University of Nevada, Reno

Geomorphic Assessment of Natural and Anthropogenic Sediment Sources in an Eastern Sierra Nevada Watershed

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Hydrology

by

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Signature Page

Abstract

Squaw Creek, a small (21.1 km^2), subalpine watershed located approximately 9.6 kilometers northwest of Lake Tahoe, California between the towns of Tahoe City and Truckee, is listed as an impaired waterway for excessive non-point source sedimentation under section 303(d) of the Clean Water Act. The watershed was evaluated from a geomorphic perspective to identify and characterize sources of sediment and sediment transport processes, quantify rates of hillslope and in-stream erosion, and assess the relative degree of impact of both natural and anthropogenic sediment sources on sediment delivery to the stream network.

Calculated hillslope erosion rates show that the principal sources of sediment are related to land use impacts. Roads in the watershed contribute to sediment production by concentrating runoff which increases sediment load to the stream network. Most unimproved (dirt) roads connect either directly or indirectly with streams and therefore act as extensions of stream networks by effectively increasing watershed drainage density and subsequently sediment loads to streams. Geographic Information System modeling indicates that hillslope erosion susceptibility has increased in the watershed since 1939 as a result of land use impacts.

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1. INTRODUCTION

Erosion from hillslopes and streams is of significant concern throughout the world. Soil erosion leads to soil degradation, diminished aquatic habitat and drinking water quality through the delivery of elevated levels of sediment into streams and decreased sustainable forest habitat through loss of topsoil (Garcia-Oliva et al. 1995). Monitoring of potential and existing eroding hillslope areas is therefore highly desirable in order to identify problems and management solutions.

Naturally functioning riparian zones are recognized as critical features in the landscape for maintenance of biodiversity and geomorphic processes, and may be severely impacted by elevated hillslope and in-stream erosion. Conversely, degraded riparian zones generally lead to stream bank erosion and problems related to increased sediment load. Throughout North America and Europe, more than 80% of riparian corridors have disappeared in the last 200 years (Hupp 1999). The 1992 National Water Quality Inventory of rivers states that only 56 percent of streams fully supported multiple uses, including drinking water supply, fish and wildlife habitat, recreation, and agriculture, as well as flood prevention and erosion control. In the remaining 44 percent of stream miles inventoried, sedimentation and excess nutrients were the most significant causes of degradation (FISRWG 1998). An assessment of sedimentation problems resulting from soil erosion within watersheds and streambanks that have been altered to suit the needs of society can provide a useful framework from which to develop land management strategies in order to reduce or mitigate disturbance impacts.

Regionally, state and federal regulatory agencies are in the process of identifying degraded streams and associated land management issues. Squaw Creek has been listed as impaired by sedimentation under section 303(d) of the federal Clean Water Act by the State of California because of its high sediment production and turbidity levels relative to other tributary watersheds to the Lower Truckee River. The Desert Research Institute (DRI) was contracted by the State of California Lahontan Regional Water Quality Control Board (LRWQCB) to conduct a sediment source assessment of the Squaw Creek watershed as a result of the stream's relative prominence as a sediment supplier to the Lower Truckee River. This thesis was conducted as part of DRI's sediment source assessment and focused on contributions from hillslope and in-stream sources to sediment supply.

1.1 Purpose and Objectives

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

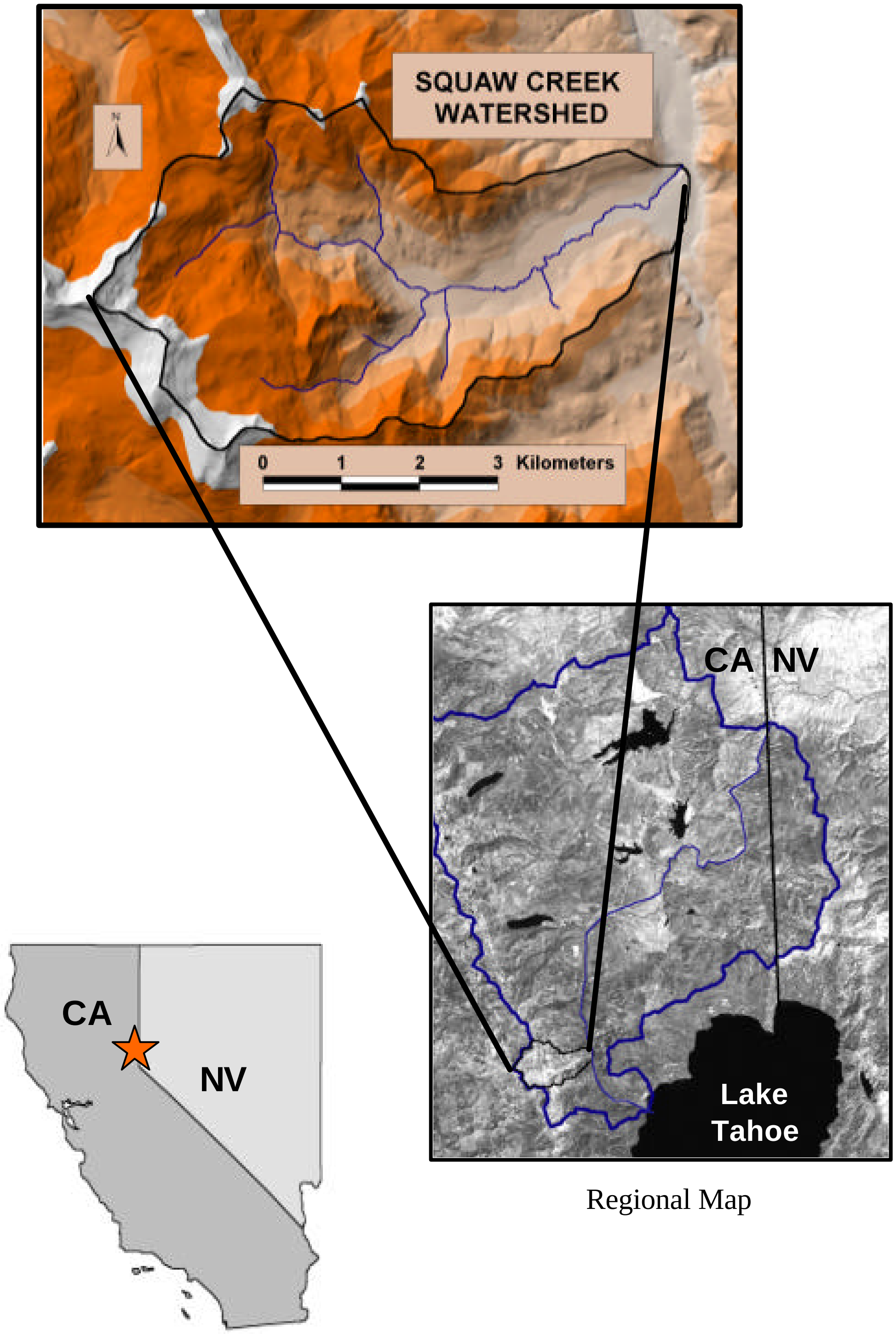
(1) Conduct a watershed scale geomorphic process-response analysis;
(2) Qualitatively and quantitatively analyze hillslope and in-stream erosion and storage;
(3) Evaluate the influence of land use and cover on sediment supply and transport processes.

