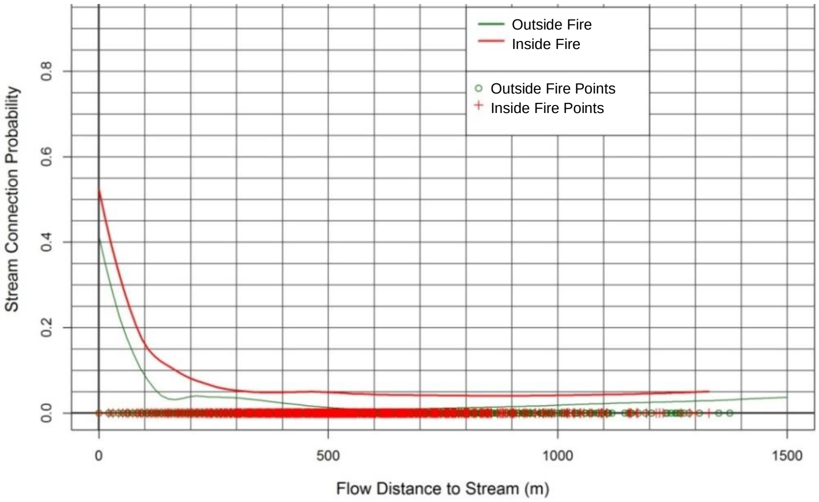

Figure 10. There is a higher probability of stream connection at the same drain point distance to stream within the Moonlight fire perimeter compared to drain points for the entire study area. Stream connection probability with distance to TauDEM modeled stream for drain points outside the perimeter is similar to that of all points.

This relationship is stronger for drain points within the Moonlight fire perimeter (Figure 11). There were 4,316 drain points outside the fire perimeter, and 5,182 within. There is a higher probability of stream connection with drain point distance to modeled stream within the Moonlight fire perimeter. Stream connection probability with distance to modeled stream for drain points outside the perimeter is similar to that of all points. Outside of the fire, for drain points that discharge within a 30 m grid cells that contains a modeled stream, there is a 40% chance that the drain point will be stream connected (Figure 11). For drain points within the fire perimeter that probability is 50%. Outside the fire perimeter, and similar to all drain points, over a distance of 200 m (655 ft), probability of connection decreases sharply from 10% at 100 m (330 ft) to about 5% at 300 m (980 ft). At those same distances, probability that a drain point within the fire perimeter would be stream connected is much greater with a 15% chance at 100 m (330 ft), and 10% at 300 m (980 ft).

4.2 Fine Sediment Production and Delivery

Fine sediment production at a drain point (E) is estimated with a base erosion rate and the properties of two flow paths along the road (Luce and Black 1999, Cissel et al. 2012A, Prasad 2007), as shown below.

$$E = B \times L \times S \times V \times R$$

B is the base erosion rate[1] (kg/m)
L is the road length (m) contributing to the drain point
S is the slope of the road contributing to the drain point (m/m)
V is the vegetation cover factor for the flow path
R is the road surfacing factor

Delivery of eroded sediment to the channel network is determined by observations of each place that water leaves the road. Each of these drain points is classified as either delivering or not delivering. No estimate of fractional delivery is made, because there is insignificant hillslope sediment storage in locations where there is a clear connection to the channel under most circumstances. A map of the road surface sediment delivery and the accumulated sediment delivered through each drain point is shown for the whole watershed (Appendix B, Maps 1a and 1b), as well as for a road along the mainstem Lights Creek and upper East Branch North Fork Lights Creek (Figure 14).

Delivery of fine sediment occurs through a mix of road drainage features, including broad based dips, diffuse road segments, ditch relief culverts, lead-off ditches, non-engineered drains, waterbars, and others (Appendix A, Figure 12). In Table 2, sediment delivery is broken out by drain type to assess their effectiveness in preventing sediment from entering the channel. There were 9,536 drain points observed, of which 1,154 were observed to deliver sediment to stream channels. Model prediction estimated 347 Mg/yr of road surface sediment was routed through the observed stream connected drain points, or 12% of the 2,920 Mg/yr generated on the road surfaces and ditches (Appendix B, Maps 2a-3b). Diffuse drains, ditch lead-offs, and waterbars were equally effective. Collectively they received 19% of sediment produced, but routed only 6% of sediment to streams. Stream crossings, broad based dips (likely many were near stream crossings), and non-engineered drain points (likely many were near stream crossings) routed the most sediment to streams (91% collectively, 111 Mg/yr, 90 Mg/yr, and 78 Mg/yr, respectively; Figure 12). Though stream crossings received a small percentage of all sediment produced (4%), they routed the majority of delivered sediment (32%). This is a strong indicator that drainage features on road approaches to streams would help to reduce sediment routed directly to stream crossings. Sediment delivery in the study area is generated by a very

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[1] For this analysis, an annual base erosion rate of areas underlain by volcanics was 78 kg/meter of road elevation, and for granitics was 30 kg/meter was applied (Luce and Black, 1999). Areas underlain by geology types other than volcanic or granitic were assigned to one or the other based on likeness of fine road sediment.

small percentage of all drain points. Less than 5% of drain points deliver 90% of delivered sediment (Figure 13).

The fraction of sediment produced and delivered from the road system can also be evaluated in the context of road length. Of the 691 km (429 mi) of total inventoried road length, 92 km (57 mi, 13%) deliver sediment to streams (Table 2).

***Table 2**. Summary of sediment production and delivery at drain points.*

Drain Type	**Count**	**∑ Sediment Production (kg/yr)**	**DP's % of Total Sediment Production**	**∑ Sediment Delivery (kg/yr)**	**% Sediment Delivery within each DP Type**	**DP's % of Total Sediment Delivery**	**Length Connected (m)**	**% Length Connected within each DP Type**	**DP's % of Total Length Connected**
Broad Based Dip	2,598	989,120	34%	89,600	9%	26%	17,080	8%	19%
Diffuse Drain	554	224,830	8%	7,290	3%	2%	1,870	3%	2%
Ditch Relief Culvert	2,289	590,770	20%	44,500	8%	13%	16,650	10%	18%
Lead Off Ditch	349	126,450	4%	6,160	5%	2%	1,260	6%	1%
Non-Engineered	2,156	672,840	23%	78,390	12%	23%	15,040	12%	16%
Stream Crossing	469	111,630	4%	111,630	100%	32%	37,480	100%	41%
Sump	20	8,200	0.3%	0	0%	0%	0	0%	0%
Waterbar	1,074	192,960	7%	6,480	3%	2%	1,640	4%	2%
Excavated Stream Crossing	27	3,120	0.1%	3,120	100%	1%	560	100%	1%
All Drains	**9,536**	**2,919,920**	**100%**	**347,170**	**12%**	**100%**	**91,580**	**13%**	**100%**

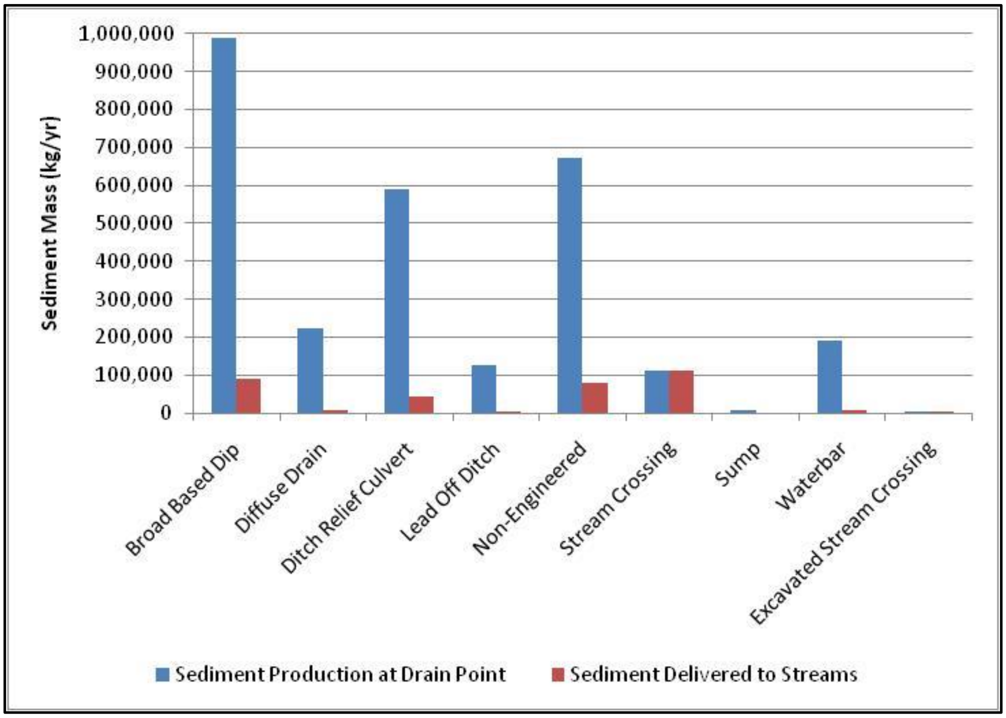

Figure 12. Sediment production and delivery by drain point.

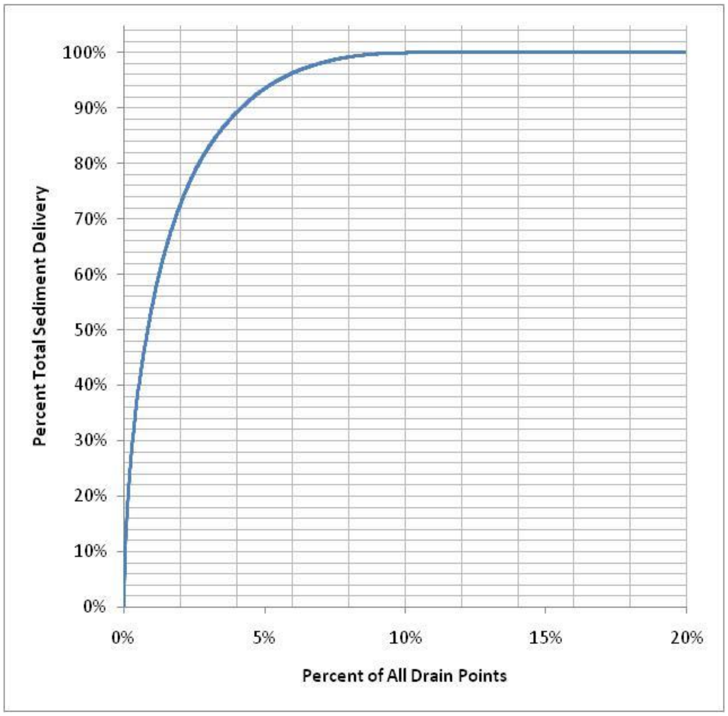

Figure 14. Percent total sediment delivered to streams by percent of drain points. 4.5% of all drain points deliver 90% of the delivered sediment.

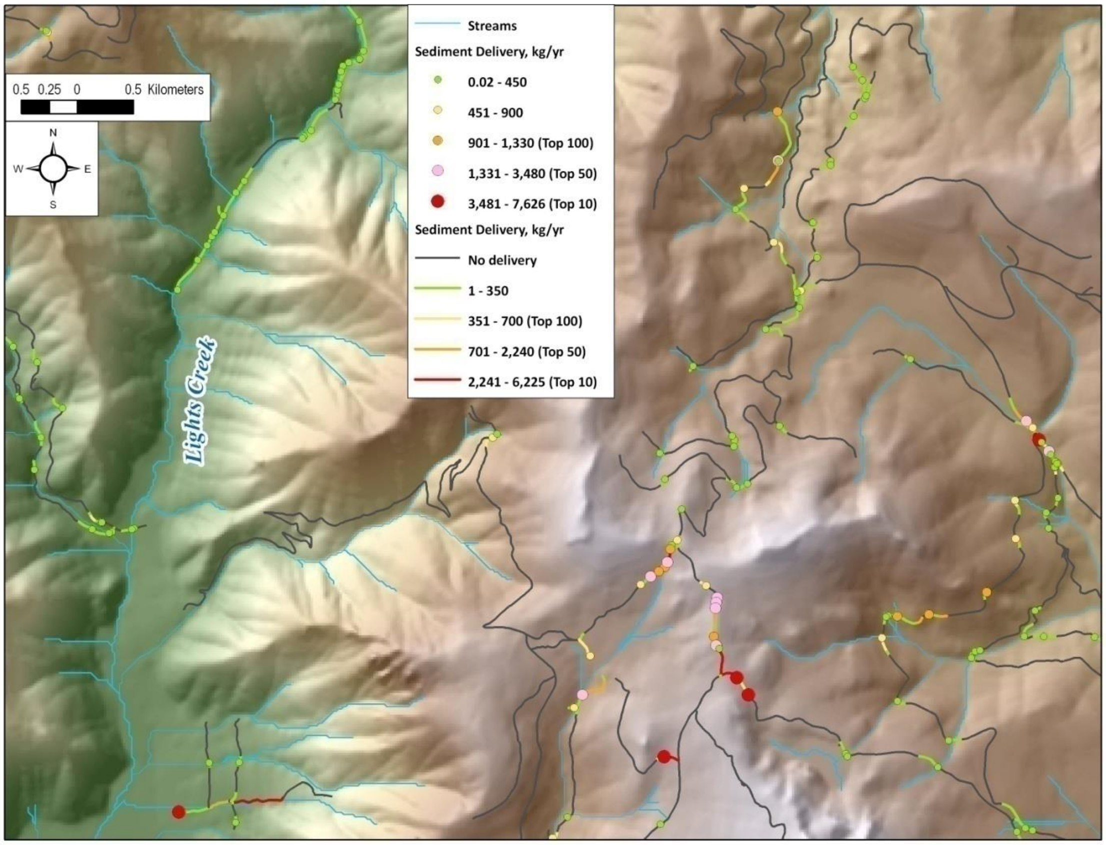

Figure 13. Fine sediment delivery to channels by road segment and drain point along the mainstem Lights Creek and upper East Branch North Fork Lights Creek. The road lines are colored to indicate the mass of fine sediment delivered to channels. Drain points that do not deliver sediment are not included.

Road tread surface condition played a role in sediment delivery. Where erosional force was adequate to erode road surfaces, rills, ruts, and rocky surfaces were formed. The same force which caused increased erosion on the surfaces may be a factor in increasing delivery from surfaces that were more eroded. Surface condition information was collected in the field for each road segment. A road segment was classified as being in good condition if there was little erosion present. Where road surfaces were more eroded, the road segments were classified from least to most eroded as being rilled and/or eroded, rutted, or rocky (Cissel et al. 2012A). There were 551 km (342 mi, 81%) classified as being in good condition, while the remaining 19% of road length had some surface problem. In Table 3, sediment produced and delivered from each of these surface condition types was normalized by the total road length for each erosion category. Figure 15 and Table 3 show that sediment production was lowest on road surfaces in good condition (16% of normalized total), followed equally by surfaces that had been eroded to rutted, or rilled/eroded (26%). Surfaces that had eroded to rocky condition had the highest sediment production with 33% of the normalized total. Sediment delivery was highest on surfaces eroded to rocky condition (40% of normalized total), followed nearly equally by surfaces that had eroded to rilled/eroded, and rutted (26% and 23%, respectively). Good surfaces had the lowest delivery rate (11%).

Road surface type also had a strong roll in sediment production and delivery. 449 km (279 mi, 65%) had a native surface and produced 84% (2,460 Mg), and delivered 80% (280 Mg) of fine sediment. 217 km (135 mi, 31%) had a rocked surface, produced 31% (450 Mg), and delivered 20% (68 Mg) of fine sediment. Paved roads (25 km, 16 mi) produced and delivered a very small fraction of fine sediment.

Table 3. *Sediment production and delivery by surface type (top), and normalized by percent road length for each surface type (bottom).*

Surface Condition	**∑ Length (m)**	**% Total Length**	**∑ Sediment Production (kg/yr)**	**∑ Sediment Delivery (kg/yr)**	**% Sediment Delivery**
Good	550,600	81%	2,071,400	222,620	65%
Rilled/eroded	72,750	11%	449,840	67,220	20%
Rutted	31,720	5%	195,890	24,050	7%
Rocky	20,700	3%	162,140	28,700	8%
Total	**675,770**	**100%**	**2,879,270**	**342,590**	100%

Surface Condition	**∑ Sediment Production, Normalized (kg/m yr)**	**∑ Sediment Delivery, Normalized (kg/m yr)**	**% Total Sediment Production, Normalized**	**% Total Sediment Delivery, Normalized**
Good	3.8	0.4	16%	11%
Rilled/eroded	6.2	0.9	26%	26%
Rutted	6.2	0.8	26%	23%
Rocky	7.8	1.4	33%	40%
Total	**24**	**3.5**	**100%**	**100%**

Figure 15. Normalized sediment production and delivery by road surface condition. The values are normalized by road length for each surface condition category.

Non-system roads produced similar results to system roads, but since the selection method was a focused approach targeting roads that cross or are near streams, results for non-system roads may overestimate the non-system road fraction of the entire study area's sediment production and delivery. The following results present the subset of data from non-system roads. The values presented are included in the total values for the entire study area. 9.8 km (6.1 mi, 13%) of non-system road surfaces contribute about 48 Mg/yr of fine sediment to the stream network; or about 14% of the whole study. Non-system road surfaces produced 321 Mg/yr of fine sediment, and have a slightly higher percent delivery rate than that of the entire study; 15% vs. 12%. Many of the non-system roads surveyed were small, closed or unmaintained roads and had native surfaces. The majority were treated with waterbars or other effective drainage structures, had relatively high vegetation growth, and had excavated stream crossings; therefore pose little to no potential risk to streams. Eight were decommissioned or had ripped surface treatments. However, a small number have significant active problems. Rilled or eroded surfaces were rare but several were noted. Nine were streamside. See Conclusions for more specific locations.

4.3 Downstream Sediment Accumulation

Road surface derived fine sediment mass predicted by the model was routed to drain points that were observed in the field to be stream connected. The delivering sediment was then routed by the GRAIP model to a TauDEM modeled stream network. The road-related sediment amount was accounted for in the stream segment it was routed to, and GRAIP then calculated two measures of road sediment for each stream segment. The first measure, sediment accumulation (Figure 16), was the mass of road-related sediment that passes through each stream segment per year, expressed in kilograms per year. Each addition of sediment to a stream segment via its contributing drain points was added to the sum of all sediment routed from upstream. In other words, starting at the top of the stream network, the accumulated sediment value in the uppermost stream segment is that which is routed from all delivering drain points to that segment. For the next stream segment downstream, its accumulated sediment value is the sum of new sediment inputs from drain points routed to the 2nd segment, plus the sediment amount from upstream, and so on downstream throughout the stream network. In the absence of detailed information on sediment routing, the assumption is that road surface-related fine sediment has a residence time of less than one year. This is likely independent of pulsed, mass-wasting driven coarse sediment transport (Benda and Dunne 1997). The second measure, specific sediment accumulation (Figure 17), is the mass of accumulated road-related sediment in a given stream segment normalized by the upstream contributing area, expressed in megagrams per square kilometer per year. In this metric, area is used as a proxy for discharge, allowing us to compare the sediment impacts to channel segments with differing contributing areas. Maps for sediment accumulation and specific sediment accumulation for the entire watershed area are in Appendix B, Maps 4a–5b.

Accumulated and specific sediment values on Indian Creek below Antelope Lake dam include sediment trapped by the reservoir as if the sediment were routing through the system without the presence of the dam. The value of accumulated sediment in Indian Creek at the dam was 82 Mg/yr.

Accumulated and specific sediment values reported here for areas that did not have a complete survey of all roads in the watershed are likely lower than actual values because they do not include sediment values from all roads in the area (Figure 7). In the Moonlight Project this was the case within subwatersheds containing very large areas of private timber lands including East Branch Lights Creek and upper Lone Rock Creek. Lower than actual values may be reported in middle and lower Lights Creek where roads within private mining lands and the main Plumas County road were not surveyed.

Road surface-related sediment at the mouths of Lights and Indian Creeks totaled 192 Mg/yr, and 155 Mg/yr, respectively (Figure 16, Table 4). Specific sediment in some small catchments was as high as 27 Mg/km^2/yr. Specific sediment at the mouths of Lights and Indian Creeks was 0.71 Mg /km^2/yr, and 0.64 Mg/km^2/yr, respectively (Figure 17, Table 4). Of the other streams, Hungry Creek had the highest sediment accumulation, with 61 Mg/yr, and high specific sediment at 1.2 Mg/km^2/yr. The unnamed subwatershed south of Peters Creek had the highest specific sediment with 2.5 Mg/km^2/yr, and high sediment accumulation at 34 Mg/yr. Boulder and Lone Rock Creeks had the lowest accumulated sediment at their mouths at 8 Mg/yr. Specific sediment for each was 0.17 Mg/km^2/yr and 0.25 Mg/km^2/yr, respectively.

Including the sediment from road-related landslides (not including cutslope failures), gullies, and fill erosion at drain points (see Sections 4.4, 4.5, and 4.7), in addition to that from the road surface, the total annual road sediment accumulation at each of the mouths of Lights and Indian Creeks was 3,538 Mg/yr, and 607 Mg/yr, respectively. The specific sediment for each was 4.8 Mg/km^2/yr and 2.5 Mg/km^2/yr, respectively. Of the other streams, West Branch Lights Creek had the highest sediment load, with 2,160 Mg/yr accumulated sediment, and 29 Mg/km^2/yr specific sediment (Table 4).

The large increase in specific sediment at the mouths of Pierce and Upper Lights Creeks was due to gully and landslide sediment. Increases in Hungry and Indian Creek below Antelope Dam, and the tributary south of Peters Creek were due almost entirely to gully sediment. East Branch Lights Creek increase is due to gully and fill erosion sediment. The increases in West Branch Lights Creek were mostly due to landside sediment. In Lights Creek, increases were due mostly to landslides, but about 30% were due to gully and fill erosion sediment combined. (See Appendix B, Maps 8a, 8b, 9a, and 9b).

***Table 4.** Study area streams and sediment accumulation and specific sediment accumulation at the stream mouth, calculated using only delivering road surface-related sediment and all delivering road sediment sources (landslides, gullies, and fill erosion at drain points).*

Sub-watershed	**Stream Name**	**Road Surface Sediment at Mouth (Mg/yr)**	**Road Surface Specific Sediment at Mouth (Mg/km^2 yr)**	**All Sediment Sources at Mouth (Mg/yr)**	**All Sediment Sources Specific Sediment at Mouth (Mg/km^2 yr)**
Indian	Boulder Creek	8	0.17	22	0.5
	Pierce Creek	37	2.2	330	20
	Lone Rock Creek	8	0.25	9	0.3
	Indian at Pierce Creek	22	1.1	24	1.2
	Indian Creek at Antelope Dam	***82***	***0.62***	***393***	***3.0***
	Hungry Creek	61	1.2	84	1.7
	Indian Creek at Gennessee Valley	***155***	***0.64***	***607***	***2.5***
Lights	West Branch Lights Creek	24	1.2	2,160	29
	East Branch Lights Creek	21	0.56	145	3.8
	Upper Lights Creek	22	0.72	129	4.2
	Cooks Creek	21	0.37	51	0.9
	Moonlight Creek	16	0.68	18	0.7
	Peters Creek	28	1.1	29	1.1
	Unnamed south of Peters	34	2.5	71	5.1
	Lights Creek	***192***	***0.71***	***3,538***	***4.8***
	Moonlight Project Area	**347**	**0.68**	**4,145**	**8.1**

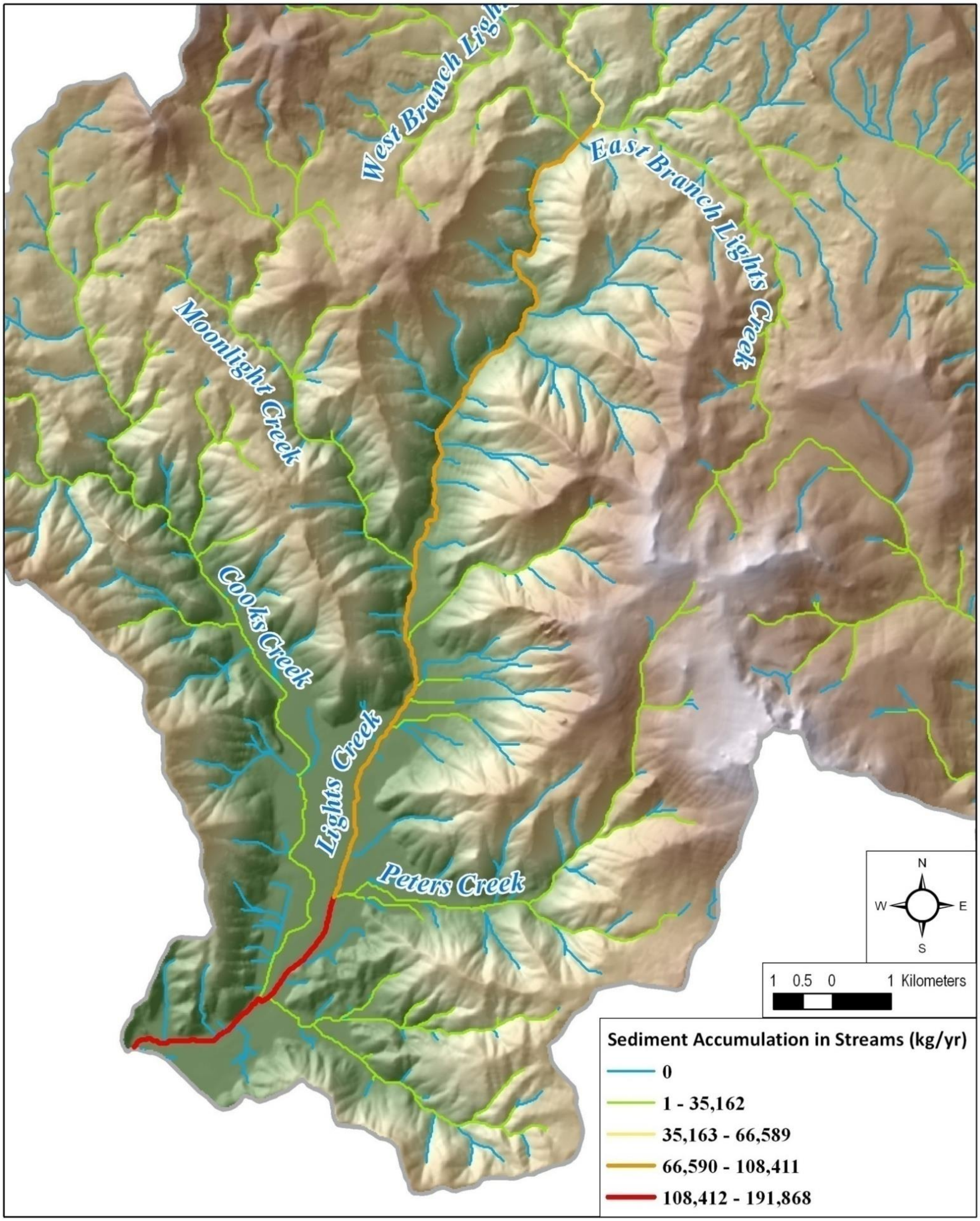

Figure 16. Sediment accumulation from roads to streams in the Lights Creek Watershed.

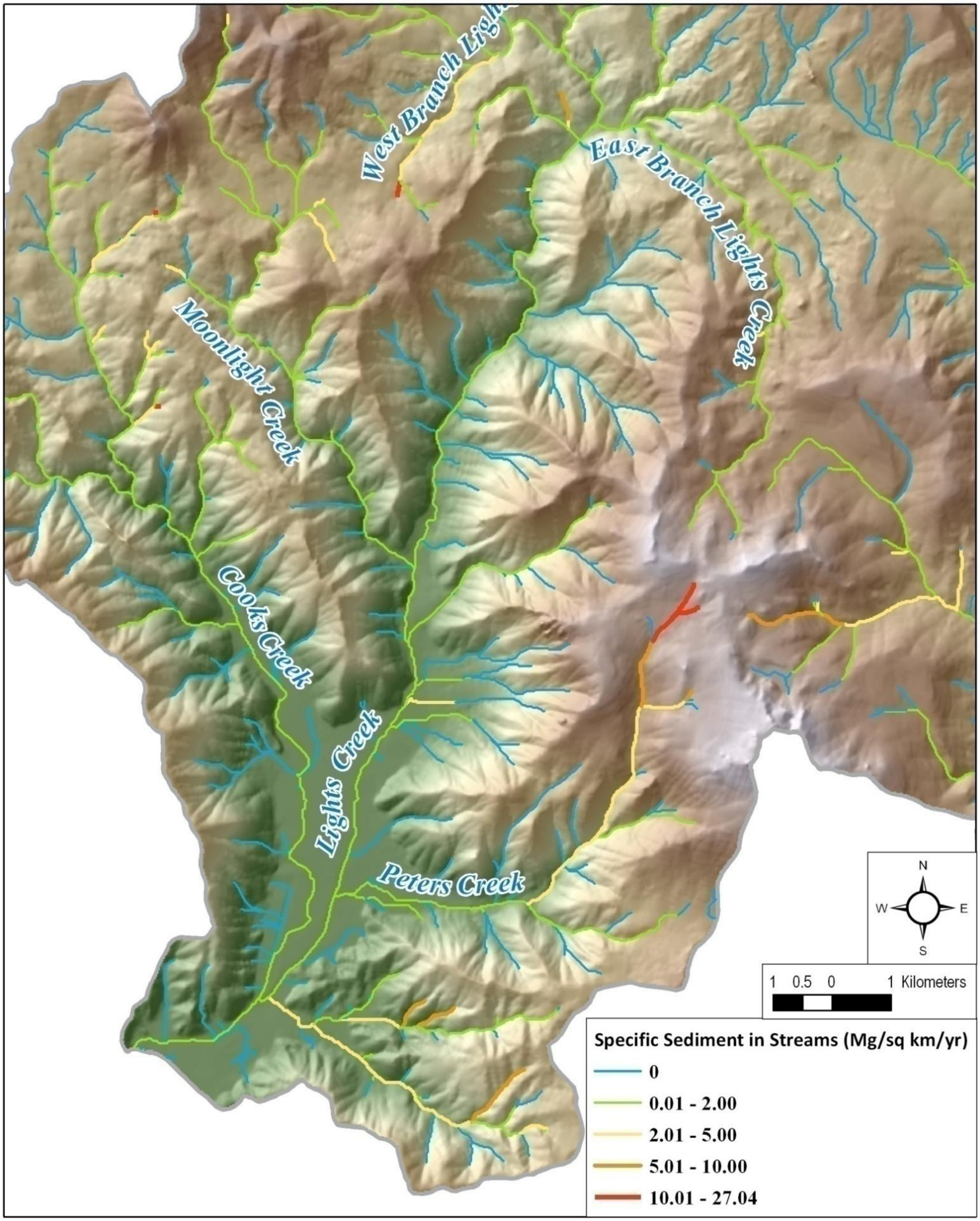

Figure 17. Specific sediment from roads to streams in the Lights Creek Watershed.

4.4 Landslide Risk

Existing Landslides

In the Lights Creek and Indian Creek watersheds, shallow landslides along roads occurred most frequently when the road traversed earthflow terrains. The inventory recorded 76 landslides (Table 5), totaling 538,080 m^3 (703,800 yd^3). The majority were located in the road fillslope or hillslope below the road. Few were in the cutslope. Landslide volume was estimated for all landslides visible from the road greater than a minimum threshold of 10 feet in slope length and slope width. There were 21 landslides estimated to be less than five years of age (190 Mg delivered), 34 between five and ten years old (64,960 Mg delivered), and 21 landslides were between ten and 15 years old (0 Mg delivered). There were 71 that were related to the road in some way; road-related landslides totaled 313,780 m^3 (410,420 yd^3). Including non-road related landslides, there were 14 cutslope failures (4,300 m^3, 5,640 yd^3, Figure 18), 41 fillslope failures (164,590 m^3, 215,270 yd^3), and 21 hillslope failures (369,190 m^3, 482,890 yd^3, Figure 19). Locations of all observed slides are shown on Appendix B, Maps 7a and 7b, which also shows the predicted natural risk (see below). Appendix B, Maps 8a and 8b show locations of observed landslides by size and mass delivered.

The study area had large areas of earthflow terrain (Cruden and Varnes 1996) that underlay several roads. They were easily visible on LiDAR and some were mapped on the 1:100,000 Susanville quadrangle geology map (CGS 2013). Thirty nine of the recorded landslides were found on roads that traversed earthflow terrain along roads 28N03 (Figures 19 and 20), 28N02, and 28N39 in upper West Lights Creek; 28N19, 28N19D, and a spur

Table 5. *Number and types of observed landslides, as well as masses and volumes of sediment generated and delivered to the stream channel network in the Lights Creek and Indian Creek watersheds*

Location		**Count**	**Volume (yd3)**	**Volume (m3)**	**Mass Produced (Mg)**	**Mass Delivered (Mg)**	**% Mass Del**	**Mass Delivered (Mg/yr) over 20 yr**
	Road Relation							
Cutslope		**14**	**5,640**	**4,300**	**6,890**	**0**	**0%**	**0**
	Not Road Related	*1*	*60*	*40*	*70*	*0*	*0*	*0*
	Road Related	*13*	*5,580*	*4,260*	*6,820*	*0*	*0*	*0*
Fillslope		**41**	**215,270**	**164,590**	**263,340**	**16,700**	**6%**	**840**
	Not Road Related	*1*	*70*	*60*	*90*	*90*	*100%*	*10*
	Road Related	*40*	*215,200*	*164,530*	*263,250*	*16,610*	***8%***	*830*
Hillslope		**21**	**482,890**	**369,190**	**590,710**	**48,450**	**8%**	**2,420**
	Not Road Related	*3*	*293,250*	*224,200*	*358,720*	*0*	*0%*	*0*
	Road Related	*18*	*189,640*	*144,990*	*231,990*	*48,450*	*21%*	*2,420*
Totals		**76**	**703,800**	**538,080**	**860,940**	**65,150**	**8%**	**3,260**
	Not Road Related	***5***	***293,380***	***224,300***	***358,880***	***90***	***0.03%***	***10***
	Road Related	***71***	***410,420***	***313,780***	***502,060***	***65,060***	***13%***	***3,250***

off 28N02 in the inner gorges of upper Indian and Pierce Creeks (Figure 21). A smaller area of earthflow terrain was in Hungry Creek but caused few road problems and contained only one observed landslide. The mobile surface on which the roads were constructed increased road fill instability resulting in a high landslide frequency on some roads. Some of the recorded features represent shallow rotational slump features occurring mostly within fill material. Others represent motion within the larger terrain which mobilizes the entire road prism as part of a larger feature. Of the features nested within a larger earthflow terrain context, landslide dimension measurements were focused on the smallest, discretely measurable feature immediately affecting, and including the road prism. While most of the features associated with the road prism did not deliver, the large, earthflow terrain features generally encompass entire sub-watersheds. Instability on roads in these areas was noted to be initiating in 2009 as part of the BAER post Moonlight Fire surveys, and by 2013 had increased dramatically to the degree of effectively closing some of the roads (USDA 2013, roads 27N65, 28N03, and 28N17).

The remaining landslides were shallow landslides, and one was a rock slide. Another notable landslide area was along the fillslope of Plumas County road PC-213 where it runs directly adjacent to Lights Creek. The landslides were occurring in fill material undercut by an active stream at high flow. Several had rip-rap at their bases along the channel. Although they were small, they were one third of features that are stream connected, but only 50 Mg of the total mass delivered from all landslides.

Landslides were determined to be connected to the channel network if an associated drain point was connected to the channel network, if an associated road surface flow path that would be expected to intercept the landslide sediment was connected to the network, or if the landslide was observed in the field to be connected to the network. There were 14 (18%) landslides found to be stream connected. Using a bulk density for fill of 1.6 Mg/m^3 (Madej 2001), the mass of sediment generated at all connected landslides was estimated to be 65,150 Mg, or 8% of all landslide-generated mass (Table 5). If it is assumed delivery was constant over a 20-year period, sediment delivery rate is about 3,260 Mg/yr. Albeit somewhat arbitrary, it is a useful method for drawing a comparison of episodic sediment production and delivery from landslides to the annual sediment production and delivery from fine road surface sediment. By this method of comparison, sediment delivery from landslides was roughly greater than 9 times larger than the annual road surface fine sediment delivery. Or put another way, regardless of the duration and mechanism of landslide delivery, it would take the road surfaces 9 years to deliver the same mass landslides delivered. In reality, landslide masses represent pulsed and inconstant, as opposed to steady and chronic sediment inputs to streams, so in any given year, the amount of sediment delivered to streams is likely to be higher or lower than the estimated 3,260 Mg/yr annual rate. Estimates of total mass delivered represent the entire landslide volume and do not account for partial delivery of landslide sediments (i.e. not all sediment from a road related landslide is likely to be delivered, even if some of the sediment is). Due to those uncertainties surrounding the timing of these events actual volumes may be lower. Appendix B, Maps 8a and 8b show locations of observed landslides by size and mass delivered.

Figure 18. Cutslope failure type landslide in earthflow terrain.

Figure 19. Fillslope failure type landslides in earthflow terrain.