The watershed scale geomorphic process assessment included analysis of drainage basin morphometric characteristics and parameters, such as drainage frequency and density, basin shape, longitudinal profiles, and the development of hypsometric curves. Geomorphic processes and sediment movement are influenced by climate, geology, soils, and vegetation. Therefore utilizing direct field measurements, a

Geographic Information System (GIS), and reconnaissance of geomorphic attributes, a qualitative and quantitative assessment of the spatial and temporal variability of these factors was completed. Historic and present-day erosion susceptibility models were then created by compiling field and morphometric data to aid in the assessment of land use and land cover influences on sediment sources. The models were developed utilizing a GIS, field investigations, and modified published methodologies (e.g., Dietrich et.al, 1989; Walling, 1983; Reid and Dunne, 1996; Oguchi, 1997), to identify and characterize natural and anthropogenic influences on sediment production, transport, and storage in the basin.

2. ENVIRONMENTAL SETTING

Squaw Creek, a tributary of the Lower Truckee River, is a small (21.1 km^2 [8.2 square miles]), subalpine watershed located approximately 9.6 km (6 miles) northwest of Lake Tahoe in Placer County between the towns of Tahoe City and Truckee (Figure 1) on the Tahoe City and Granite Chief 7.5 Minute Quadrangles. Elevation of the watershed ranges from 2,745 m (9,006 ft) at the highest point to 1,865 m (6,120 ft) at the confluence of Squaw Creek and the Truckee River. Squaw Creek consists of a main, low-gradient trunk that is formed from the confluence of two primary forks in the north and south subwatersheds in the western portion of the watershed, as well as numerous first through third order streams feeding into the main channels. As is typical of many Sierra Nevada high altitude environments, precipitation in the Squaw Creek watershed is primarily in the form of snow, with some minor thunderstorm activity occurring during the summer and fall. Therefore, snowmelt runoff and rain-on-snow events are the primary climatic drivers of surface water hydrology (e.g., peak flows) and sediment



Regional Map

Figure 1. Location map of the Squaw Creek watershed. Blue outline on regional map represents the Lower Truckee River watershed boundary.

movement within the watershed and occur mostly during late spring and early summer. The main channels of the stream generally maintain base flow throughout the year, although during dry years base flow may be minimal or subsurface.

2.1 Climate

The climate of the Squaw Creek watershed is characterized by varied microclimatic weather patterns within the basin. Average daily temperature ranges from a minimum of -1°C (30°F) to a maximum of 13°C (56°F) (WRCC, 2001). Summer average daily temperatures range from 24°C to 27°C (75°F to 80°F). Typical minimum temperatures during winter months range from -9.4°C to –6.7°C (15°F to 20°F) and are rarely below –18°C (0°F). Winds are predominantly from the west and occasionally from the south.

Hecht and Jett (1988) report that the mean annual precipitation measured at the Squaw Valley Fire Station is approximately 143 cm (56 inches) on the valley floor and is primarily in the form of snow. Long-term average annual snowfall is about 500 cm (200 inches). At elevations above 2,100 m (7,000 feet), average annual snowfall may reach 610 cm (240 inches). Precipitation in the form of snow accounts for approximately 50% of the total winter precipitation at low altitudes (below 2,400 m [7,900 feet]) and 90% of the winter total for higher altitudes (above 2,400 m [7,900 feet]), with snow accumulations being greatest on north-facing slopes (Nolan and Hill, 1991). During periods outside of the winter season, precipitation amounts are relatively small, resulting from infrequent summer convective thunderstorms (JARA, 1975).

2.2 Geology and Geomorphology

The Squaw Creek watershed is a typical sub-alpine drainage that has been affected by glacial erosion and deposition and subsequent post-glacial geomorphic processes that have exerted great influence on the relief and topographic character of the area. The lithology, vegetation, and morphometry of the watershed reflect the geologic and geomorphic processes, including glacial activity and volcanism, which have occurred throughout the formation of the Sierra Nevadas (Birkeland, 1961; Nolan and Hill, 1991). The geology is composed principally of Lower Jurassic metasedimentary and metavolcanic rocks (Tr-Jr), Cretaceous intrusive granitic rocks of differing composition (mostly diorite and granite; Kg), and Late Tertiary (Pliocene) basaltic andesite and pyroclastics (Ta) (Figure 2). Quaternary surficial geologic units are comprised of glacial deposits (lateral and terminal moraines), colluvial and alluvial fans at the intersection of the valley side slopes and the meadow, and fluvial deposits in meadow portions of the creek (Birkeland, 1961; Birkeland, 1962; Birkeland 1963). Table 1 shows the relative percentages of geologic units in the watershed.

North and northwestern trending faults are prevalent throughout the Tahoe-Truckee area and have been mapped in the central portion of the Squaw Creek watershed. These faults separate the granitic units from the younger volcanics and have vertically displaced and offset the granitic bedrock and the volcanic Pliocene rocks (Saucedo and Wagner, 1992; Hecht and Jett, 1988).

<u>Granitic rock units</u> – Cretaceous granite and granodiorite (Kg) are exposed in the western portion of the watershed encompassing the north fork and south fork of Squaw Creek, providing the bedrock over which much of the streams flow. The exposed

granodiorite and granite outcrops in the Squaw Creek basin are portions of the Sierra Nevada batholith (known as the Sierra Nevada). Granitic rocks underlie approximately 37% of the overall watershed. Granitic rock represents approximately 63% of the north fork and 40% of the south fork sub-basin bedrock, respectively.

Table 1. Relative percentages of geologic units in (a) Squaw Creek watershed, (b) north fork of Squaw Creek, and (c) south fork of Squaw Creek.

	(a) Squaw Creek [A = 21.1^2 km]		**(b) North Fork** [A = 9.3 km^2]		**(c) South Fork** [A = 4.7 km^2]	
Geologic Map Unit	**Area km^2 (mi^2)**	**Area (%)**	**Area km^2 (mi^2)**	**Area (%)**	**Area km^2 (mi^2)**	**Area (%)**
Granite (Kg)	7.8 (3.0)	37	5.9 (2.3)	63	1.9 (0.7)	40
Andesite (Ta)	7.2 (2.8)	34	3.1 (1.2)	33	1.9 (0.7)	40
Metamorphic Rocks (Tr-Jm)	0.3 (0.1)	1	0.3 (0.1)	3	--	--
Glacial Deposits	4.2 (1.6)	20	--	< 1	0.8 (0.3)	17
Valley Fill Alluvium (Qal)	1.1 (0.4)	5	--	< 1	--	< 1
Alluvial Fans (Qf)	0.2 (0.1)	1	--	--	--	--

Volcanic rock units – The volcanic rocks are comprised predominantly of highly weathered andesitic breccias and mixed pyroclastics and andesitic flows (Birkeland, 1961; Saucedo and Wagner, 1992). These units typically form resistant ledges and prominent cliff faces and palisades, as can be seen on the southern side of the watershed near Squaw Peak (Figure 3). The volcanic rock units near the Watson Monument marking the emigrant pass, have a characteristic volcaniclastic texture that also form rugged cliffs which can cast off large amounts of weathered coarse and fine-grained debris. Volcanic rocks underlie approximately 34% of the watershed.