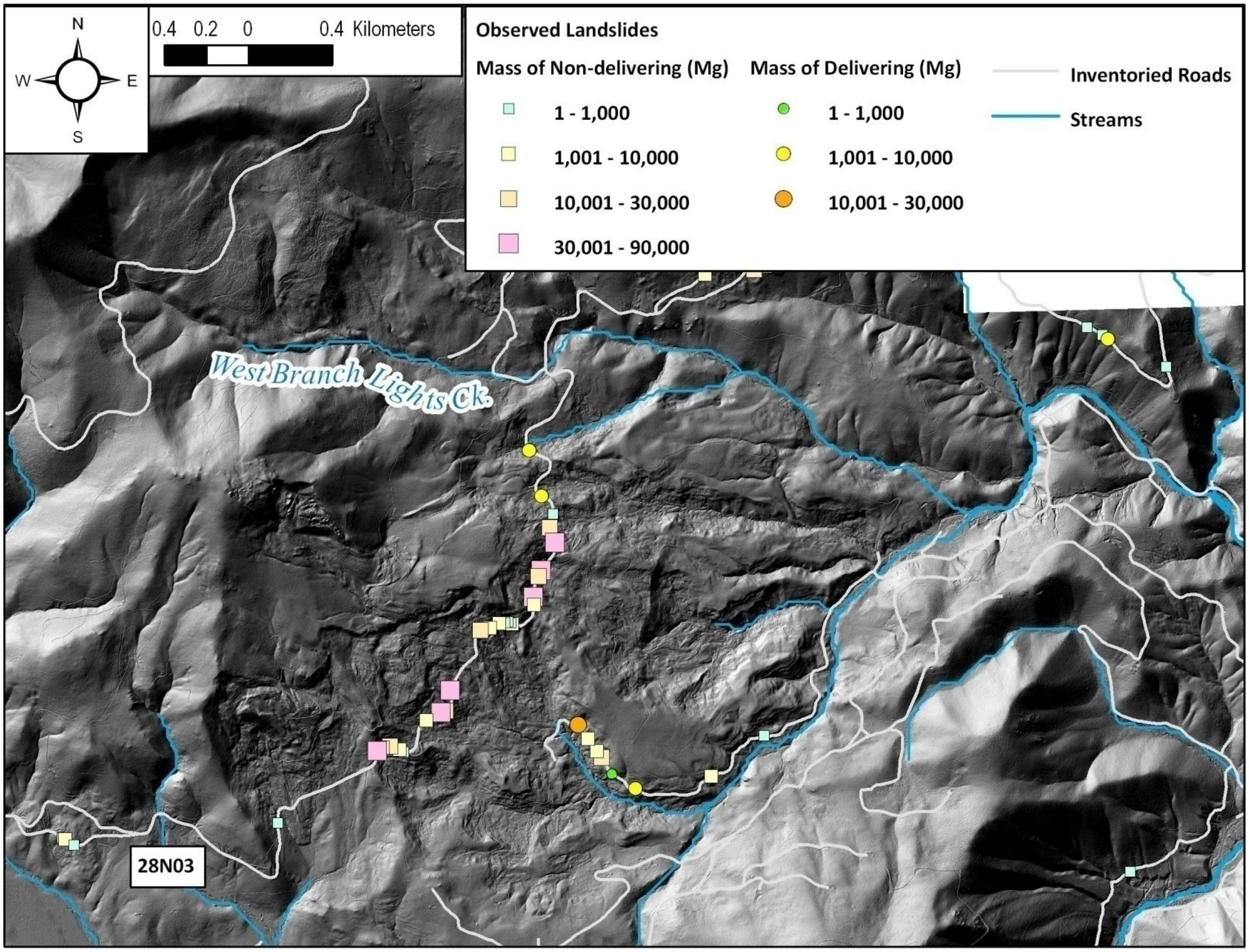

Figure 20. Locations of observed landslides interacting with the road prism in a very large, earthflow terrain area around 28N03 in West Branch Lights Creek.

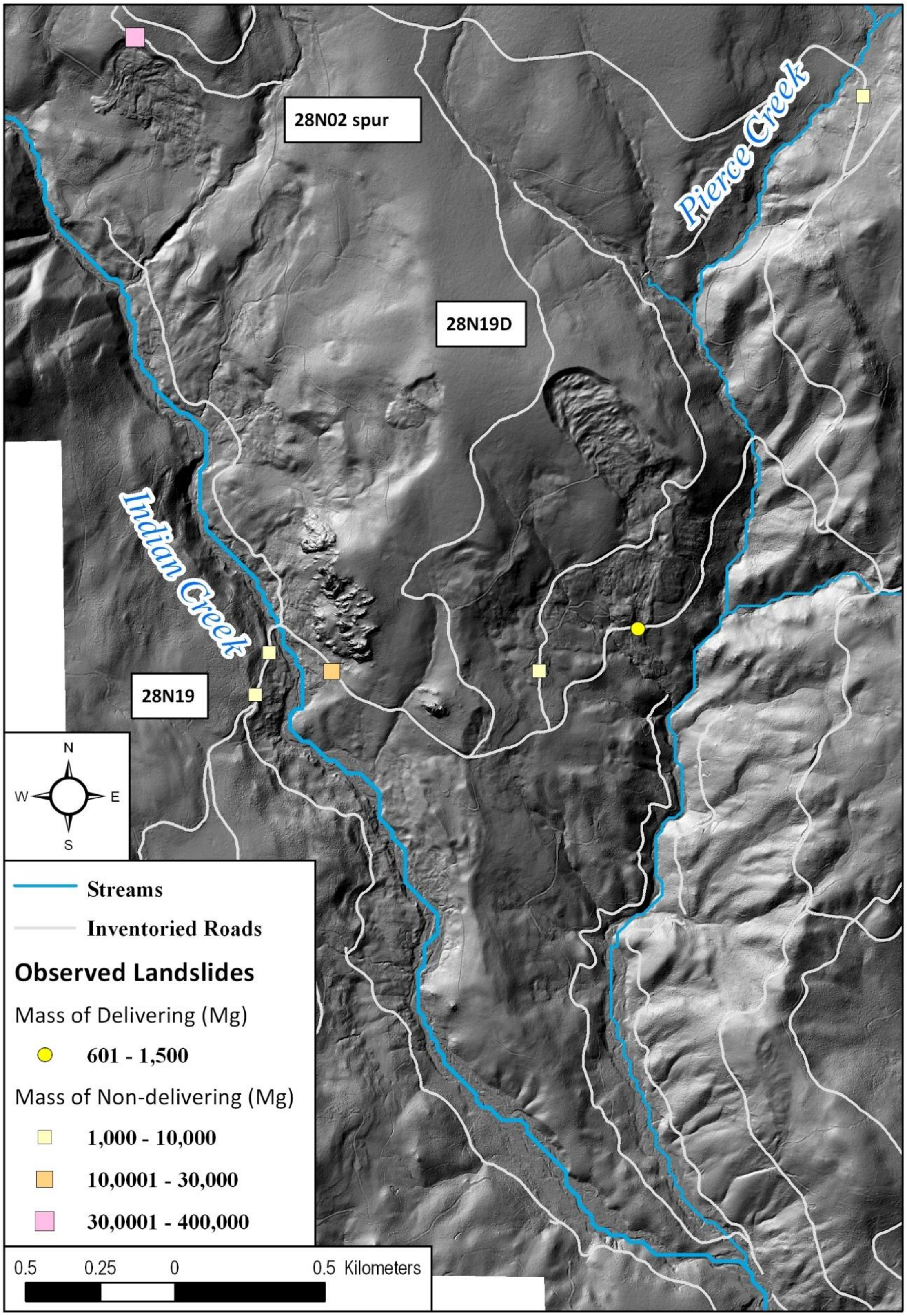

Figure 21. GRAIP observed landslides interacting with the road prism within earthflow terrain around Pierce and Indian Creeks.

Changes to Landslide Risk Due to Roads

The risk of shallow landslide initiation is predicted using SINMAP 2.0 (Pack at al. 2005, http://hydrology.neng.usu.edu/sinmap2/), modified to account for contributions of road surface runoff, and locally calibrated to known locations of landslides (Plumas NF 2013). SINMAP has its basis in the infinite plane slope stability model and produces raster grids that illustrate slope stability based on hillslope and specific catchment area at each DEM grid cell. Un-roaded and roaded risk grids are subjected to a series of mathematical operations that result in grids that show the important changes to landslide risk due to the presence of the roads. These change grids are compared to the natural landslide risk grid to show how the roads affect slope stability in the context of the background risks (i.e. the risks without the influence of road drainage). Important grid cell changes are those un-roaded to roaded differences that show a risk change from stable to unstable, or the areas that were unstable without roads and became less stable after road construction.

Calibration was performed using a set of points locating shallow landslide features visually identified on the Plumas National Forest (2013) LiDAR layer coverage. Large scale earthflows or features within earthflows were not used for calibration. Only features that met selection criteria with a high degree of certainty were used for the calibration, so it is likely there are a greater number of shallow landslides which exist that were not used in the calibration. Thirty

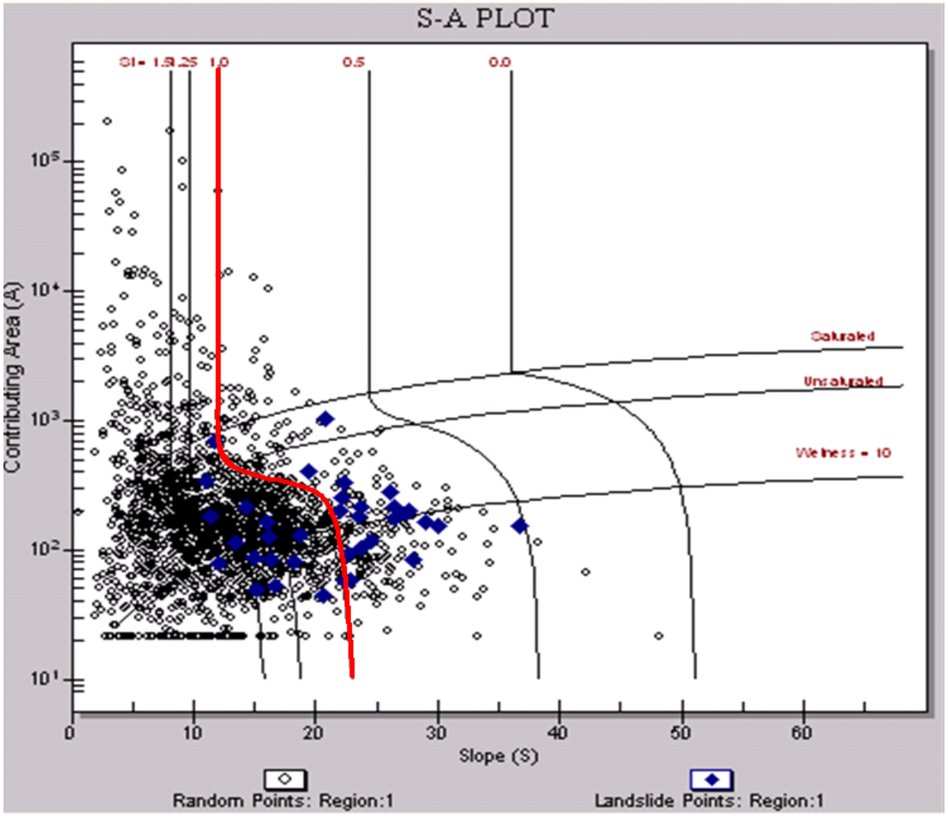

Figure 22. SINMAP generated calibration graph. Points that lie to the right of the red line are considered to be unstable.

eight features with distinct headscarp, body, and toe were identified by a search at 1:3,500 scale; which dictated a minimum feature size of roughly 10 meters wide. There were no age limits. No road related, rotational, bedrock, stream bank, mining related, or features within deep seated earthflow terrains were selected. There was no maximum feature size. Features were marked with a single point at the top of headscarp. Some verification of LiDAR identified features was possible by comparison with features mapped on field maps made by Plumas National Forest personnel (USDA 1980). The field maps confirmed that features identified on LiDAR were indeed natural landscape features. Several features on field maps were identified on LiDAR but not used for calibration because they did not qualify for other reasons. Two features used in calibration appeared on field maps.

Figure 22 shows the calibration plot for all areas within the watersheds from SINMAP (see documentation on the SINMAP website, above). Two types of points are plotted on the contributing area-slope graph. The first type is a random selection of points throughout the watershed that represent the slope-area distribution throughout the watershed, and the second type is the landslide calibration points. Points that fall to the right of the red line are considered to be at high risk.

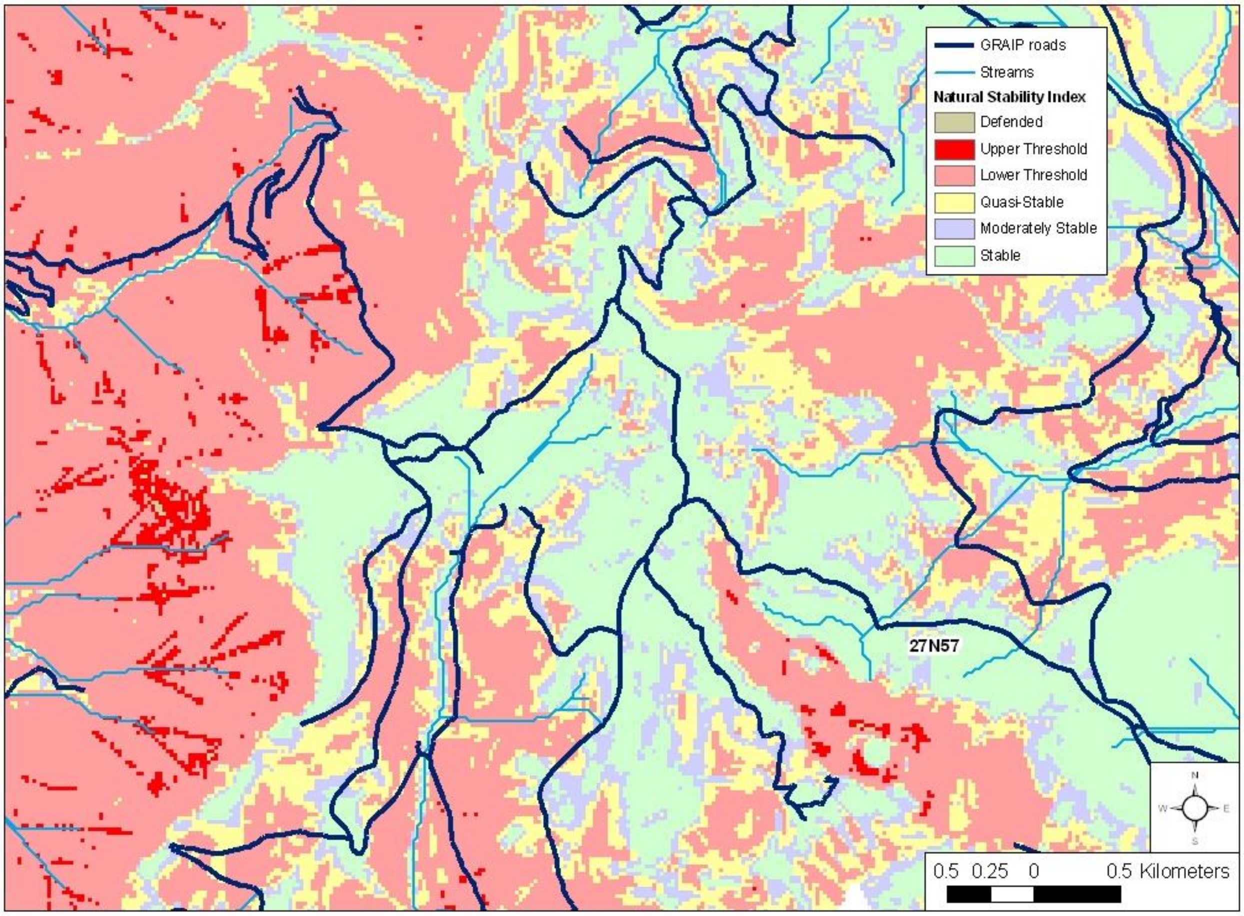

Figure 23. Natural slope stability in the south central portion of the Lights Creek and Indian Creeks watersheds. The yellow, blue, and green cells are generally considered to be stable, while the pink, red, and dark tan cells are generally considered to be unstable.

Figures 23, 24, and 25 illustrate the natural slope stability risk and change in risk with the addition of water from roads to hillslopes in the south central portion of the Lights Creek and Indian Creek watersheds. SINMAP was calibrated and run initially to determine the intrinsic stability of the slopes over which the road traverses and to identify locations that are at a high risk of failure without the road. The roads were well distributed across various landscapes. Inherent landslide risk is generally high across the steepest slopes throughout the watershed (Figure 23; Appendix B, Maps 8a and 8b).

A second calibrated stability index run was performed to address the effects of road water contribution to drain points. In Figure 24, the areas in the south central portion of the watershed where the road changed the risk from the stable category (stable, moderately stable, quasi-stable (from Figure 23 above) to the unstable category (lower threshold, upper threshold, defended) are shown in red. These are areas where road drainage was installed over slopes predicted by SINMAP to be naturally stable, and the added water increased the predicted instability of the area into the unstable category.

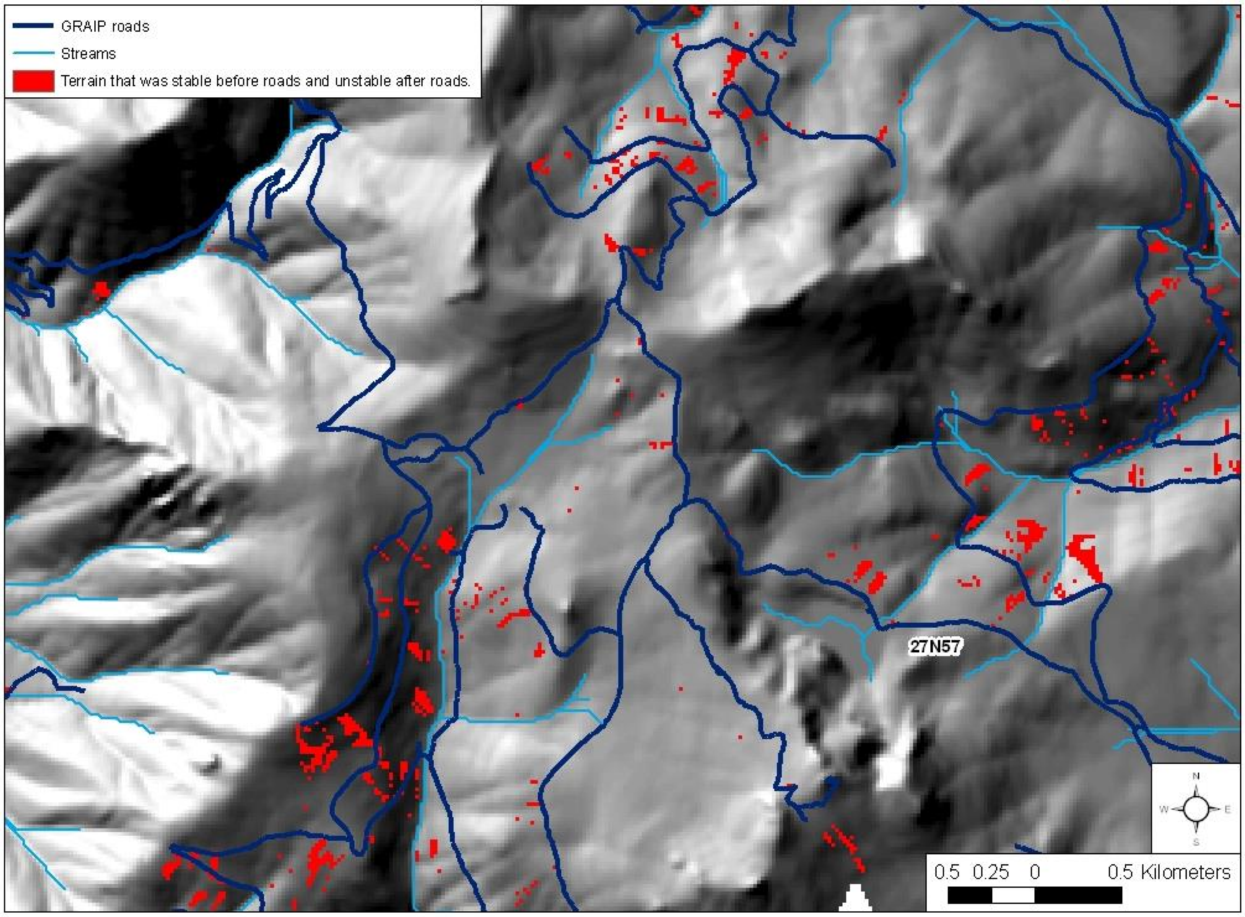

Figure 24. The most significant slope stability risk changes due to the roads in the south central portion of the Lights Creek and Indian Creek watersheds. The risk in the red areas was significantly increased.

Figure 25 adds the areas where the risk of shallow landsliding was high both before and after road construction. The orange cells are areas where the predicted risk increased (became less stable) after road construction, and the terrain was unstable prior to road construction. This is due to the installation of road drainage over naturally unstable slopes. Risk may not extend as far downslope as is shown. In steep and wet areas with naturally high landslide initiation risks such as this, it is difficult to place road drainage in such a way that risk is not significantly increased.

Figure 26 adds all areas where SINMAP predicted naturally high risk. They are shown in light grey hatches and correspond to the tan, red, and pink unstable categories (lower threshold, upper threshold, and defended) on the natural slope stability image (Figure 23). This allows areas to be shown where naturally high risk areas were not increased to even higher predicted risk categories with increased road flow.

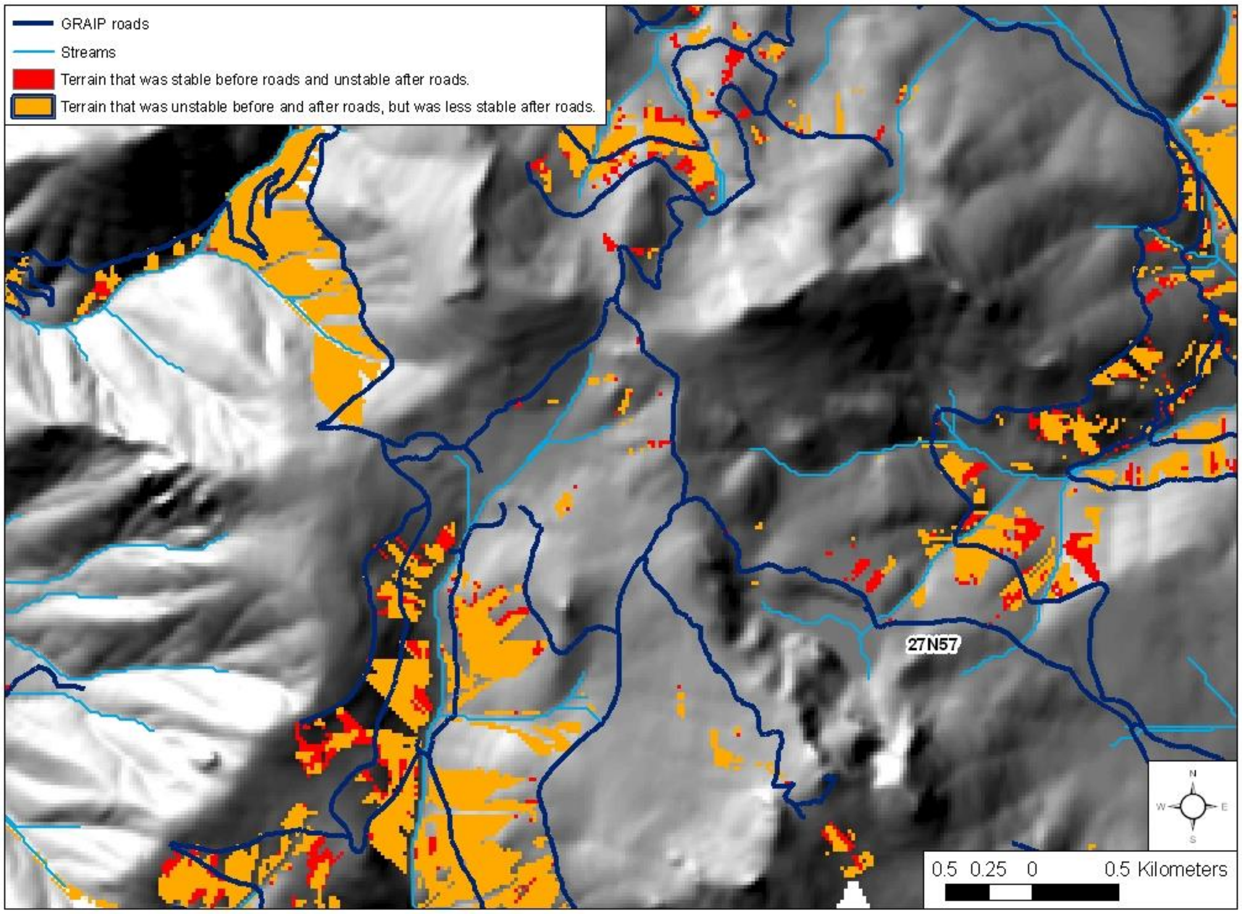

Figure 25. Changes in slope stability risk in the south central portion of the Lights Creek and Indian Creek watersheds. Orange areas are where the risk increased.

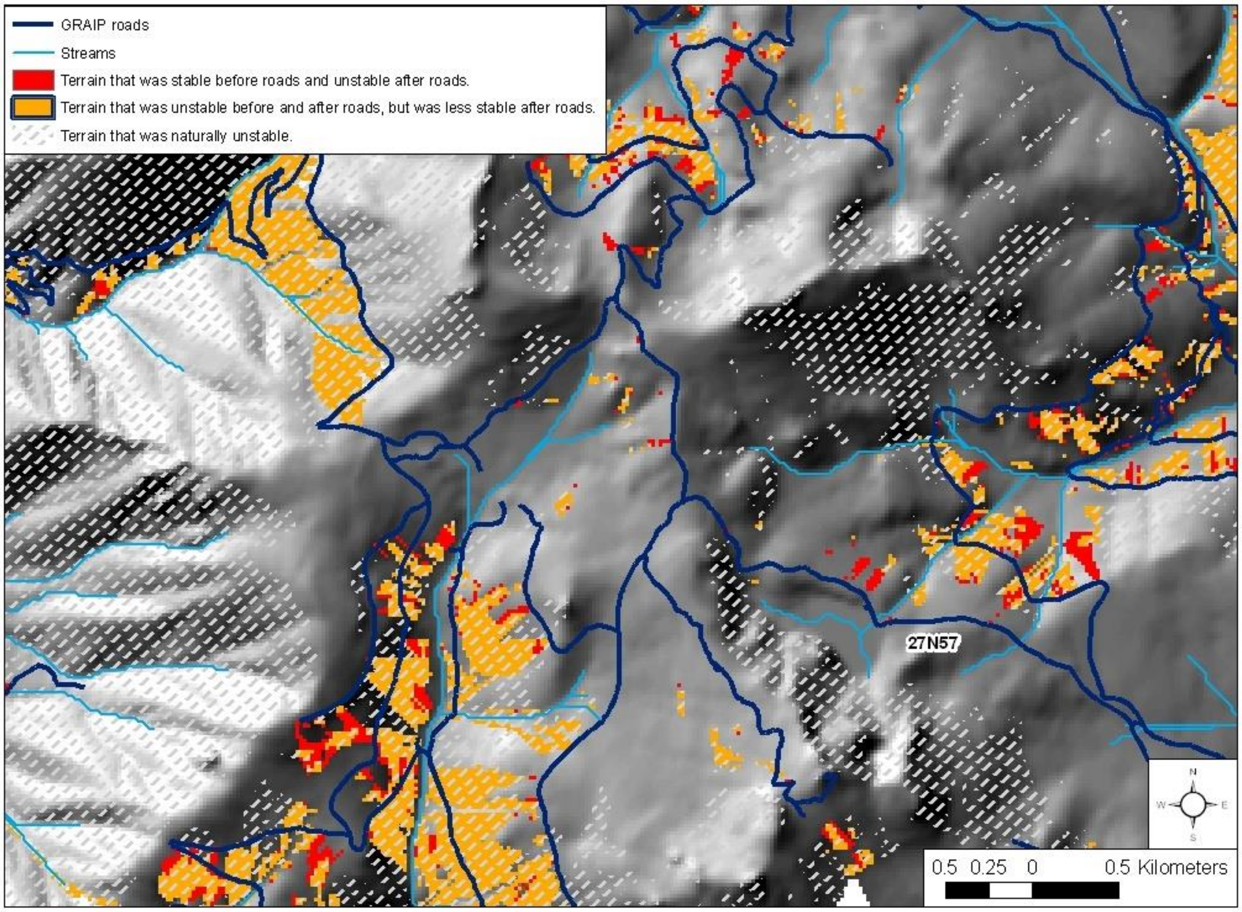

Figure 26. Areas of naturally high risk and risk changes, south central portion of the Lights Creek and Indian Creek watersheds.

Table 6. *Landslide risk changes in the Lights Creek and Indian Creek watersheds by category and area.*

Risk Category	Area (m²)	% of Total Area	# of Landslides	% of Total Landslides
Total Area of Watershed (m²)	572,820,000[1]	100%	76	100%
Area Naturally Stable (m²)	361,217,600	63%	28	37%
Area Stable Before Roads, Now Unstable (m²)	5,297,800	1%	14	18%
Area Naturally Unstable (m²)	211,602,480	37%	14	18%
Area Unstable Before Roads, Now Less Stable (m²)	26,617,400	5%	20	26%
Total Area Affected by Road Water Discharge (m²)	**31,915,200**	**6%**	**34**	**45%**

[1] Area is greater than study area because it includes a 500 m buffer as the SINMAP analyses areas do.

Appendix B, Maps 7a and 7b and Table 6 show areas of SINMAP predicted risk, changes in predicted risk, and locations of landslides identified in the GRAIP study across the whole watershed. Of the 514 km^2 (199 mi^2) that comprise the Lights Creek and Indian Creek watersheds, 5.3 km^2 (2.1 mi^2, 1.0%) were stable before road construction and are now unstable, and 27 km^2 (10 mi^2, 5.2%) were unstable before road construction and are now less stable due to road drainage (Table 6). This is a total of 32 km^2 (12 mi^2, 6.2%) of the watershed that has experienced an increase in SINMAP predicted landslide risk due to roads.

There was low correlation between SINMAP predicted high risk areas and field observed landslides where field observed landslides occur within road fill near streams, and in road fill where roads traversed earthflow terrain. Of the 28 landslides that occurred in naturally stable areas with no increase in instability risk after roads, over half were in earthflow terrain and 6 were in inner gorge areas. Of the 14 landslides that occurred in naturally unstable areas with no increase in instability risk after roads, half were in earthflow terrain and 1/3 were in inner gorge areas. Of the 14 landslides that occurred in areas that increased from stable to unstable, all but one were in earthflow terrain. Of the 20 landslides that occurred in areas that increased from unstable to less stable, over half were in earthflow terrain and 6 were in inner gorge areas. The low correlation is because landslides observed in the field differ in two ways from landslide points used to generate predicted stability in SINMAP. Many of the field identified landslides were cutslope and fillslope failures, and were unlikely to correlate well with the SINMAP risk, which is designed to predict hillslope risks rather than risks within the road prism. Additionally, the landslide points were collected from the road in the field, as opposed to the head scarp of the landslide which is the point of reference SINMAP uses. There was better correlation between observed shallow landslide types and areas predicted unstable by SINMAP. So increase in predicted stability risk was best used to predict shallow landslides on hillslopes below roads rather than within the road prism or where roads traversed earthflow terrain. Overall, nearly half (45%) of all observed landslides occurred in areas predicted by SINMAP to have an increased instability risk after roads.

Options for treatment of high risk areas are few. Additional drainage can be added to reduce the length of road that drains to a given point or points, and therefore reduce the quantity of water, but this may result in even more road-related unstable area if the drain spacing is not close enough. Additionally, if a slope is naturally unstable, as is much of the area of the Lights Creek and Indian Creek watersheds, then any addition of water, however small, will only decrease stability further and increase risk. Another option is to remove drainage features that occur at high risk locations, and instead route water further down the road to a more stable area. However, this may result in excessive road surface or ditch erosion, and the point to where the water is routed may then become unstable or it might deliver large quantities of sediment to the stream. As failure rate is highest and most unpredictable in earthflow terrain, the best option in those areas may be to reroute the road entirely.

4.5 Gullies and Gully Initiation Risk

Existing Gullies

The Lights Creek and Indian Creek watersheds have an incidence of road-related gullies of about one gully per 4 km (2.5 mi). To distinguish between road-related gullies and natural incipient channel heads, a feature was mapped as a gully if it occurred below a road drain point, but was absent on the uphill side of the road. A gully was defined as a linear erosional feature at least ten feet long and six inches deep. There were 167 gullies observed (at 2% of all drain points) during the course of the survey, with a total volume of 6,350 m^3 (8,300 yd^3, Table 7). There were 107 gullies that occurred only on the hillslope (4,270 m^3, 5,590 yd^3), 20 that occurred only on the fillslope (330 m^3, 440 yd^3), and 40 that occurred on both the fillslope and hillslope below a drain point (1,750 m^3, 2,270 yd^3), and one above the road. There were 6 gullies that occurred in a wet swale, 27 that had flow contribution from springs, seeps, or flow diversions, and 18 that terminated in a stream. 29 gullies were no longer actively eroding, while 139 were actively eroding. This allows areas to be shown where naturally high risk areas were not increased to even higher predicted risk categories with increased road flow. Figure 27 shows a typical gully below a ditch relief culvert. Appendix B, Maps 9a – 9d show the locations, delivered and non-delivered mass, and activity, of all inventoried gullies, as well as information pertaining to gully risk (see below). Figure 28 shows the locations of the gullies in the southeast portion of the watershed, as well as the same gully initiation risk information.

Table 7. *Inventoried gullies in the Lights Creek and Indian Creek watersheds (does not include those observed on road surfaces).*

Location of Gully *Activity of Gully*	**Count**	**Volume (yd3)**	**Volume (m3)**	**Number That Occur in Wet Swale**	**Number With Flow Contributions From Springs and/or Flow Diversion**	**Number That Terminate At A Stream**
Above Road	**1**	**20**	**10**	**0**	**0**	**0**
Still Eroding	1	20	10	0	0	0
Hillslope	**107**	**5,590**	**4,270**	**3**	**16**	**11**
Not Active	21	1,790	1,370	0	1	0
Still Eroding	86	3,800	2,900	3	15	11
Fillslope	**20**	**440**	**330**	**0**	**3**	**1**
Not Active	3	50	40	0	0	0
Still Eroding	17	390	290	0	3	1
Fillslope and Hillslope	**40**	**2,270**	**1,750**	**3**	**8**	**6**
Not Active	5	630	490	0	4	0
Still Eroding	35	1,640	1,260	3	4	6
Totals	**167**	**8,300**	**6,350**	**6**	**27**	**18**
Not Active	**29**	**2,470**	**1,900**	**0**	**5**	**0**
Still Eroding	**139**	**5,850**	**4,460**	**6**	**22**	**18**

Gullies can be determined to be connected to the stream channel network if an associated drain point that discharges through the gully is connected to the channel. There were 69 gullies (41%) that were determined to be connected to the channel. Using a bulk density for fill of 1.6 Mg/m^3 (Madej 2001), the mass of sediment generated at all connected gullies was 8,360 Mg (Table 8). This was 82% of the mass generated at all gullies. As in the discussion of landslide sediment mass delivery in Section 4.4, it is useful to compare episodic delivery of gully sediment mass to annual road surface fine sediment delivery, by assuming a constant rate of delivery of gully sediment over a 20 year period. Over a 20 year period, 418 Mg/yr of sediment were delivered to stream channels, or about 1.2 times greater than the amount of road surface fine sediment delivered to stream channels annually. Put another way, it would take the road surfaces 1.2 years to deliver the same amount of sediment as gullies do in one year. In reality, gully mass sediment delivery is both pulsed (as the gully initiates) and chronic (as continued erosion by road surface-derived water), but it is not known what proportion belongs to each category. Actual annual sediment delivery from gullies is likely higher or lower than these estimates in any given year.

Table 8. *Sediment masses produced and delivered by active gullies in the Lights Creek and Indian Creek watersheds.*

	Mass Produced (Mg)	**Mass Delivered (Mg)**	**% Sediment Delivery**	**Average Delivery Rate Over 20 years (Mg/yr)**
Above Road	20	0	0%	0
Hillslope	6,830	5,700	83%	285
Fillslope	530	420	79%	21
Fillslope and Hillslope	2,790	2,240	80%	112
Totals	**10,150**	**8,360**	**82%**	**418**

Figure 27. Gully below the outlet of a ditch relief culvert.

Gullies observed on the road surface or in the ditch as opposed to the hillslope or fillslope are not counted in the above calculations because these gullies were not influenced by hillslope processes in the same way as are the hillslope gullies, and they eroded road surface material along road surface flow paths instead of fillslope and/or hillslope material. There were 759 Mg of additional sediment eroded from road surface and ditch gullies. Of this, 422 Mg (58%, 22 Mg/yr over 20 years) delivered to the stream network. Added to the hillslope gullies, this would be an increase of about 0.3%. Added to the road surface fine sediment erosion, this would be an increase of 6%.

Table 9. *Road surface gullies, production and delivery to streams, Lights Creek and Indian Creek watersheds.*

∑ Road Surface Gully Sediment Production (Mg)	759
∑ Road Surface Gully Sediment Delivery (Mg)	442
% Sediment Delivery	58%
Average Delivery Rate Over 20 Years (Mg /yr)	22

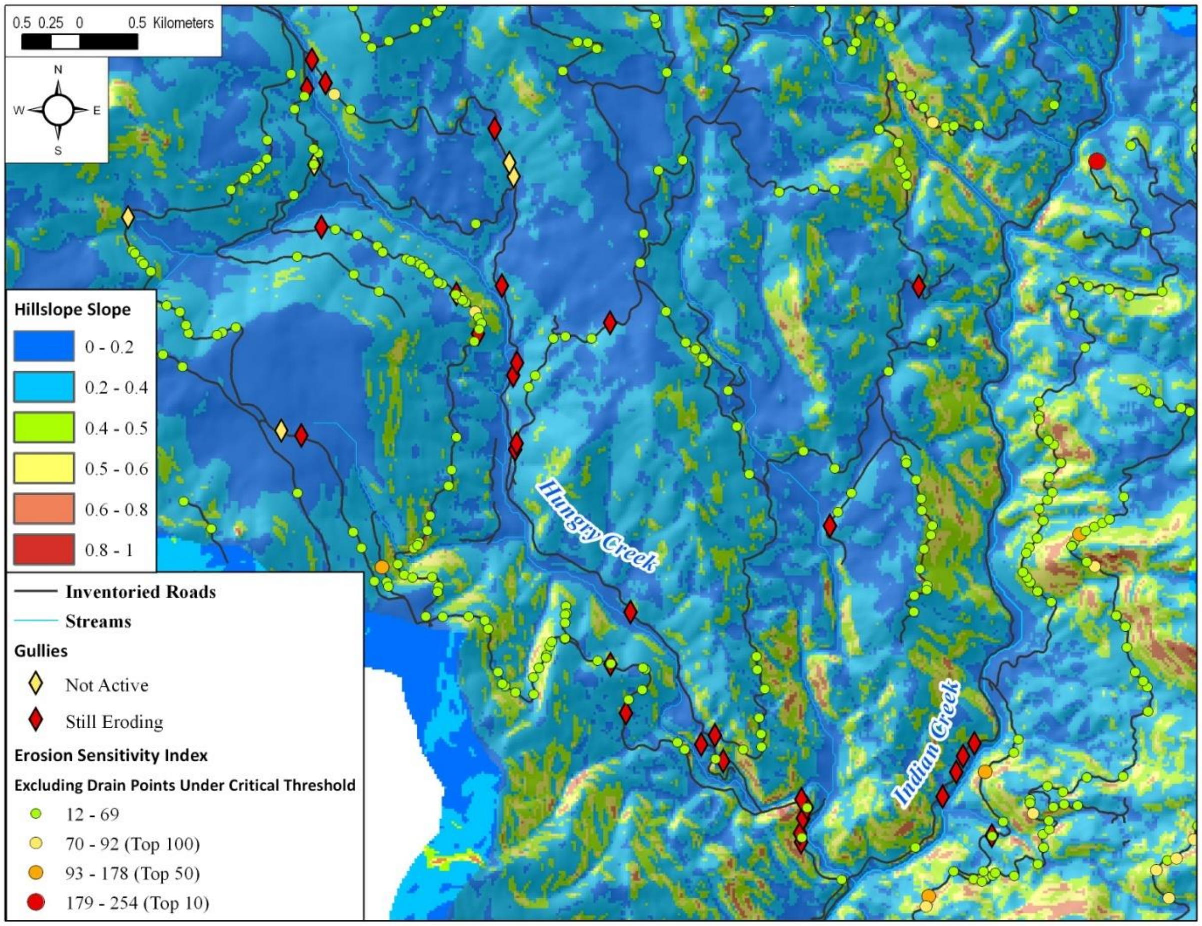

Figure 28. Locations of observed gullies and ESI risk at drain points, in southeast portion of the study area along Indian Creek and Hungry Creek.