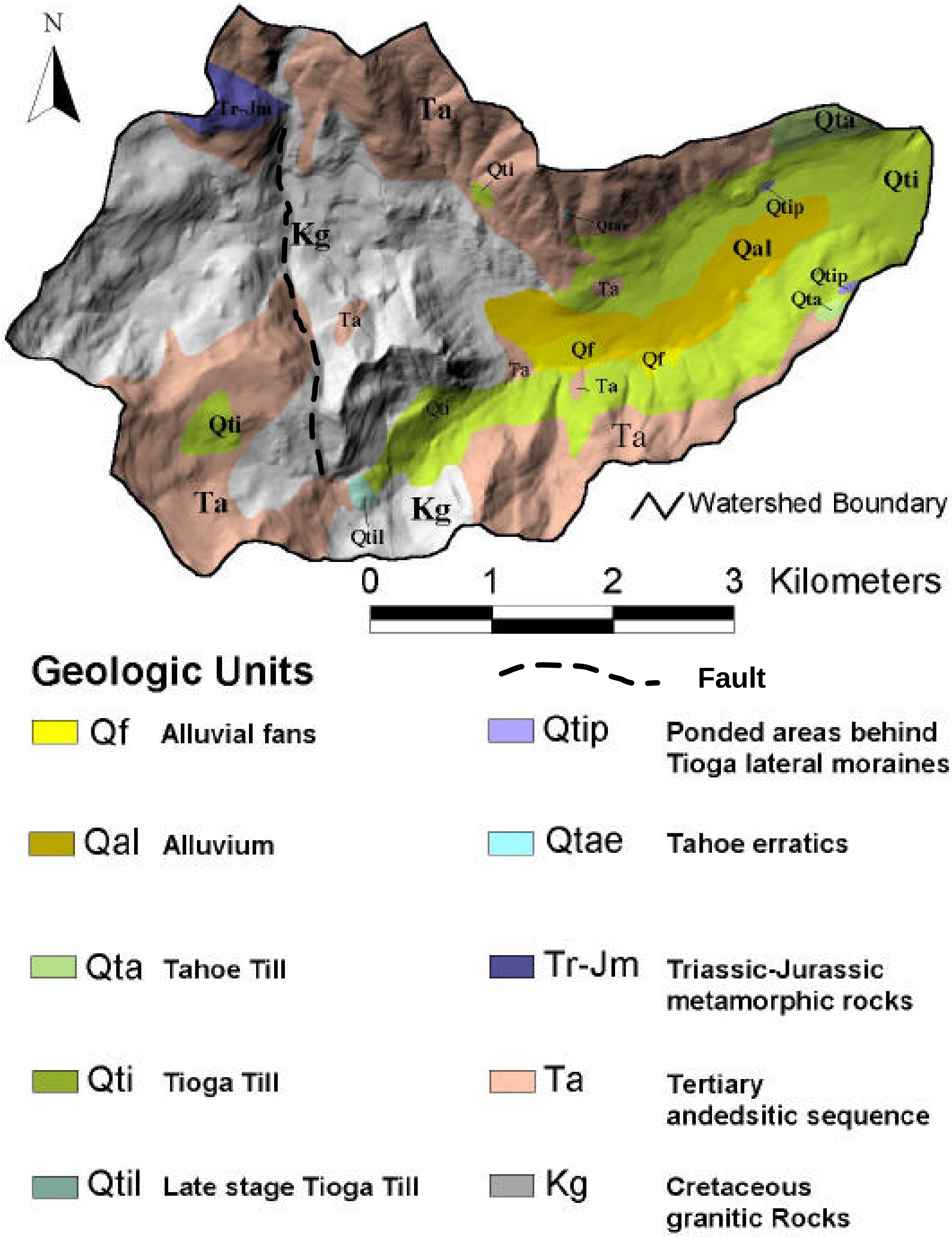


Figure 2. Geologic units of the Squaw Creek watershed (modified after Birkeland, (1961).

Quaternary geologic units – Quaternary volcanism was followed by several periods of glaciation during the Pleistocene, with individual glaciers forming at the highest elevations of the Sierra Nevada (Birkeland, 1962; Birkeland 1963). Evidence of this is provided by the prominence of glacial erosional features, such as striated granite bedrock, in the mid- to lower sections of the north and south forks of Squaw Creek (Figure 4). These glaciers carved out individual valleys during their expansion phases, creating the elongated U-shape of Squaw Valley characteristic of sub-alpine glacial valleys, steep headwall cirque basins and avalanche chutes, glacially plucked granite bedrock higher in the drainage (Figure 5), and lateral and terminal moraine deposits (Hecht and Jett, 1988). In both the north and south forks of Squaw Creek, abrasion on the gently sloping upstream side and intense quarrying, or plucking, from the downstream side has produced steep headwalls. Glacial units comprise approximately 20% of the mapped units in the watershed, most of which are located in the lower parts of the watershed.

Figure 3. Sector IV (south fork subwatershed) looking west towards Squaw Peak displaying the characteristic talus cones formed on the steep walls of Andesitic bedrock.

Figure 4. Sector V (north fork subwatershed) view of granitic bedrock with dominant vegetation coverage (mixed conifer forest).

Figure 5. Evidence of glaciation: plucked, striated and polished granite bedrock in the north fork of Squaw Creek.

Birkeland (1961) mapped glacial till within the Squaw Creek watershed connected to the Tahoe (Qta) and Tioga (Qti) glacial events, and are predominantly associated with lateral moraines comprising the north and south valley walls in the eastern portion of the watershed. Based on core data, a large portion of the underlying fill in the meadow section of Squaw Valley also appears to be comprised of this glacial till material, typically 30 to 45 meters deep (Hecht and Jett, 1988; Kleinfelder, 2000). Very few glacial deposits are mapped in the north fork of the watershed, whereas glacial deposits cover nearly 20% of the area of the south fork. Much of the glacial deposits found within the south fork are Tioga age glacial till which is composed of boulders and cobbles within a fine, silty matrix and extends approximately 200 m (600 ft) up the sides of the valley.

Following the deglaciation, isostatic rebound initiated stream incision and hillslope erosion and deposition activities, including alluvial fan and debris cones, talus, and alluvial valley fill. Alluvial fans (Qf) formed along the southern portion of the valley at the mouths of several tributary streams that feed into Squaw Creek. Their formation is post-glacial, because these features would have been removed by glacial activity. The fans are therefore interpreted to be Holocene because they have not been disturbed by the most recent glacial activity, and in most cases appear to bury glacial deposits, or are associated with streams that have incised through lateral moraines on the valley margins. Alluvial valley fill (Qal) is present within the meadow itself and is the result of initial deposition from glaciation, and lacustrine deposition from fluvial aggradation of Squaw Creek. At the base of the mountain, larger fans are present, although commercial buildings and parking lots cover the largest fan, near the mouth of the south fork.

An examination of drilling logs and associated descriptions completed by Kleinfelder (2000) as part of a groundwater geotechnical study in the Squaw Creek watershed provides insight into the composition of the alluvial sediments in the lower meadow section of Squaw Creek (Qal). A number of well cores were logged during the course of the study and generally range in depth from 4.6 m to 15.2 m (15 to 50 ft), along with several more which range in depth from approximately 22.9 m to 45.7 m (75 to 150 ft) or more.