Gully Initiation Risk

Gullying at drain points below roads can be a substantial source of sediment to stream channels. Gully initiation occurs when the shear stress applied by runoff exceeds the strength of the soil surface on the hillslope. GRAIP computes the Erosion Sensitivity Index (ESI; Istanbulluoglu et al. 2003), as shown below, at each drain point.

$$ESI = L \times S^2$$

L is the contributing road length at the drain point (m)
S is the slope of the hillslope below the drain point (%)

ESI values were calculated for all surveyed drain points, and were compared to a critical ESI threshold (ESI_{crit}) to identify areas with a higher risk of gully formation (i.e., where ESI $>\mathrm{ESI}_{crit}$). ESI_{crit} was empirically derived for the Lights Creek and Indian Creek watersheds using inventoried gullies, and was the ESI value above which the risk of gully formation increased significantly. Here, $\mathrm{ESI}_{crit} = 12$, and the risk of gully formation roughly triples above that value (Table 10).

Calibrations were completed using a logistical regression technique (local fit, locfit) in the R statistical computing environment (Figure 29) and a length-slope plot of the drain points with and without gullies was generated (Figure 30). Note that each point on Figure 29, which represents the probability of a gully (no = 0, yes = 1) vs. ESI value, corresponds to a point with the same ESI value on Figure 30. In Figure 29, while there are a number of gullies below the chosen ESI_{crit} threshold, the number of gullies vs. the number of non-gully drain points begins to increase significantly at $\mathrm{Log}_{10}\mathrm{ESI} = 1.14$ (ESI = 12).

Table 10. *Distribution of drain points by ESI value, Lights Creek and Indian Creek watersheds.* $\mathrm{ESI}_{crit} = 12$.

	$<\mathrm{ESI}_{crit}$	**$>\mathrm{ESI}_{crit}$**	**$>\mathrm{ESI}_{crit}$**		
ESI Value	**< 12**	**>12 (all)**	**12 - 50**	**50 - 100**	**> 100**
# Sites With Gullies	86	34	30	4	0
# Sites Without Gullies	6,130	1,347	1,168	145	34
Total # of sites	***6,216***	***1,381***	***1,198***	***149***	***34***
% of Total With Gullies	1%	3%	3%	3%	0%
% of Total Without Gullies	99%	97%	98%	97%	100%
Gully Rate **(# Gullied/Total sites in ESI_{crit} category)**	**1%**	**3%**	3%	3%	0%

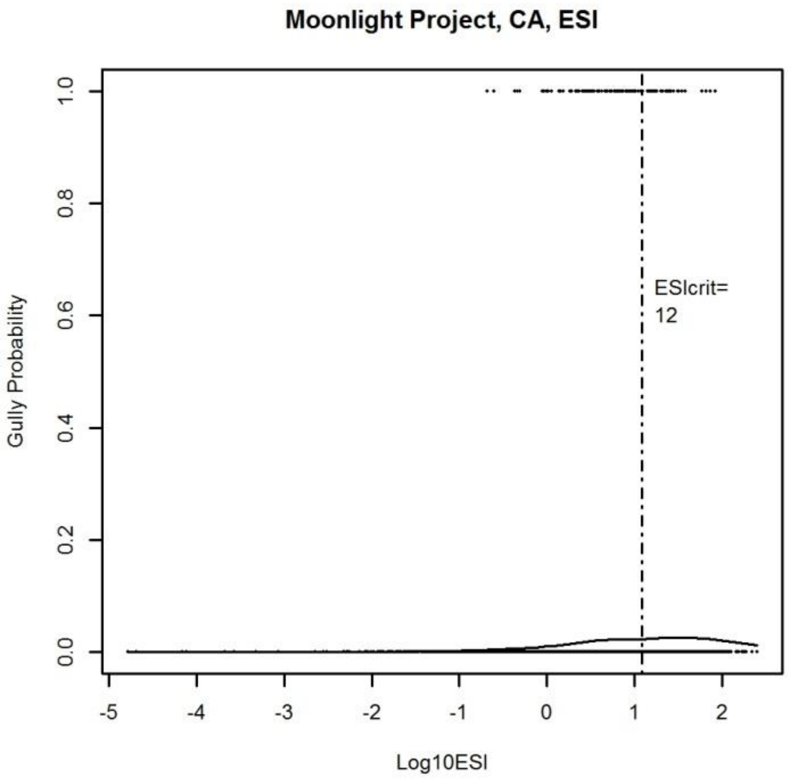

Figure 30. Calibration graph from the R local fit calibration. Gully probability is a binary yes/no field. Log$_{10}$ ESI corresponds to an ESI value. Although there are gullies below the chosen ESI$_{crit}$ value of 12, their probability is very low.

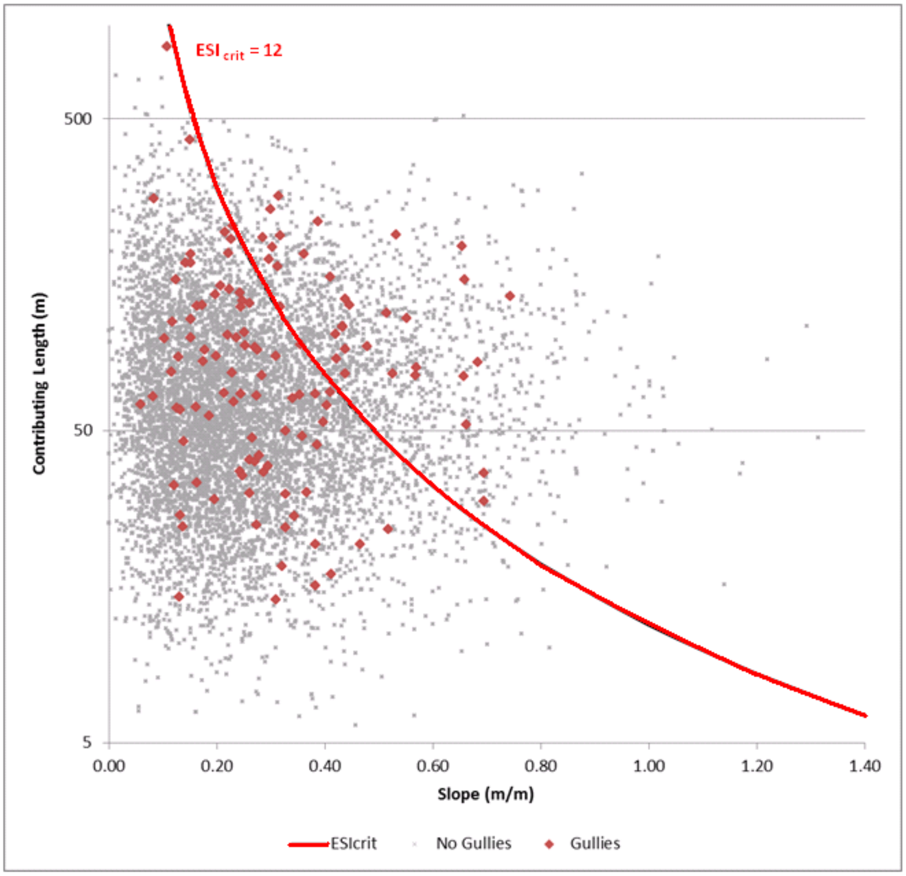

Figure 29. Length-slope plot that shows the distribution of gullied and non-gullied drain points. Notice that there are more non-gullied points towards the left of the graph. As the ESI increases (upper right part of the distribution), there are about the same number of gullied points. Above the red ESI$_{crit}$ = 12 line, there is a 3% chance of a point being gullied, while below the ESI$_{crit}$ line, there is a 1% chance.

An easy way to conceptualize this is to think of these distributions as densities. That is, while the density of non-gully drain points decreases as ESI gets larger, the density of gullied points does not change much. Therefore the ratio of gullied to non-gullied points increases as ESI increases. In this case, the occurrence gullied points increases relative to non-gullied points from about 1% below ESI_{crit}, to about 3% above ESI_{crit}. In this study area, if a road was newly built or upgraded with 100 drains placed with spacing and hillslope slopes below that resulted in an ESI ($L\ X\ S^2$) for each drain point of less than 12, there would be the chance that one drain point would develop a gully. If a different road was built or upgraded with 100 drains placed with spacing and hillslope slopes below that resulted in an ESI ($L\ X\ S^2$) for each drain point of greater than 12, there would be the chance that three drain points would develop a gully. See below for a guide for drain point maximum spacing by slope for this study area. For more information on ESI in GRAIP, see Cissel et al. (2012A), specifically, pages 105-109 and page 126.

Diffuse drain points, stream crossings, and drain points that did not have an associated road surface flow path (i.e. orphan drain points, Appendix A) were not included in this analysis, because these types of drain points do not behave in such a way that the ESI is a useful metric. Diffuse points represent a road segment that does not concentrate flow, and so does not pose a gully risk. Streams have their own, and often non-road related, controls on their propensity to incise, and so cannot be treated the same as other drain points. Orphan drain points have a contributing length of zero, and so have an ESI of zero, which throws off a meaningful average.

Table 11. *Further distribution information of drain points by ESI value.*

	Contributing Length (m)		Average ESI	Total Number of All Drain Points	Where ESI >ESIcrit	
	Total	Average			Number	Percent
Drain Points With Gullies	12,495	104	11	120	34	28%
Drain Points Without Gullies	577,186	77	8.0	7,477	1,347	18%
All Drain Points	589,681	78	8.1	7,597	1,382	18%

A total of 7,597 non-diffuse, non-stream crossing, non-orphan drain points were used in this analysis (Table 10). There were 1,382 (18%) with ESI >ESI_{crit}, and 6,216 drain points (82%) with an ESI <ESI_{crit}. 120 (2%) had gullies. Of those 120 drain points with gullies, 34 (28% of gullied points) had an ESI>ESI_{crit}. This left 86 gullied drain points (72% of gullied points) with an ESI <ESI_{crit}. The gully rate for drain points with ESI >ESI_{crit} among all 1,382 drain points above ESI_{crit} was 3%, and it was 1% for points with ESI <ESI_{crit} (Table 10). The average ESI for all 7,597 drain points across the Lights Creek and Indian Creek watersheds was 8.1, with an average contributing road length of 78 m (256 ft, Table 11). The average ESI of drain points with gullies was 11, while the average ESI of drain points without gullies was 8.0. The average contributing length at drain points with gullies was 104 m (341 ft), while it was 77 m (253 ft) at drain points without gullies. Figure 28 shows the distribution of gully risk in the southeast portion of the Lights Creek and Indian Creek watersheds, and Appendix B, Maps 9a and 9b show the same for the entire watershed. Only 34 (3%) of the 1,382 drain points have ESI>ESI_{crit}. So a gully point superimposed with a drain point on the maps is infrequent, and ESI is only a moderate predictor of gully formation in the Lights Creek and Indian Creek watersheds.

In order to reduce gully risk, drain points must either be spaced close enough together to prevent too much water from discharging at a single point, or they must be removed from steep slopes and high risk locations. However, if drain point spacing is not close enough, risk may be reduced somewhat in one place, but then increased above the critical threshold in another, which may lead to further gully formation. Given the known ESI_{crit} for the watershed and the measurable hillslope slope at a given point on the landscape, it is then possible to calculate the theoretical maximum contributing stable road length (Table 12). These drain spacing values can be used in the planning phase of future projects.

Table 12 .*Maximum contributing road segment length for a given average hillslope required to prevent drain points from exceeding ESI_{crit}.*

Average Hill Slope (%)	Maximum Road Segment Length (m)	Maximum Road Segment Length (ft)
10%	1,200	3,940
20%	300	985
30%	133	435
40%	75	245
50%	48	160
60%	33	110
70%	25	80
80%	16	50
90%	15	50
100%	12	40

Though the frequency of gully occurrence was low for the study area at only 2% of all drain points, delivery rate for gullies was high (82%), and the delivered mass was significant at 1.2 times greater than annual road surface fine sediment delivery. While gully occurrence was not the biggest concern in this area, it can be managed for by designing road drainage with adequate drainage spacing to reduce contributing road length, and avoiding placing drainage onto steep slopes. Road design which inhibits gully formation on road surfaces and in ditches such as outsloping and reducing drainage spacing can also significantly reduce sediment delivery.

4.6 Stream Crossing Failure Risk

Besides contributing fine sediment to streams through road surface erosion, stream crossings may fail catastrophically when blocked and deliver large sediment pulses to stream channels. Stream crossing failure risks were assessed using the Stream Blocking Index (SBI, Flanagan et al. 1998). The SBI characterizes the risk of plugging by woody debris by ranking two stream crossing characteristics: the calculated ratio of the culvert diameter to the upstream channel width (d/w), and the measured skew angle between the channel and the pipe inlet. Culverts sized to be the same diameter as the channel width or larger have a diameter to channel width ratio greater than or equal to 1 ($d/w \geq 1$), and received a rank of 1. Culverts sized with a diameter slightly less than the width of the stream to half the width of the stream have diameter to channel width ratios between 1 and 0.5 ($1 > d/w \geq 0.5$), and received a rank of 2. Culverts sized with a diameter less than half the channel width have a diameter to channel width ratio, less than 0.5 ($d/w < 0.5$), and received a rank of 3. Skew angles greater than 45 degrees received a rank of 1. SBI is a total of the two ranks. SBI values range from 1 to 4, where 1 suggests no risk of blockage, and 4 suggests a high risk of blockage.

Field crews recorded 469 stream crossings in the Lights Creek and Indian Creek watersheds. Only the 352 crossings with a culvert were included in the SBI calculations. The 117 crossings that did not have a culvert were natural fords (104 crossings), 1 concrete ford (Lower Lights Creek fish ladder), bridges (8), log culverts (2), and bottomless arch culverts (3), or were

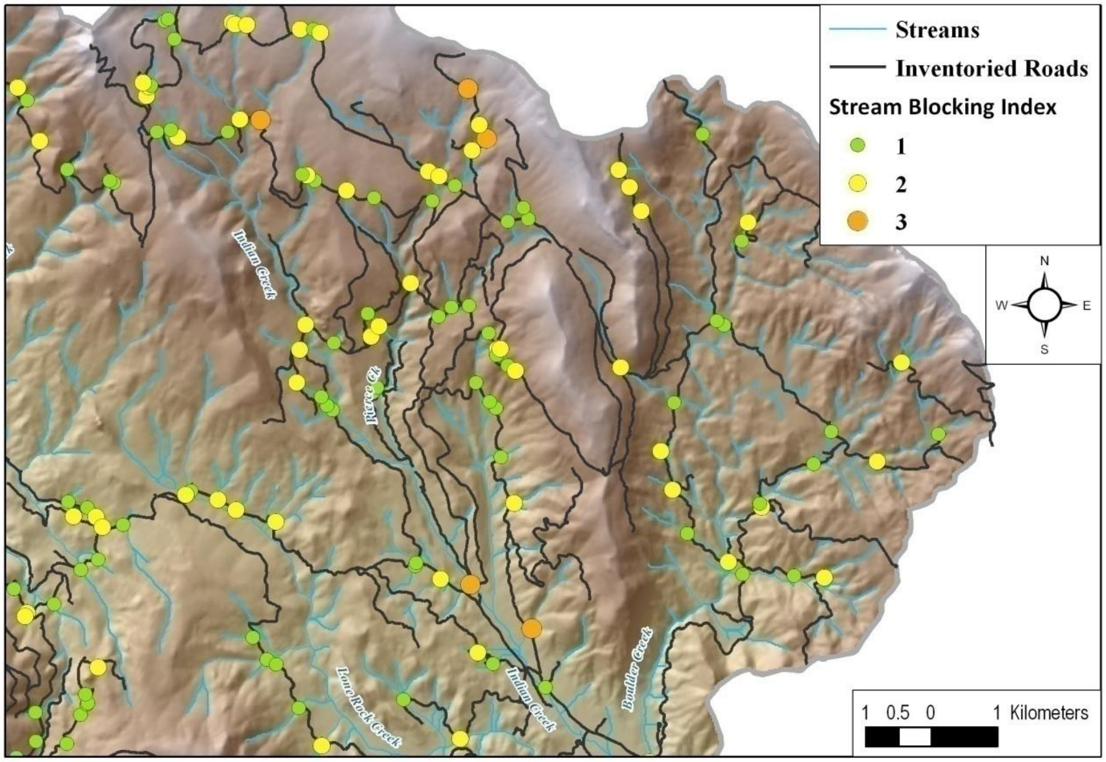

Figure 31. SBI values for the stream crossings in the northeastern part of the Lights Creek and Indian Creek watersheds.

excavated crossings (272), and were not included. Risk of pipe plugging is not a factor at these crossings.

The SBI values for Lights Creek and Indian Creek watersheds had an average of 1.5 for the 469 stream crossings. This is out of a range of 1 to 4, where 1 suggests no risk of blockage, and 4 suggests a high risk of blockage. There were no stream crossings with an SBI of 4. There were 17 crossings with an SBI of 3, 131 crossings with an SBI of 2, and 204 crossings with an SBI of 1 (Figure 31 and Figure 32); Appendix B, Maps 10a and 10b). Plugging risk at crossings throughout the watersheds was due mostly to pipe diameters sized smaller than channel widths than to high skew angle, but skew angle was a factor in about half the crossings with the highest SBI=3. Of the crossings with SBI=3, 7 (41%) had pipe diameter to channel width ratios less than 0.5, and as low as 0.16, so their SBI value and high plugging risk was due entirely to undersized culvert diameter and not to high skew angle. The remaining 10 crossings with SBI=3 had pipe diameter to channel width ratios of 0.5 to 0.86; so were all moderately undersized culverts with moderate plugging risk coupled with moderate plugging risk from high skew angle to create high plugging risk overall. One was totally blocked and none were partially blocked for a 6% blocking rate for crossings of SBI=3. Of crossings with SBI=2, most (115, 89%) had pipe diameter to channel width ratios between 1 and 0.5, and all less than 0.84; so their SBI value and moderate plug risk overall was due entirely to undersized culvert diameter and not to high skew angle. Only 16 crossings with SBI=2 had pipe diameter greater than or equal to channel width, so their overall moderate risk of plugging was due more to high skew angle than pipe size. For crossings with an SBI of 2, 5 were totally blocked, and 16 were partially blocked, and 3 had flow around the pipe for an 18% blocking rate. Of crossings with SBI =1, all had a pipe diameter greater than or equal to channel width, low skew angle, and had no plugging risk. However, 13 were partially blocked, 2 were totally blocked, and one had flow around pipe for an 8% blocking rate. The moderately high blocking rate for crossings with an SBI of 1 could be due to impacts of fire which released large amounts of fine sediment in streams when wood burned in the channels, but this hypothesis is not confirmed.