The overlying meadow alluvial deposits appear to consist of fluvial and lacustrine deposits, with the top 1.5 m to 4.6 m (5 to 15 ft) consisting of a matrix of sandy silt with some clay and a high organic matter content. Aggradation of the valley floor during the Holocene is represented in the 2 m (6 ft) of fluvial sediments that are clearly exposed in the meadows section of Squaw Creek. These exposed deposits lend evidence to Holocene aggradation by their lack of cut and fill features that suggest few major fluctuations in base level conditions of Squaw Creek over the past few thousand years. Sediments beneath the fluvial and lacustrine sediments alternate between silty clay and silty sand to clayey sand and occasional gravel layers. Deeper core depths > 13.7 m (> 45 ft) encounter cobbles with sand and weathered or altered rock, and finally bedrock at depths near 45.7m (150 ft) (Kleinfelder, 2000). Additionally, Birkeland (1961) mapped terminal moraines and glacial erratics above current valley elevations that suggests that lacustrine deposition has occurred in the meadow reach of Squaw Creek and is thus further evidence of valley floor aggradation during the Holocene. Data from the drill log cores and mapping completed by Birkeland (1961) suggest that the alluvial valley sediments consist of a mixture of fluvial, lacustrine, and colluvial deposits that overlie approximately 30.5m (100 ft) of glacial till near the base of the valley.

Hillslope deposits include thin mantles of weathered materials that may be in excess of several meters near the base of slopes, and thicker mass wasting and debris flow deposits near the base of steep slopes. Small fans (<100 m^2) also occur in portions of the north and south fork sub basins where significant changes in slope occur and local drainages go from confined to unconfined. There is evidence that one particularly large alluvial fan in the south fork was previously used for gravel mining operations. Because of the steep nature of the terrain, many of the cliff areas contain local storage sites where talus cones have formed, some of which have established vegetation. Several landslides (Ql) are also evident along the northern portion of the valley (Figure 6).

Figure 6. Landslides in northern portion of valley occurred on morainal and volcanic material.

Stratigraphic relationships with the alluvial valley fill indicate the landslides are probably the youngest geologic units in the watershed. Aerial photographs from 1939 show the presence of trees on portions of the landslides. This is indicative that the slides are probably not a result of anthropogenic disturbance in the watershed, as is suggested by Jones (1981) because a number of the trees are at least two to three hundred years in age, which means that the landslides occurred prior to European settlement in the watershed.

2.3 Soils

Five major soil-forming factors are responsible for the development of soils (Miller and Donahue, 1995). These are:

Parent Material - Parent rock types experience different rates of weathering, are comprised of different nutrients as a result of mineralogy, and weather down to different particle sizes, all of which variably influence soil formation. The composition of the parent material may be the prevailing factor in determining soil properties in slightly weathered soils, such as those in the Squaw Creek watershed.

Climate – As time increases, climate becomes an increasingly dominant factor in soil development, mostly due to effects of precipitation, temperature, and its indirect effect on the types of vegetation that are established in a given area.

Biota – Biota refers to the direct influence of the activity of plants and animals on soils, such as rooting depth, burrowing accomplished by animals and resultant soil mixing, and the types of litter that accumulates under differing vegetation (e.g., needles from conifers versus leaves from deciduous trees).

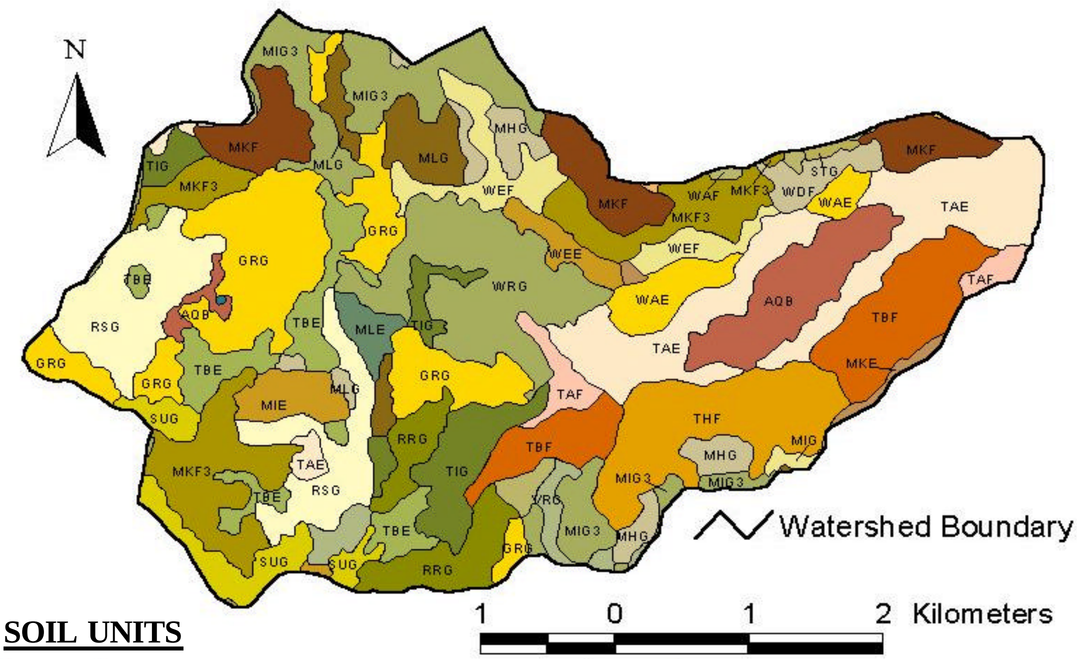
Topography – Through slope, aspect, and elevation, topography influences the water and temperature relations of soil development. The effect of slope, in relation to the Squaw Creek watershed, is best observed in noting that soils on steep hillsides sharing similar parent material typically have thin developing horizons because less water moves down through the soil profile as a result of rapid surface runoff and therefore high rates of erosion. The resulting deposition of soil materials downslope rapidly covers developing soil layers, thereby influencing development. Soils on south and west facing slopes are warmer and drier than north and east facing slopes because they receive more direct sun, which in turn affects the types and rates of vegetation establishment and decomposition rates of organic material.

Time – Time allows soil development processes to proceed in a systematic manner. As time increases, the relative degree of influence of soil development factors changes such that parent material and topography become less important, and climate and biotic influences become more important in the formation of the soil horizons.

Other factors that might affect soil development in Squaw creek watershed include: low relative humidity (little growth of microorganisms such as algae, fungi, and lichens); resistant parent rock materials, such as granite (slow weathering); very steep slopes (erosion efficiently removes soil); and cold temperatures (all chemical and microbial processes slowed) (Miller and Donahue, 1995). These other factors are most evident in higher portions of the watershed comprised mostly of exposed bedrock, which inhibit infiltration and promote concentrated runoff due to minimal vegetation and little or no soil, potentially leading to increased erosion rates. Variability in soil-forming factors across the landscape results in spatial variation in the types and degree of development of the soils and their associated hydrologic properties. Consequently, variability exists within the Squaw Creek watershed in the relative sensitivity of the landscape to erosion or disturbance.

The soils within the Squaw Creek watershed (Figure 7) have been mapped and classified by the U.S.D.A. Forest Service, Tahoe National Forest (1994). The watershed includes soils formed on nearly level valley floors to soils formed on moderate (2-30%) to very steep (30-75%) slopes of high elevation mountainsides. Most of the soils found in the watershed are minimally developed and are comprised of seven major soil series (Tahoe National Forest, 1994), which are described in Appendix A.

At elevations above about 1,980 m (6,500 feet), soils have formed primarily from weathered volcanic and granitic rocks and include glacial and alluvial deposits. Soils at lower elevations in the eastern half of the watershed are formed on alluvial and glacial deposits. These hillslope soils found on the gradual and steeper slopes generally are comprised of the Jorge, Meiss, Tallac, and Waca soil series (Tahoe National Forest, 1994). These soils are generally highly susceptible to erosion (high to very high erosion hazard) and are therefore more sensitive to changes in soil forming factors. Waca and



SOIL UNITS

AQB	Aquolls and Borolls	SUG	Rubble land-rock outcrop complex
GRG	Granitic rock outcrop	TAE	Tallac very gravelly sandy loam (2-30% slope)
JSG	Jorge Cryumbrepts	TAF	Tallac very gravelly sandy loam (30-50% slope)
JWF	Jorge Waca-Tahoma Complex	TBE	Tallac Cryumbrepts (2-30% slope)
MHG	Meiss-Gullied land-Rock outcrop complex	TBF	Tallac Cryumbrepts (30-50% slope)
MIE	Meiss-Gullied land-Rock outcrop complex (2-30% slope)	THF	Tallac gullied land-Cryumbrepts
MIG	Meiss-Gullied land-Rock outcrop complex (30-75% slope)	TIE	Tinker granitic rock outcrop-(2-30%) Cryumbrepts, severely eroded
MIG3	Meiss-Gullied land-Rock outcrop complex, severely eroded	TIG	Tinker granitic rock outcrop-(30-75%) Cryumbrepts severely eroded
MKE	Meiss-Waca complex (2-30% slope)	VRG	Volcanic rock outrcrop
MKF	Meiss-Waca complex (30-60% slope)	WAE	Waca-Windy complex (2-30% slope)
MKF3	Meiss-Waca complex (30-60% slope), severely eroded	WAF	Waca-Windy complex (30-50% slope)
MLE	Meiss-Waca Cryumbrepts (2-30% slope)	WBF	Waca Cryumbrepts (2-30% slope)
MLG	Meiss-Waca Cryumbrepts (30-75% slope)	WDF	Waca-Meiss complex
RRG	Granitic rock outcrop-Tinker complex	WEE	Waca-Meiss Cryumbrepts (2-30%)
RSG	Granitic rock outcrop-Tinker Cryumbrepts	WEF	Waca-Meiss Cryumbrepts (30-50%)
STG	Rubble land-Jorge complex	WRG	Ledford Variant-rock outcrop complex

Figure 7. General soil map for Squaw Creek watershed (Tahoe National Forest, 1994).

some Tallac soil units include Cryumbrepts, which commonly have an impermeable substratum in the subsoil that reduces infiltration capacity, therefore making them subject to ponding and susceptible to erosion during snowmelt. The principal series found on the valley floor and areas of very low slope (0-5%) include Aquolls and Borolls. Generally, these soils are excessively drained to moderately well-drained, although some poorly drained soils can be found in small internally-drained high mountain lake basins and the meadows section of lower Squaw Valley. Most have vegetation including grasses, sedges, and forbs. Because these soils are found in areas of very low slope, they are less prone to erosion, except when disturbed from natural or anthropogenic sources (e.g., stream channel modification or urban development).

2.4 Vegetation

Vegetation in the Squaw Creek watershed is largely stratified by elevation, slope, and aspect and is comprised of lower montane, upper montane, and subalpine vegetation zones (Murphy and Knopp, 2000). Each of these zones contains components of forest, meadow, montane chaparral, wet meadow, and riparian vegetation types and is described below (Mayer and Laudenslayer, 1988). Vegetation type distributions are shown on the combined land cover and land use map (Figure 8). A list of potential common and special interest plant and wildlife species for the Squaw Creek watershed is provided in Appendix B. In general, the vegetation consists of mixed conifer forest (white fir and Jeffrey, sugar, and lodgepole pine species), red fir forest, subalpine forest (whitebark pine and mountain hemlock), montane meadow, alpine meadow, alpine rock communities, and montane chaparral (ceanothus species, manzanita, and bitterbrush) and wet meadow grasses and riparian vegetation (willow, aspen, dogwood, and alder).