The risk of stream crossing failure can also be viewed in the context of the consequences of failure (Flanagan et al. 1998). A consequence of concern at these stream crossings is the erosion of fill material into the stream channel. We calculated the fill material that would likely

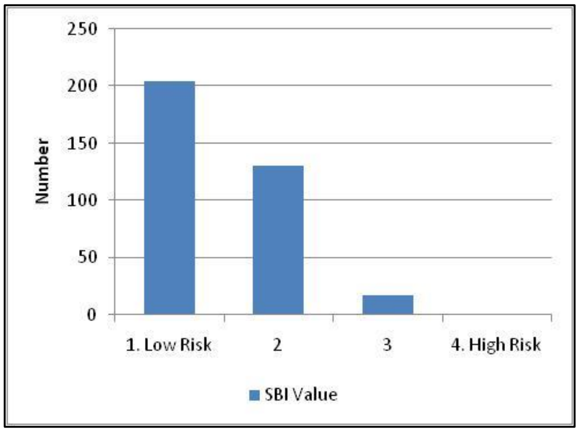

Figure 32. Distribution of SBI values for the Lights Creek and Indian Creek watersheds.

be excavated in an overtopping type failure. Crossing fill depths and pipe gradients were surveyed, and volume of the prism of fill at risk was calculated assuming that the prism was bounded at the base by an area 1.2 times the channel width, with side slopes climbing to the road surface at a slope of 33%. The total fill volume at risk for all the stream crossings with pipes was 25,150 m^3 (32,900 yd^3, 40,240 Mg). Fill volumes ranged from 2 m^3 (3 yd^3, 3 Mg) to 810 m^3 (1,060 yd^3, 1,296 Mg), and had a mean volume of 54 m^3 (71 yd^3, 86 Mg). This type of fill failure will not occur at bridges, fords, or excavated stream crossings so no fill volume risk was calculated at these locations. Fill volumes were not calculated at the log crossings or bottomless arches, so they may have fill that poses some unmeasured magnitude of risk.

Another consequence of concern at failed stream crossings is the diversion of stream flow onto road surfaces and unchanneled hillslopes. Once a crossing becomes occluded and begins to act as a dam, failure can occur in one of several ways. If the road grade dips into and rises out of the crossing, the failure is likely to be limited to a localized overtopping of the stream crossing. However, if the road grades away from the crossing in one or more directions, the flow may be diverted down the road and ditch and onto adjacent hillslopes, where it can cause gullying and/or landsliding (Furniss et al. 1998, Best et al. 1995). In these situations, volumes of sediment far exceeding those at the crossing can be at risk. GRAIP addresses this issue by classifying the potential for stream crossings to divert streamflow down the adjacent road as: no potential, potential to divert in one direction, or potential to divert in two directions. In the Lights Creek and Indian Creek watersheds, 115 of 469 stream crossings (25%) had the potential to divert in one or more directions. Bridges and fords had no diversion potential.

There were 3.4 km (2.1 mi, 0.5% of all road inventoried) of road lines with active stream flow diverting along the road with 14 Mg/yr of fine road surface sediment production, and 11 Mg/yr of fine sediment delivery, or 3% of all fine road surface sediment delivery. Delivery was routed through 45 drain points (0.5% of all drain points), 38 of which were connected, and most of which (68%) are stream crossings. Because stream flow diversion carries highly unpredictable risk of creating gullies, landslides and large volumes of erosion, and that connectivity of drain points which route diverted flow was high, these road segments and drain points are good candidates for risk reduction treatments. See Appendix B, Maps 12a and 12b for locations of road lines and drain points by type and connectivity routing diverted stream flow.

The highest risk crossings in the Lights Creek and Indian Creek watersheds were high risk in all three stream crossing risk areas (high SBI, more than 100 m^3 [160 Mg], of fill at risk, diversion potential in one or both directions). There were five crossings with an SBI of 3 and more than 100 m^3 of fill at risk, but no diversion potential (Figure 33). There were two crossings with both a high SBI and the potential to divert streamflow. Both had more than 100 m^3 of fill at risk. These two crossings had the highest combined stream crossing risk and are good candidates for risk reduction treatments. Non-system roads presented similar risks as crossings in the entire study. Of 61 stream crossings, 12 had culverts in place. Of those with culverts, five had an SBI=3, three had failing culverts in place, and five had diverted stream flow.

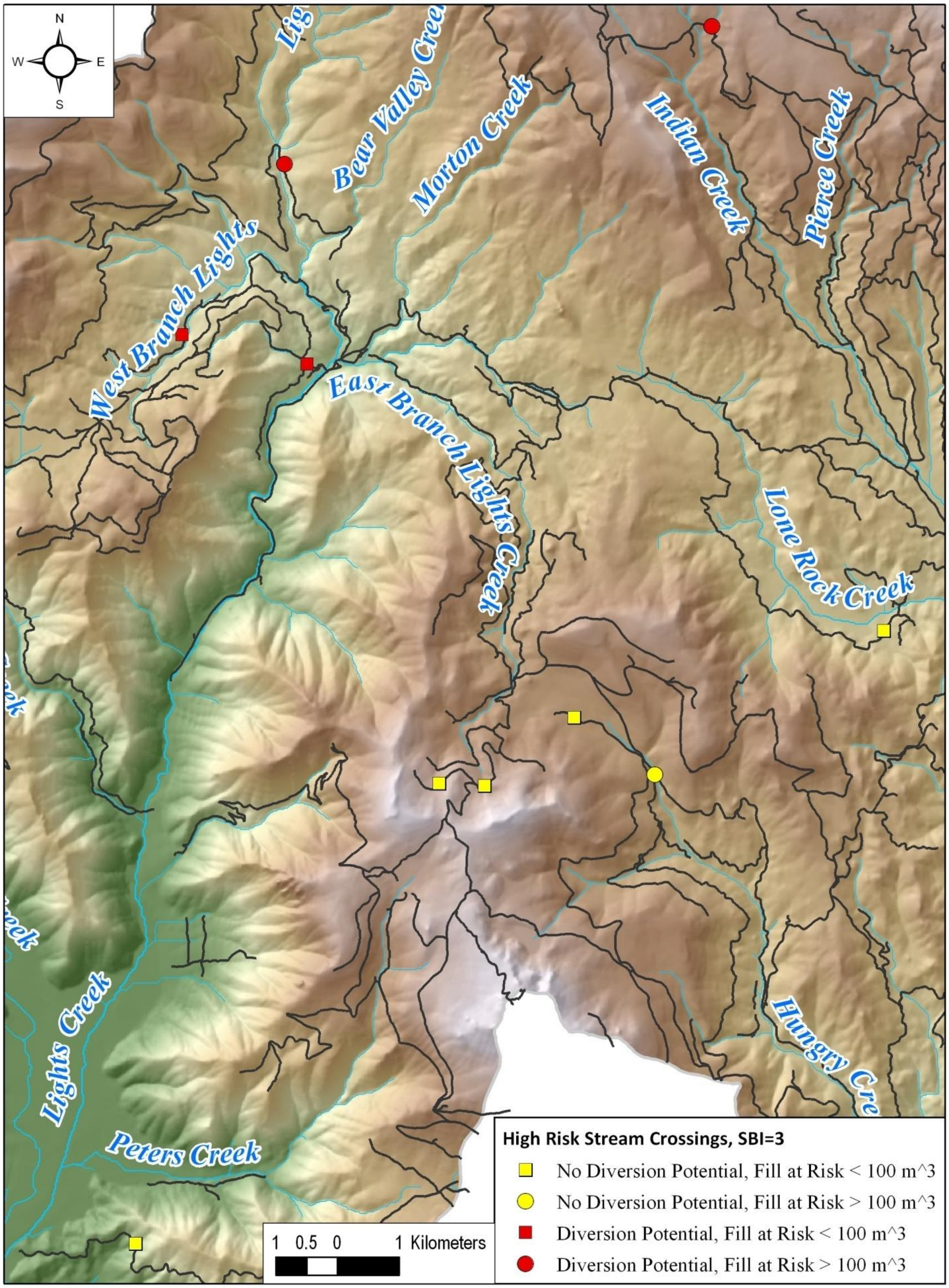

Figure 33. The stream crossings with the highest risk of plugging and the most severe consequences of failure in the Lights Creek and Indian Creek watersheds. Extent includes all qualifying crossings in the study.

4.7 Drain Point Condition and Fill Erosion

The GRAIP inventory assessed the condition of each drain point and a determination of how well it was performing its intended function. Problems with drain point condition were pre-defined for each drain type. Broad based dips were considered to be in poor condition if they did not drain due to insufficient outslope, or ponded water on the road. Ditch relief culverts were defined to be in poor condition if they had more than 20% occlusion within the pipe or was totally buried by sediment, significant rust, substantial inlet crushing, flow around the pipe, or had a drop at the outlet of greater than one foot high. Ditch lead-offs were considered problematic if they had excess deposition or gullying. Non-engineered features were almost always a problem due to a diverted flow path, blocked ditch, gully, broken outside berm or fill erosion, but were not considered problematic if they occurred due to an outsloped road and did not have any fill erosion. Stream crossing culverts were considered a problem if the pipe inlet was partially or totally blocked by sediment or wood, or crushed; if the pipe was rusted significantly; if due to inlet plugging, flow scoured or washed out fill, or flowed around the pipe; or had a high SBI, or moderate SBI with diversion potential (see previous section for more detail on SBI and diversion). Waterbars that were damaged, under-sized, or did not drain properly were defined as problematic. Sumps were a problem if they ponded water on the road surface or caused saturated fill. Diffuse drains (outsloped or well vegetated roads) were rarely observed to have problems. Excavated stream crossings were a problem if side slopes were eroded. Figure 34 shows number of drain point problems by drain point type.

Table 13. *Drain point condition problems and fill erosion below drain points, Lights Creek and Indian Creek watersheds.*

		Problems		**Site Fill Erosion at Drain Point**		**Road Surface Gully Contribution to Drain Point**	
Drain Type	**Count**	***Number***	***% of Total DP Type Count***	***Number***	***% of Total DPs with Erosion***	***Number***	***% of Total DPs with Erosion***
Broad Based Dip	2,598	220	9%	9	2%	26	26%
Diffuse Drain	554	0	0%	3	1%	0	0%
Ditch Relief Culvert	2,289	912	40%	105	28%	27	27%
Lead Off Ditch	349	9	3%	3	1%	3	3%
Non-Engineered	2,156	1,243	58%	198	54%	32	32%
Stream Crossing	469	65	14%	41	11%	7	7%
Sump	20	1	5%	0	0%	0	0%
Waterbar	1,074	55	5%	12	3%	4	4%
Excavated Stream Crossing	27	3	11%	0	0%	0	0%
All Drains	**9,536**	**2,508**	**26%**	**371**	**100%**	**99**	**100%**

Within the Lights Creek and Indian Creek watersheds, 26% of all drain points (2,508 of 9,536) had one or more problem of some type (Table 13; Figure 34; Appendix B, Maps 11a and 11b). Non-engineered drain points had the highest rate of problems (1,243 of 2,156, 58%), followed by ditch relief culverts (912 of 2,289, 40%). 14% of stream crossings had problems (65 of 469). Other drain point types had far fewer problems. Diffuse road segments (554 features total) did not have any problems.

Table 14. *Fill erosion below drain points, volumes and masses, Lights Creek and Indian Creek watersheds.*

Drain Type	Site Fill Erosion Mass Produced (Mg)	Site Fill Erosion Mass Delivered (Mg)	Road Surface Gully Mass Produced	Road Surface Gully Mass Delivered	Total Mass Sediment Produced (Mg)	Total Mass Sediment Delivered (Mg)	% of Total Mass Delivered	Average Delivery Rate Over 20 Years (Mg/yr)
Broad Based Dip	68	64	81	18	149	82	4%	4
Diffuse Drain	1	0	0	0	1	0	0%	0
Ditch Relief Culvert	131	20	124	21	255	41	2%	2
Lead Off Ditch	23	0	3	0	26	0	0%	0
Non-Engineered	570	248	455	332	1,026	580	25%	29
Stream Crossing	1,525	1,522	71	71	1,596	1,593	69%	80
Sump	0	0	0	0	0	0	0%	0
Waterbar	72	29	24	0	97	29	1%	2
Excavated Stream Crossing	0	0	0	0	0	0	0%	0
All Drains	**2,390**	**1,883**	**759**	**442**	**3,149**	**2,325**	**100%**	**116**

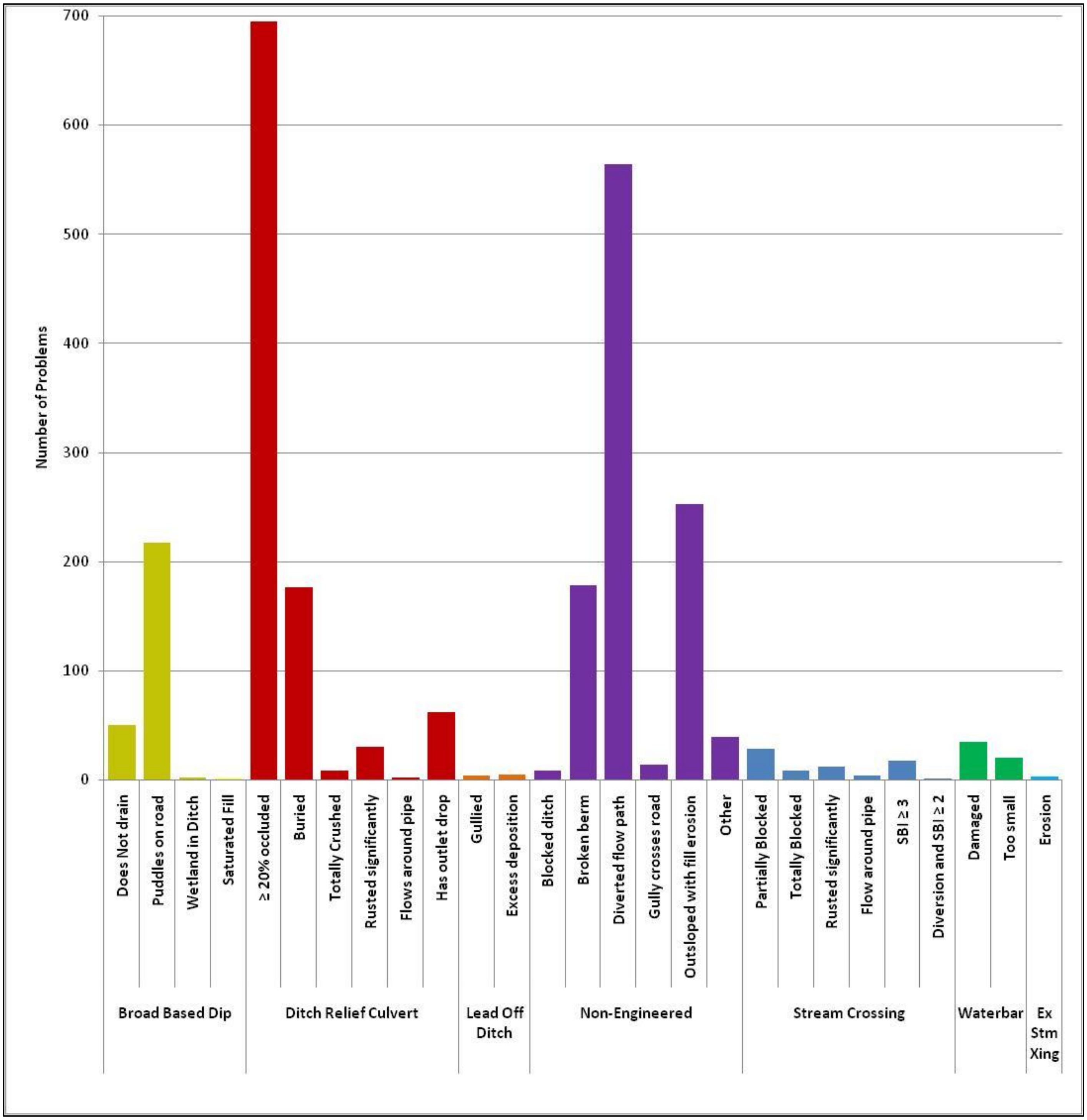

Figure 34. Number of problems by drain point type in the Lights Creek and Indian Creek watersheds.

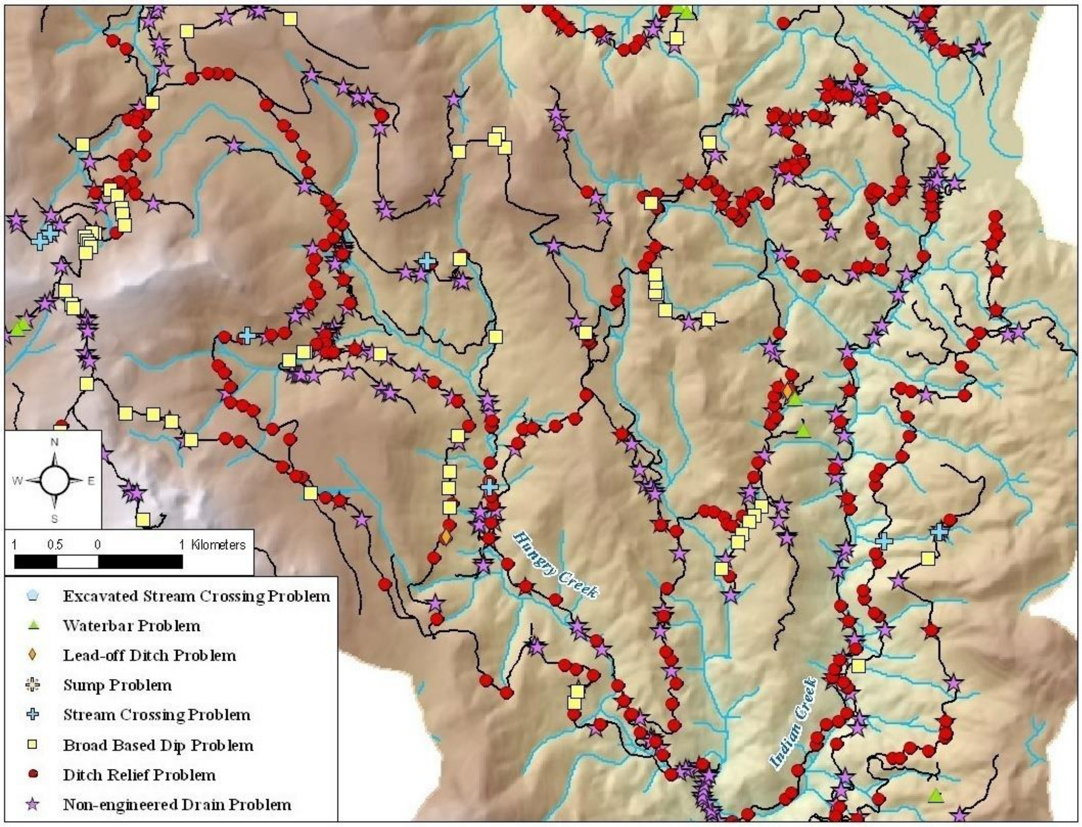

Figure 35. Locations of problems by drain point type in the southeast portion of Indian Creek watershed.