The lower montane zone is found in elevations ranging from the valley floor to approximately 2,100 m (6,890 ft). Three primary forest vegetation types are found in this zone. These are, in relative order of decreasing abundance: mixed-conifer forest, Jeffrey pine forest, and white fir forest. Non-forest vegetation types in the lower montane zone include montane chaparral, meadow, and riparian. Mixed conifer forest is dominated by a varied combination of conifer species, including Jeffrey pine (Pinus jeffreyi), white fir (Abies concolor), sugar pine (Pinus lambertiana), and incense cedar (Calocedrus decurrens). In mixed conifer forest stands, no one species of conifer contributes more than half of the total number of trees or canopy cover on average. Jeffrey pine forest type is dominated by Jeffrey pine (*Pinus jeffreyi*), with minor associated conifer species such as white fir (*Abies concolor*) and incense cedar (*Calocedrus decurrens*). White fir forest is dominated by white fir (*Abies concolor*), but red fir (*Abies magnifica*) is an occasional associate of this forest type (Murphy and Knopp, 2000). Lodgepole forest, dominated by lodgepole pine (*Pinus contorta*), is an uncommon forest type in the lower montane zone, but does occur in small, fairly homogenous stands at the edges of the meadow below the confluence of the North and South forks of Squaw Creek, particularly near the bridge on Squaw Valley Road close to the Squaw Creek and Truckee River confluence.

Montane chaparral in the lower montane zone is represented both as an understory component of the three forest types described above and as a dominant vegetation type on hillslopes. Montane chaparral is dominated by a diverse assemblage of shrub species, including manzanita (*Arctostaphylos patula*), Sierra chinquapin (*Chrysolepis sempervirens*), huckleberry oak (*Quercus vaccinifolia*), bitterbrush

(*Purshia tridentata*), creeping snowberry (*Symphoricarpos mollis*), and ceanothus species such as whitethorn (*Ceanothus cordulatus*), tobacco brush (*C. velutinus*), and squawcarpet (*C. prostratus*). Sagebrush (*Artemisia tridentata*) and rabbitbrush (*Chrysothamnus naseosus*) are also associated with the montane chaparral vegetation type. Riparian vegetation is dominated by the presence of willow (*Salix spp.*) growing along stream banks and in small clumps within the meadow below the confluence of the North and South forks of Squaw Creek. Riparian vegetation following drainages dominates streamside vegetation, and consists not only of willow species, but includes creek alder (*Alnus incana*) and dogwood (*Cornus sericea*) as well. The meadow vegetation type includes both wet and dry meadow associations and consists of numerous species of grasses, sedges (*Carex spp.*), rushes (*Juncus spp.*), and herbaceous plants.

The upper montane zone is found in elevations ranging from approximately 2,100 m to 2,600 m (6,890 to 8,530 ft). Mixed conifer forest may occasionally occur in this zone, the most common forest type is the red fir forest, which is characteristically dominated by red fir (*Abies magnifica*). Species associated with this forest type include western white pine (*Pinus monticola*), lodgepole pine (*Pinus contorta),* and white fir (*Abies concolor*). Red fir forest contains less cover by shrubs and herbs than the lower montane forests. Riparian vegetation occurs in this zone as the dominant streamside vegetation and is comprised of willow (*Salix spp.*), creek alder (*Alnus incana*) and dogwood (*Cornus sericea*). Stands of aspen (*Populus tremuloides*) also occur in riparian areas where local subsurface water tables remain high throughout the year. As in the lower montane zone, lodgepole forest types occur in locally wet areas at the edge of meadows and streams in the upper montane zone. The upper montane meadow vegetation type is found in small patches where drainage gradients are locally flat and includes both wet and dry meadow associations consisting of numerous species of grasses, sedges (*Carex spp.*), rushes (*Juncus spp.*), and herbaceous plants. Chaparral vegetation is limited in distribution in the upper montane zone, consisting of the same species described in the lower montane chaparral, but tends to be dominated by manzanita (*Arctostaphylos patula*).

The subalpine zone is found in elevations above approximately 2,600 m (8,530 ft). The most common forest type in this zone is the mixed subalpine woodland. Mixed subalpine woodland forest type is dominated by white bark pine (*Pinus albicaulis*), mountain hemlock (*Tsuga mertensiana*), and conifer species common in the upper montane zone, such as white fir (*Abies magnifica*), lodgepole pine (*Pinus contorta*), and western white pine (*Pinus monticola*). However, mountain summits and peaks are generally barren and devoid of vegetation, with patches of herbaceous vegetation, such as mule's ear (*Wyethia mollis*).

2.5 Land Use

Land use practices have exerted a tremendous influence over the hillslope and fluvial processes in the watershed since the arrival of Europeans nearly one hundred fifty years ago. During the late 1800's cattle ranching, sheep herding, and logging activities were initiated in the watershed and continued to occur through the first half of the next century, though to a lesser extent.