Fill erosion was present at 470 (5%) of all drain points, and produced a total of 1,970 m^3 (69,570 ft^3, 3,149 Mg; Table 14). Estimated total fill erosion sediment delivery was 1,453 m^3 (51,310 ft^3, 2,325 Mg), or about 74% of total fill erosion mass produced.

Two types of fill erosion were recorded at drain points. The first was site fill erosion that occurred within the fill at the location of the drain point site. The second was erosion generated from gullies within the road surface that was routed along the gullied road surface flow path to the drain point. Site fill erosion production was observed at 371 (4%) of all drain points (1,494 m^3, 52,760 ft^3, 2,390 Mg), and comprised 47% of total fill erosion produced. Road surface gully fill erosion production was observed routing to 99 (1%) drain points totaling 474 m^3 (16,740 ft^3, 759 Mg), and was 53% of total fill erosion produced.

Delivered site fill erosion sediment was 1,176 m^3 (41,530 ft^3, 1,883 Mg), or about 79% of all site fill erosion produced. Delivered road surface gully fill erosion sediment was 276 m^3 (9,750 ft^3, 442 Mg), or about 58% of all road surface gully fill erosion produced. Site fill erosion sediment delivered was about 81% of all fill erosion mass delivered, and road surface gully sediment delivered was about 19% of all fill erosion mass delivered.

Site fill erosion was most common at non-engineered drain points at 198 of 371 (54%) of non-engineered points eroding (356 m^3, 12,570 ft^3, 570 Mg). Fewer stream crossings (11%, 41 of 371) had fill erosion, but produced and delivered greater volume of fill erosion than all other drain point types. Stream crossings produced 953 m^3 (33,555 ft^3, 1,525 Mg) of eroded fill. Of that amount nearly all was delivered (951 m^3, 33,580 ft^3, 1,522 Mg), or about 81% of all site fill erosion delivered. Road surface gully erosion routed to nearly equal numbers of broad based dip, ditch relief culvert, and non-engineered drain points, but delivered the most sediment (203 m^3, 7,170 ft^3, 332 Mg) through non-engineered drain points.

Using the same approach as for landslides in Section 4.4, episodic fill erosion delivery was compared to annual road surface fine sediment delivery by averaging fill erosion delivery mass over a 20 year period. For all fill erosion mass delivered this was a rate of 116 Mg/yr, or roughly 0.3 times the fine sediment delivered from road surfaces. For site fill erosion and road surface gully fill erosion annual sediment delivery rate was estimated to be 94 Mg/yr, and 22 Mg/yr respectively, or about 0.3 times, and 0.7 times that of road surface fine sediment delivered, respectively. This mass of sediment may be pulsed (if the fill failure happens at once), chronic (if the fill gradually erodes), or pulsed and then chronic (initial failure, followed by more gradual erosion); it is unknown what proportion of this mass belongs to each category. Actual annual sediment delivery from fill erosion is likely higher or lower than these estimates in any given year.

Non-system roads present similar risks as crossings in the entire study. Of 61 stream crossings, 11 had eroding stream crossings with a total of 614 Mg of past eroded fill, and are likely to produce more. Of 20 excavated stream crossings, two are actively eroding.

Figure 36. Problems with ditch relief culverts. The left culvert is rusted through. The right culvert has an occluded inlet.

5.0 Comparison to Other Studies

The Geomorphic Road Analysis and Inventory Package (GRAIP) provides spatially explicit predictions of road-related sediment production, delivery, and accumulation within the road-stream network based on a detailed inventory of roads and drain points within a target watershed. To gain better understanding of the relative magnitude of sediment production and delivery in Lights Creek and Indian Creek watersheds, several useful comparisons were made to results from watershed studies in the same area, in the greater East Branch North Fork Feather River, and in other geologically similar areas. The most useful comparisons were base erosion rates derived from direct field collection of road surface sediment, percent delivery of road fine sediment produced, and annual sediment production and delivery rates normalized by area or by length of road. To normalize sediment production by area from road related sources alone, or including hillslope sediment sources, total mass from sediment sources produced annually for an area was divided by the area to get specific sediment with the units Mg/km^2 yr. To normalize sediment delivery by area from road related sources alone, or including hillslope sediment sources, total mass delivered annually to a point in the stream network was divided by total upstream watershed area to get specific sediment with the units Mg/km^2 yr. Annual sediment production or delivery from road related sources can be normalized by dividing by length of road from which the sediment was produced, and is expressed as Mg/km yr. This can be done for road fine sediment alone, or can include sediment contributions from road related gullies, landslides, and fill erosion. Where the mass of gullies, fill erosion, and landslides was included, the total mass was annualized over 20 years so that an annual production or delivery rate could be compared.

Several watershed and sediment production studies were available. Two studies in the Sierra Nevada on similar plutonic and volcanic soils in Sierra National Forest watersheds, and one GRAIP study in the Idaho batholith in the Boise National Forest provided comparisons of road related specific sediment production and delivery rates. Those three studies, plus four GRAIP studies in northern Idaho batholith, Columbia basalt, and Montana metasedimentary geologies provided a comparison of base erosion rates. Among the two Sierran, non-GRAIP studies, base erosion rates were derived from direct collection methods similar to GRAIP methods; therefore they were the most useful comparisons. For comparison of sediment delivery rates from road related sources in this study to regional background sediment delivery rates from all erosion sources including road and hillslope sources, two studies were available which used accumulated sediment in Antelope Reservoir to get specific sediment delivery rates for all watersheds above Antelope Lake including Boulder, Indian, and Lone Rock Creeks. Another study which looked at roads alone, as well as all sediment sources for the entire East Branch North Fork Feather River provides greater regional context.

The most basic comparison between studies was of base erosion rate. Refer to section 2.0 Objectives and Methods for a discussion of base erosion rates. The base erosion rates derived in Lights and Indian Creeks were 78 kg/yr/m for volcanic soils, and 30 kg/yr/m for granitic soils. These base erosion rates reflect one summer season of sediment measurements, and will change as more data are collected. Base erosion rates for Lights Creek and Indian Creek watersheds may adjust upwards if addition of production during winter seasons plays as large of a roll as production from summer thunderstorms. Coe (2006) showed production rates 3-4 times higher in one normal precipitation year compared to two dry years on established roads. Or they may adjust downwards, as the other longer term GRAIP (3-5 years) studies have, due to increased armoring of the road surface (Megahan and Kidd, 1972, Black and Luce 1999). The first year commonly produces higher rates due to the freshly disturbed surface from plot installation.

Compared with other studies, the base erosion rates in Lights Creek and Indian Creek watersheds were higher than studies with more stable geology, or where geology was similar but roads studied were older, more established, and experienced low traffic; and were very similar to studies done in areas with similar geology but the roads were well established, and the studies were conducted over longer periods and included wetter years. For the non-GRAIP studies in the Sierras, where geology was similar, but roads studied were more established, and the study included some wetter years (Stafford 2011, Coe 2006), base erosion rates on native roads for granitic soils were 44 kg/yr/m (Stafford 2011) and 35 kg/yr/m (Coe 2006), and 76 kg/yr/m (Coe 2006) for volcanic soils (calculated with data from NCASI 2008). The studies reported much higher sediment production for recently graded roads, for which surface type was more similar to the newly disturbed study plots in Lights and Indian Creeks. This similarity suggests Lights and Indian Creeks base erosion rates may be high, and may decrease as the study plots become more armored and established with time. In the Idaho batholith, similar granitic plutonic rock, the base erosion rate was 72 kg/yr/m over 6 years of sediment collection (Megahan and Kidd, 1972). It was considered a high rate because it was derived from newly constructed roads and includes mass wasting from roads. The following comparisons are to GRAIP studies. The base erosion rate for native roads from a study on Idaho Batholith granitic soils in Lightning Creek watershed in the Boise National Forest was 21 kg/yr/m. It was an average over 5 years. Similar road types on Columbia basalt in the East Fork Weiser River watershed in the Payette National Forest, Idaho, generated a base rate of 27 kg/yr/m over two years of study. These may be lower base erosion rates because they were derived from sediment collected on older, well established roads with low traffic. The lowest base erosion rates were from native roads on the more stable metasedimentary geology in the Lolo National Forest near Seeley Lake, Montana. Open roads with low traffic had a base rate of 14 kg/yr/m, and closed roads with minimal traffic had a base erosion rate of 1 kg/yr/m.

Lights Creek and Indian Creek watersheds were similar, or slightly lower in annual road fine sediment production and delivery by road length for native surfaces compared to studies conducted over three to six years in the Sierra Nevada (Coe 2006, Stafford 2011), and over one year in the Bear Valley watershed in the Idaho batholith (Fly 2010). Average sediment production in Lights Creek and Indian Creek watersheds was 4.3 Mg/km yr. Other Sierran values were 5.6 Mg/km yr (Coe 2006) and 13 Mg/km yr (Stafford 2011). The rate in the Idaho batholith was 12 Mg/km yr. The lower rate from Lights and Indian Creeks may be due to a base erosion rate derived from one summer season of sediment measurements, and the fact that the GRAIP average rate by road length is dividing sediment production from all road surface types by the entire road length, averaging all surface types rather than from native surfaces alone as in the other Sierran studies. When comparing native surfaces, the rates are much more similar. Coe (2006) reports 5.5 Mg/km yr, and this study, 5.6 Mg/km yr for native surfaced roads. However, when comparing rocked roads, this study is lower at 2.1 Mg/km yr, versus Coe's 6.0 Mg/km yr, possibly because this study applies a rocked surface factor to the base rate rather than measuring sediment production directly from rocked road plots as in Coe's study.

Sediment delivery rate by length of road from one Sierran study was 1.4 Mg/km yr (Coe 2006), and in the Idaho batholith was 1.0 Mg/km yr (Fly 2010), as compared with 0.54 Mg/km yr in the Lights Creek and Indian Creek watersheds. Percent delivery of road fine sediment produced in other studies was similar to that of Lights and Indian Creeks; 12%. In the Sierran studies it ranged between 3-30%, and in the Idaho batholith was 13%. Coe (2006) makes further reaching comparisons of percent road length connectivity. That study showed that 16% connected road length in Sierran granite was similar to that in the Idaho batholith, but far less than to that in wetter regions in northwest California (32%). The relatively lower connectivity in Lights and Indian Creeks may be due to the method for assessing delivery used in GRAIP surveys, and the dry climate in which the study was conducted.

The most similar, and direct comparison of road surface annual specific sediment production and delivery rates were to those from one GRAIP study in Bear Valley in the Idaho batholith (Fly 2010). Rates in Lights and Indian Creeks were 5.7 Mg/km^2 yr for fine road surface sediment production, and 0.68 Mg/km^2 yr for fine road surface sediment delivery. In the Idaho Batholith rates were 5.4 Mg/km^2 yr, and 0.45 Mg/km^2 yr respectively. If sediment from all road related gullies, landslides, and fill erosion is included for Lights and Indian Creeks, the rates were 97 Mg/km^2 yr for sediment production, and 8.1 Mg/km^2 yr for sediment delivery, a significant increase above fine road sediment alone. This was in sharp contrast to the Idaho Batholith in Bear Valley watershed where gully and landslide contributions were negligible. But the base erosion rate used in Bear Valley was a high rate derived from new road construction which included mass wasting contributions (Ketcheson and Megahan 1999, Megahan and Kidd 1972), so this comparison may indicate that the initial base erosion rates and resulting sediment production rates in Lights and Indian Creeks were also high.

The best comparison of specific sediment delivery rate from all road related sources in this study to regional sediment delivery rates was for watersheds contributing to Antelope Reservoir. Two studies surveyed total accumulated sediment trapped in the reservoir after its initial construction in 1965 (Anderson 1998, Gentry 1990). Both agreed very closely on annual specific sediment delivery rates for each of the contributing subwatersheds. 200 Mg/km^2 yr was reported for average specific sediment delivery rate to Antelope Reservoir from all sources of hillslope erosion. That included a small portion from subwatersheds not included in this GRAIP study. Average annual specific sediment delivery rate from all road related sources in subwatersheds to Antelope Reservoir in this GRAIP study was 3.0 Mg/km^2 yr, or about 1.5% of reservoir deposition rate.

One further comparison to regional erosion rates was to a study quantifying erosion from all sources, including roads, gullies, sheet erosion, and stream bank erosion for subwatersheds throughout the East Branch North Fork Feather River (USDA 1989). It reported for Lights Creek and Indian Creek watersheds an annual specific sediment production rate of 526 Mg/km^2 yr, and an annual specific sediment delivery rate of 337 Mg/km^2 yr for all sources including roads. Specific sediment production from all road related sources in this GRAIP study was 91 Mg/km^2 yr, or about 17% of regional erosion rate. Specific sediment delivery rate for from all sediment sources in this GRAIP study was 8.1 Mg/km^2 yr; or about 2% of regional sediment delivery rate. The East Branch North Fork Study reported subwatersheds to Antelope Reservoir as having the highest annual specific sediment delivery from all sources at 743 Mg/km^2 yr. Specific sediment delivery values from all sediment sources in Lights Creek, and Indian Creek (below Antelope Reservoir at its confluence with Lights Creek) were also high at 256 Mg/km^2 yr, and 389 Mg/km^2 yr, respectively. Specific sediment delivery for these subwatersheds from all road related sources in this GRAIP study were, 3.0 Mg/km^2 yr, 4.8 Mg/km^2 yr, and 1.1 Mg/km^2 yr, respectively. This is 0.4%, 2%, and 0.3% of regional delivery rate in each subwatershed, and reflects the wide range of variability in sediment production and delivery through the study area.

The East Branch North Fork study also examines road related sediment production and delivery. It shows road surfaces to be about 52% of all sources of hillslope erosion at 267 Mg/km^2 yr of specific sediment production, and 138 Mg/km^2 yr of specific sediment delivery. These were radically higher rates than within the GRAIP study area (5.7 Mg/km^2 yr, and 0.68 Mg/km^2 yr). This was likely due to different study methods. In the East Branch North Fork study, road sediment production and delivery rates were not directly measured. Instead, predetermined road base rates not derived from local measurements were applied to road surface and cutslope and fillslope areas, and the cutslope and fillslope areas were much greater than just the road surface as was used in GRAIP.

6.0 Summary and Conclusions

The Forest Service Rocky Mountain Research Station conducted a Geomorphic Roads and Inventory Package (GRAIP) study in the Lights Creek and Indian Creek watersheds in summer 2014 on 691 km (429 Mi) of Forest Service and private roads in Plumas National Forest. 74 km (46 mi) were non-system roads. 92 km (57 mi, 13%) of road length, and 1,154 (12%) drain points were hydrologically connected. 9.8 km (6.1 mi) of non-system road surfaces delivered sediment to streams, or about 14% of the whole study. Total annual fine road surface sediment delivery was estimated to be 347 Mg/yr (12% of all fine road sediment produced). Sediment delivery from 14 (18% of a total of 76) landslides observed was a total of 65,150 Mg (8%), or about 3,260 Mg/yr. Sediment delivery from 69 (41% of a total of 168) gullies at 168 drain points was 8,365 Mg (82%), or about 418 Mg/yr**.** Total fill erosion mass produced was 3,149 Mg. 74% of fill erosion produced delivered 2,325 Mg to the stream network, mostly at stream crossings, which was about 116 Mg/yr.

Source	**Production (Mg/yr)**	**% of total mass produced from all sources**	**Delivery (Mg/yr)**	**% of total mass delivered from all sources**
Road surface fines	2,920	6%	347	8%
Landslides	43,050	92%	3,260	79%
Gullies	510	1%	418	10%
Fill Erosion (including road surface gullies)	158	0.3%	116	3%
Total	**46,640**	**100%**	**4,140**	**100%**

Episodic risks such as landslide risk, gully risk, stream crossing failure risk, and fill erosion risk, were found to be generally moderate across the watershed, but delivered a significant mass to streams totaling about 17 times the total road-surface fine sediment annually. This level of risk was consistent with other regional GRAIP studies. Landslides delivered 9 times more than sediment from road surfaces.

Specific sediment production from all road related sources in this study was 91 Mg/km^2 yr, or about 17% of estimated regional sediment production rate from all hillslope erosion sources including roads. Specific sediment delivery rate from all road related sediment sources for the entire study area was 8.1 Mg/km^2 yr, or about 2% of estimated regional sediment production rate from all hillslope erosion sources including roads. Specific sediment delivery rate from all road related sources for subwatersheds contributing to Antelope Reservoir in this study was 3.0 Mg/km^2 yr, or about 1.5% of reservoir deposition rate from all hillslope erosion sources including roads.

The majority (74%) of drain points were broad based dips (27%), ditch relief culverts (24%), and non-engineered drain points (23%), but the bulk of the hydrologic connectivity occurred at stream crossings (41%). Within the study area, the probability of a drain point being stream connected increased sharply when drain points were within 150 m from a stream. This correlation was stronger within the fire perimeter with a sharper increase in probability of connectivity began where drain points were further, within 200 m from a stream. Road-stream hydrologic connectivity occurred at 12% of drain points, but the majority (90%, 336 Mg/yr) of delivered road surface fine sediment was through less than 5% of drain points. All delivering drain points are shown in Appendix B Maps 2a and 2b. The top 10 drain points that delivered the highest amount of road surface fine sediment delivered 3.5-7.6 Mg/yr per drain point. They are, in order from highest to lowest, one non-engineered drain in Upper Lights Creek on 28N02, two broad based dips on 27N57 and one ditch relief culvert on 27N09 in Hungry Creek, one ditch relief culvert on 28N17 in lower Pierce Creek, one non-engineered drain on 26N02 in the unnamed creek south of Peters Creek, two non-engineered drain points on 28N52 and 28N15 in upper Pierce Creek, one stream crossing on 26N30 in lower Lights Creek, and one stream crossing on 27N43B in upper Peters Creek.

The magnitude of sediment delivery routed through drain points corresponds well with high specific sediment values in stream channels, and portrays the streams with the highest road surface fine sediment impact. They are shown on Maps 5a and 5b in Appendix B. Road surface specific sediment was as high as 27 Mg/km^2 yr in stream segments in the upper reaches of some catchment basins. Stream segments with road surface specific sediment values higher than 5 Mg/km^2 yr were about 2% of total stream length. Streams with high road surface specific sediment values were Upper Peters Creek at high elevation where the majority of surface area was bare and there was mining activity, in Upper Indian Creek, in Pierce Creek, in the unnamed stream south of Peters Creek, the south branch of Hungry Creek, and West Lights Creek, and Upper Lights Creek.

Specific sediment depends on basin area and magnitude of annual total sediment delivery routed to a point along a stream, hence it tends to be elevated in locations where roads cross the stream headwaters. The road surface sediment component of the sediment budget increases as sediment production and percent connectivity increase. Road surface sediment production and delivery were controlled by several factors within the study area. Native surfaces that were rocky, rilled and/or eroded, or rutted produced and delivered the most fine road surface sediment and may continue to erode because the properties of eroded road segments such as that enabled them to become eroded remain. Investigating properties of eroded road segments (high slope, greater interception of flow, high drainage spacing and long effective segment length, less resistant material) could indicate which may most need to be altered to prevent further erosion of those road segments. Geology was a factor in fine sediment production. Volcanic lithologies had a base erosion rate about 2.6 times as granitic lithologies. Fewer roads were underlain by volcanic lithologies. Roads in volcanic lithologies were 128 km (80 mi, 18%) of road length, produced 554 Mg/yr (19%), and delivered 105 Mg/yr (30%). Roads in granitic lithologies were 563 km (350 mi, 82%) of road length, produced 2,366 Mg/yr (81%) and delivered 242 Mg/yr (70%). Though there was similar percent of total sediment production to percent of road total for each geology type, there granitic geology had a greater percent of all sediment delivered. Non-system roads generally had lower fine sediment production due to good surface vegetation cover and frequent drainage structures, but had a slightly higher percent sediment delivery rate than that of the entire study; 15% of all sediment produced by non-system roads was delivered vs. 12% for all roads. Any of these factors, or a combination thereof could be contributing to the areas with high roads to stream sediment impacts.

Specific sediment at the mouths of each major stream, from road surface sediment input alone was compared to specific sediment at the same point from all sediment sources (road surface, landslides, gullies, and fill erosion). Specific sediment at the stream mouths from all sediment sources increased dramatically over that for road surface inputs alone for some streams (Table 4). The greatest increases were at West Branch Lights (from 1.2 to 29 Mg/km^2 yr), Pierce (from 2.2 to 20 Mg/km^2 yr), the unnamed stream south of Peters Creek (from 2.5 to 5.1 Mg/km^2 yr), Upper Lights (from 0.72 to 4.2 Mg/km^2 yr), and East Branch Lights Creeks (from 0.56 to 3.8 Mg/km^2 yr). The increase in West Branch Lights Creek was mostly due to landside sediment. Increases in Pierce and Upper Lights Creeks were due to gully and landslide sediment. The increase in the tributary south of Peters Creek was due almost entirely to gully sediment. Increases East Branch Lights Creek were due to gully and fill erosion sediment. (See Appendix B, Maps 8a, 8b, 9a, and 9b).

The strongest predictors of landslide location within road fill were where roads traversed earthflow terrain, roads near streams, roads on steep terrain, and landslides associated with gullies. Underlying geology was not a strong predictor of where landslides occurred. The best SINMAP prediction of landslide location was for shallow landslides on hillslopes below roads rather than within the road prism or where roads traversed earthflow terrain. SINMAP prediction of increased slope instability risk correlated moderately to locations of observed landslides. The model predicted that of the 514 km^2 (199 mi^2) that comprise the Lights Creek and Indian Creek watersheds, 32 km^2 (12 mi^2, 6.2%) of the watershed has experienced an increase in SINMAP predicted landslide risk due to roads. 45% of total observed landslides occurred in areas predicted by SINMAP to have increased instability risk due to roads. After the Moonlight Fire, landslide occurrence in roads increases dramatically in deep seated earthflow terrain.

The largest delivering landslides occurred in earthflow terrain on the west end of road 28N03, the west end of 28N39, and east end of 28N19; associated with gullies at the north ends of 28N08 and 27N45; in steep terrain on the east end of western 28N03; and on roads near streams in the central portion of PC-213. Significant non-delivering landslides which close roads were on western 28N03, and in the center of 27N95 (see Appendix B, Maps 8a and 8b).

The frequency of gully occurrence was low for the study area at only 2% of all drain points, but the delivered mass is significant at 1.2 times greater than annual road surface fine sediment delivery. The critical gully initiation index (ESI_{crit}) was found to be 12, but was only a moderate predictor of gully occurrence. Gully occurrence rate increased from 1% below the critical gully initiation index to 3% above, so as contributing road length to, and hillslope slope below drain points increased, gully formation increased. Of 7,597 applicable drain points, 1,381 (18%) had an elevated risk of gullying. While gully occurrence was not the biggest concern in this area, delivery rate from gullies was high at 82%, and it can be managed for by designing road drainage with adequate drainage spacing to reduce contributing road length, and avoiding placing outlets onto steep slopes. For the average contributing road length for delivering road segments in this study of 80 m (260 ft), the drains would have to discharge onto hillslopes with less than 40% slope to remain below the ESI_{crit} value of 12. Road design which spaces drains more closely can position drain outlets on hillslope slopes greater than 40% (Table 12) without exceeding the ESI_{crit} of 12. Road design that must discharge onto steeper than 40% hillslopes should consider spacing drainage at less than 80 m (260 ft) of contributing road length. Road design with adequately placed drainage, or outsloped surfaces inhibits gully formation on road surfaces and in ditches, and can also significantly reduce sediment delivery.

Gullies in the study area occurred most frequently in areas with low vegetation cover as within the Moonlight Fire perimeter such as on steep slopes in West Lights Creek and the stream south of Peters Creek, and below drain points from paved, or regularly graded and highly compacted surfaces such as in Hungry and lower Indian Creeks. The 12 most significant active and delivering gullies with delivered mass greater than 100 Mg were in the following areas: Three were on 29N46 on the south end of the main paved road along lower Indian Creek; one on the west end and one on the far east end of 28N02; one on north 28N31 in Pierce Creek, one on 27N10 in the southwest part of the study area south of Peters Creek; one on central Hungry Creek road 27N09; one on the north end of an old, stream side non-system road 27N09-xxx; and two on eastern end of western 28N03. The area surrounding the triple confluence of West, East, and Upper Lights Creeks had extensive and large mining features that resemble gullies. Many of the old mining features were still bare of vegetation and had recent, active gullying, especially along 28N30, and 28N03 just east of the confluence. The area along 28N03 had two gullies active and delivering. Two not active, but delivering gullies were large and significant. One is the second largest gully and is associated with a landslide on 28N08 in the upper western portion of the study area. The other is the fourth largest gully and is on the very actively eroding, near stream non-system road 28N03-8. The gully was not active, but may reactive in large storm events. Gully density for the entire study area was 0.25/km (0.4/mi). Areas with the most significant gully densities were as follows:

Region	Road number	Density (#gullies/km)	Density (# gullies/mi)	Number of active and delivering gullies
Upper Lights Creek	28N03	1.9	3.0	3
West Lights Creek	28N39	1.5	2.4	7
Lone Creek	28N00	1.2	2.0	2
Lower Indian Creek	29N46	1.2	2.0	5
Unnamed south of Peters Ck.	27N10	0.9	1.5	2
Hungry Creek Road	27N09	0.7	1.2	4

352 of 469 (75%) stream crossings have culverts in place. Risk of culvert plugging by woody debris was evaluated using the Stream Blocking Index (SBI) that assigns a value from 1 to 4 based on pipe diameter to upstream channel width ratio, and skew angle between pipe

longwise direction and stream flow direction at the inlet. No stream crossings had an SBI of 4. 17 had an SBI of 3, 131 had an SBI of 2, and 204 had an SBI of 1. Though higher SBI indicates a higher probability of culvert plugging, blocking rate for partially or totally blocked or plugged culverts was 6% for SBI of 3, 2% for SBI of 2, and 7% for SBI of 1. The high blocking rate for crossings with an SBI of 1 could be due to impacts of fire which released large amounts of fine sediment in streams when wood burned in the channels, but this hypothesis is not confirmed. Stream crossing failure risk for all stream crossings with culverts, in terms of crossing fill volumes totaled 25,150 m^3 (32,900 yd^3, 40,240 Mg). Fill volumes ranged from 2 m^3 (3 yd^3, 3 Mg) to 810 m^3 (1,060 yd^3, 1,296 Mg), and had a mean volume of 54 m^3 (71 yd^3, 86 Mg). The largest stream crossing fill masses greater than 500 Mg were on 28N03 at Lone Rock Creek just about Antelope Lake and three at tributaries to East Lights Creek just upstream from the East Lights confluence with Lights Creek, on 29N46 at Hungry Creek, on 28N30 at Lights Creek, on 28N08 at a tributary to West Branch Lights Creek, on 27N95 at the main east branch of upper Cooks Creek, on 27N09 at lower Hungry Creek, and two on 28N31 at tributary to, and at upper Willow Creek.

There was diversion potential at 115 (25%) of stream crossings. 3.4 km (2.1 mi, 0.5% of all road inventoried) of road lines had active stream flow diverting to 45 drain points (0.5% of all drain points). These road segments were estimated to have delivered 11 Mg/yr of fine sediment delivery, or 3% of all fine road surface sediment delivery, through 38 drain points, most of which (68%) are stream crossings. Because stream flow diversion carries highly unpredictable risk of creating gullies, landslides and large volumes of erosion, and that connectivity of drain points which route diverted flow was high, these road segments and drain points are good candidates for risk reduction treatments. See Appendix B, Maps 12a and 12b for locations of road lines and drain points by type and connectivity routing diverted stream flow. Roads with stream flow diversion of high sediment delivery greater than 100 Mg/yr are at three drain points on non-system road 27N51-Lucky near Lucky Mine in upper Peters Creek, at a stream crossing on non-system road 28N30B-2 in upper West Branch Lights Creek, at a stream crossing on trail TR10M41 in Cooks Creek, at a stream crossing on non-system road 26N42-5 and a stream crossing on 26N02 in the upper reaches of a main tributary to lower Indian Creek, at a stream crossing on the non-system, old relict road up East Lights Creek gorge, at a lead off ditch on 28N30D in upper Moonlight Creek, at a stream crossing and broad based dip on 28N40 in Lights Creek just below the confluence of East Lights Creek, at two stream crossings on non-system road 28N03-8 in East Lights Creek, at an excavated stream crossing on 28N19D in upper Pierce Creek, and at a stream crossing on 28N35 in upper Willow Creek.

The highest risk crossings in the Lights Creek and Indian Creek watersheds are high risk in all three stream crossing risk areas (high SBI, more than 100 m^3 of fill at risk, diversion potential in one or both directions). There are five crossings with an SBI of 3 and more than 100 m^3 of fill at risk, but no diversion potential (Figure 33). There are two crossings with both a high SBI and the potential to divert streamflow. Both have more than 100 m^3 of fill at risk. These two crossings have the highest combined stream crossing risk and are good candidates for risk reduction treatments.

Non-system roads presented similar risks as crossings in the entire study. Of 61 stream crossings, 12 had culverts in place. Of those with culverts, five had an SBI=3, three had failing culverts in place, and five had diverted stream flow. The 7 culverts with the worst problems, in order of worst to least problems, were on non-system roads 28N03-8, which was washed out around a 36 inch culvert with a large volume (85 m^3, 136 Mg) of fill remaining; 27N16Y-3 which had two with 24 inch pipes, one of which was undersized and eroding, and one with a 36 inch pipe on a perennial stream; 28N17A-2 with two, one of which was plugged; TR11M36 which had undercut fill; 28N23-5 which was buried; 29N46-4 which was overtopped; and 26N30-2 which was washed out. Non-system roads with culverted stream crossings with no problems were on 27N07-8, 28N52-1, 28N02-1, and 27N45-2A.

The highest risk crossings in the Lights Creek and Indian Creek watersheds were high risk in all three stream crossing risk areas (SBI of 3, more than 100 m^3 [160 Mg], of fill at risk, diversion potential in one or both directions). There were five crossing with SBI of 3, fill less than 100m^3 and no diversion potential and they were on 27N09C in upper Hungry Creek, 27N57 and 27N57B in upper East Lights Creek, 27N10 in Peters Creek, and 28N00 in Lone Rock Creek. There was one crossing with an SBI of 3 and greater than 100 m^3 of fill at risk, but no diversion potential (Figure 33), and it was on 27N09 at Hungry Creek. There were two crossings with SBI of 3, greater than 100 m^3 of fill at risk, but no diversion potential on 28N39 along West Lights Creek, and on 28N40 at a tributary to Lights Creek below the West Lights confluence. There were two crossings with both a high SBI and the potential to divert streamflow, and with 100 m^3 of fill at risk. These two crossings have the highest combined stream crossing risk and are good candidates for risk reduction treatments. They were on 28N03 near upper Lights Creek, and on 28N02 in upper Indian Creek.

Drain point problems were observed at 26% off all drain points, the majority of which were at non-engineered drains (58%) and ditch relief culverts (40%). Drain point problems are problems with road infrastructure and the most common types of problems were ditch relief culverts greater than 20% occluded or buried, non-engineered drains from diverted flow paths, and non-engineered drains that were outsloped with eroded fill. See Table 13, Figure 34, and Maps 11a and 11b in Appendix B for types and locations of drain point problems.

Total fill erosion mass produced was 3,149 Mg. Mass produced from stream crossings was 1,600 Mg, and from non-engineered drain points was 1,026 Mg. Mass of fill erosion at drain points that were connected to the stream channel network totaled 2,325 Mg, or 74% of all fill erosion produced. Most fill erosion delivery occurred at stream crossings (1,593 Mg); 69% of all fill erosion sediment delivered at drain points. Nearly half of stream crossing fill erosion produced and delivered was from one failing stream crossing on 28N03-8 that had 673 Mg of past, delivered fill erosion, and about 140 Mg of fill remaining around a washed out culvert. Fill erosion mass delivered from non-engineered drain points was 580 Mg, or 25% of all fill erosion delivered.

Non-system roads had a similar rate of drain problems. Eleven had eroding stream crossings with a total of 614 Mg of past eroded fill, and are likely to produce more. Of 20 excavated stream crossings, two are actively eroding. Several roads stand out that pose continuing risk of sediment delivery. Stream side roads which present the most risk in order from worst to less worse are: 28N03-8, PC213-17, 28N40-1, East Branch Lights Gorge, 28N17-1, 27N09-XXX, 28N03-114, 28N03-115, 29N46-4, and 28N17-2. Roads with culverted stream crossings in order from worst to less worse problems are: 28N17A-1 has 2, and 12M19. Those with active fill erosion are 214P, 26N02-7, 26N02-8, 27YN09-XXX, 27N10-14. 28N30-4 had notable diversion.

In general, chronic sedimentation risks such as road surface-derived fine sediment delivery in the Lights Creek and Indian Creek watersheds were found to be high compared to studies across the western United States, but similar compared to other regional and geologically similar study areas. The risk of episodic landsliding, gullying, and stream crossing failure was found to be moderate across these watersheds. These levels of hydro-geomorphic risk are consistent with other regional GRAIP studies. It is worth noting that these episodic risks are likely to have some potentially significant component of chronic sediment input after the initial event. This GRAIP study records a snapshot in time of existing geomorphic evidence observable in the field at the time of study, and therefore reflects a short term view of the geomorphic and hydrologic conditions. It may not represent long term, average sediment production and delivery rates.

GRAIP is a thorough and detailed survey of road related sediment sources and the conditions of road infrastructure in the Lights Creek and Indian Creek watersheds. The results presented here are an overview and but a few of the analyses possible. The data are in GIS shapefile format and can be used in a myriad of combinations to answer many questions and guide a wide range of management decisions.

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Appendix A: Glossary of Selected Terms

Below is a list of terms, mostly of drainage point types, but also of some other commonly used terms, for the purpose of clarification. Adapted from Black, et al. (2011), Fly, et al (2010), and Moll (1997).

Broad based dip*. Constructed:* Grade reversal designed into the road for the purpose of draining water from the road surface or ditch (also called dip, sag, rolling grade, rolling dip, roll and go, drainage dip, grade dip). ***Natural:*** A broad based dip point is collected at the low point where two hillslopes meet, generally in a natural swale or valley. This is a natural low point in the road that would cause water on the surface of the road to drain out of the road prism.

Cross drain. This is not a feature collected specifically in GRAIP, and it can refer to a number of other drainage features. It is characterized by any structure that is designed to capture and remove water from the road surface or ditch. Ditch relief culverts, waterbars, and broad based dips can all be called cross drains.

Diffuse drain. This is a point that is characterized by a road segment that does not exhibit concentrated flow off the road. Outsloped roads or crowned roads often drain half or all of the surface water diffusely off the fillslope. Although collected as a drain point, this feature is representative of an area or a road segment rather than a concentrated point where water is discharged from the road prism. A drop of water that lands on a diffuse road segment will not flow down the road or into the ditch, but more or less perpendicular to the centerline off the road surface and out of the road prism. Also called sheet drainage or inter-rill flow.

Ditch relief culvert. This drain point is characterized by a conduit under the road surface, generally made of metal, cement, or wood, for the purpose of removing ditch water from the road prism. This feature drains water from the ditch or inboard side of the road, and not from a continuous stream channel.

Flow path. This is the course flowing water takes, or would take if present, within the road prism. It is where water is being concentrated and flowing along the road from the place where it enters the road prism, to where it leaves the road prism. This can be either on the road surface, or in the ditch.

Lead off ditch. This drain point is characterized by a ditch that moves flow from the roadside ditch and leads it onto the hillslope. Occurs most often on sharp curves where the cutslope switches from one side of the road to the other. Also known as a daylight ditch, mitre drain, or a ditch out (though this term can also describe other types of drainage features).

Non-engineered drainage. This drain point describes any drainage feature where water leaves the road surface in an unplanned manner. This can occur where a ditch is dammed by debris, and the water from the ditch flows across the road, where a gully crosses the road, where a wheel rut flow path is diverted off the road due to a slight change in road grade, or where a berm is broken and water flows through. This is different from a diffuse drain point, which describes a long section of road that sheds water without the water concentrating, whereas this point describes a single point where a concentrated flow path leaves the road.

Orphan drain point. This is any drain point that does not drain any water from the road at the time of data collection. Examples include a buried ditch relief culvert, or a water bar that has been installed on a road that drains diffusely.

Stream crossing. This drain point is characterized by a stream channel that intersects the road. This feature may drain water from the ditch or road surface, but its primary purpose is to route stream water under or over the road via a culvert, bridge, or ford. A stream for the purposes of GRAIP has an armored channel at least one foot wide with defined bed and banks that is continuous above and below the road and shows evidence of flow for at least some part of most years.

Sump. ***Intentional:*** A closed depression where water is intentionally sent to infiltrate. ***Unintentional:*** Any place where road water enters and infiltrates, such as a cattle guard with no outlet, or a low point on a flat road.

Waterbar. This drain point is characterized by any linear feature that is perpendicular to the road that drains water from the road surface and/or ditch out of the road prism or into the ditch. Waterbars may be constructed by dipping the grader blade for a short segment, or adding a partly buried log or rubber belt across the road. Some road closure features may also act as a waterbar, such as a tank trap (also known as a closure berm or Kelly hump). Cattle guards that have an outlet that allows water to flow out are also considered to be water bars. These features may also be known as scratch ditches if they drain water into the ditch.

Appendix B: Additional Maps

Larger-scale maps (11” x 17”) were created that show risk distributions across the entire Lights Creek and Indian Creek watersheds. Additionally, poster-scale maps are available. Where there are maps a and b, a is the western portion of the study area, and b is the eastern portion. Where there are maps a through d, a is the southwest and the others follow clockwise.

List of Maps

Maps 1a, 1b: Road Segments Within 50 Feet of Streams.
Maps 2a, 2b: Sediment Delivery by Drain Points
Maps 3a, 3b: Sediment Delivery by Road Lines
Maps 4a, 4b: Sediment Accumulation in Streams
Map 5a, 5b: Specific Sediment in Streams
Maps 6a, 6b: SINMAP Natural Predicted Landslide Risk, Calibrated
Maps 7a, 7b: SINMAP Predicted Landslide Risk
Maps 8a, 8b: Landslides by Mass and Delivery
Maps 9a, 9b, 9c, 9d: Erosion Sensitivity Index and Gullies
Maps 10a, 10b: Stream Blocking Index
Maps 11a, 11b: Drain Point Problems
Maps 12a, 12b: Streamcourse Flow on Road Lines and to Drain Points