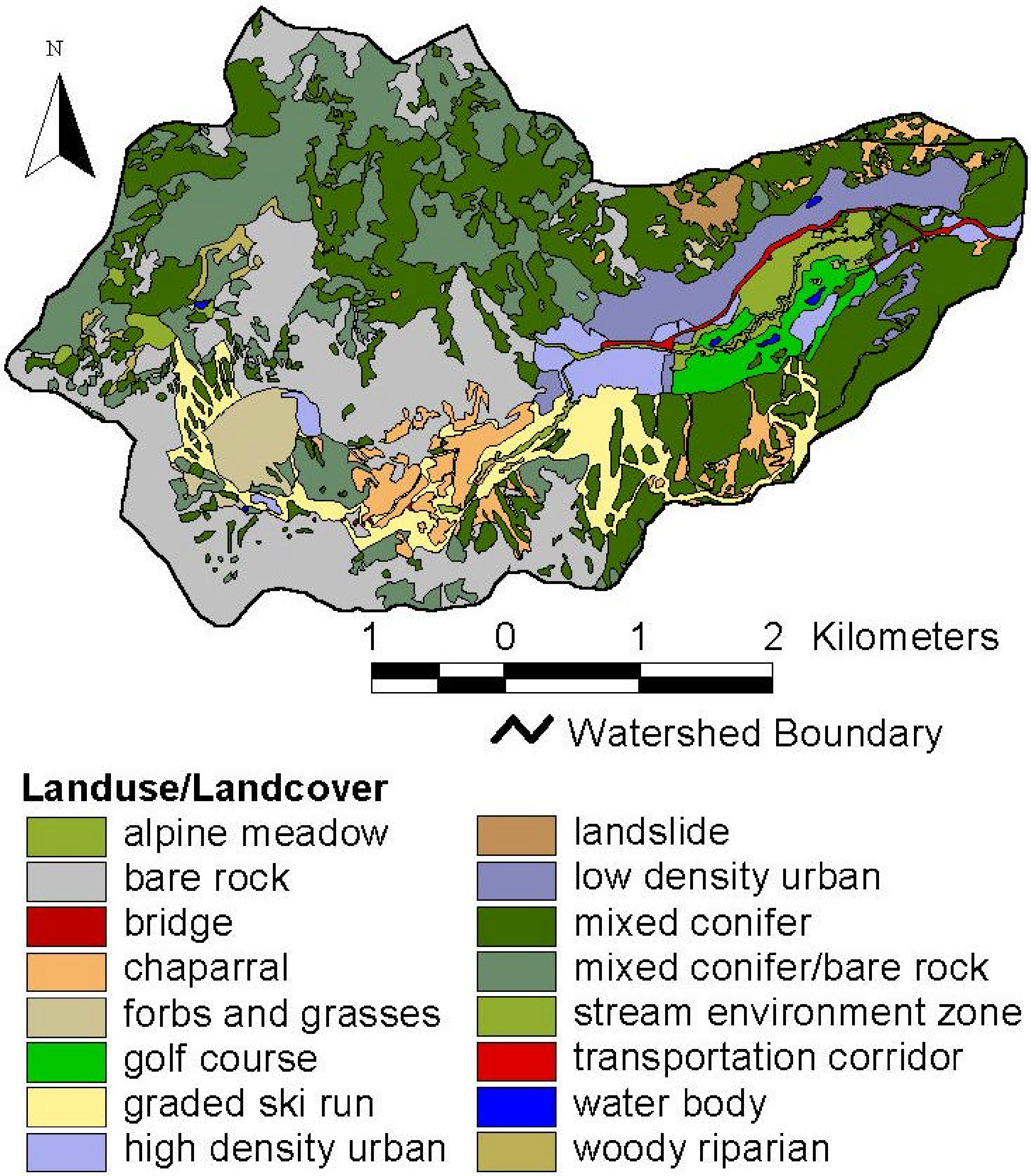


Figure 8. Land use and land cover map for the Squaw Creek watershed.

In 1949, the Valley's first ski lifts were constructed and later expanded to accommodate the 1960 Winter Olympics. On the north slopes of Squaw Valley, residential housing was developed in conjunction with the Olympics, as were other activities which impacted the main meadow portion of the stream including: channelizing a portion just below the confluence of the two forks, construction of and grading for parking areas (described in detail below), and installation of culverts (Poulsen, 1984). The U.S. Army Corps of Engineers constructed temporary parking lots in the meadow area in order to accommodate the increase in visitors during the 1960 winter Olympics (Figures 9 and 10). Bulldozers, tractors, loaders, backhoes and graders were used to completely regrade a majority of the meadow in order to obtain a 1% slope toward the creek. Much of the meadow vegetation was altered including the mistake of felling over 300 trees and completely removing all meadow grasses and associated native vegetation. Major alterations to the meadow included: blasting and removal of glacial erratics (granitic boulders) from the meadow, recontouring and removal of soil and vegetation, and installation of an extensive networking of culverts and drainage pipe along with trenches covering much of the meadow and both sides of the creek. Sawdust, woodchips and gravel were laid down in layers with snow to act as the parking area. This exotic sawdust material was left in the meadow and seeded with grass after the Olympics ended (Sullivan, 1984). Kleinfelder (2000) bore hole cores include a layer of organic content that is made up of the 1960 Olympics temporary parking lot wood chips and sawdust, which have not yet decomposed. This exotic organic layer occurs around 3.0 m to 4.9 m (10 to 16 ft) deep and in some cases 7.6 m to 13.7 m (25 to 45 ft) deep. Fluvial deposits of sand and gravel that are subangular to subrounded overlie the sawdust layer (Kleinfelder, 2000).

Current land uses include an expanded ski resort with year-round recreational opportunities, a golf course in a portion of the meadow (Figure 11), commercial equestrian operations, sports fields, a network of hiking and bicycling trails, logging roads, residential development, and ski resort maintenance access roads. These land uses have the potential to impact geomorphic process operating within the watershed and were therefore considered in the overall geomorphic and sediment source analysis.

Figure 9. Squaw Creek meadow being used for parking during 1960 Olympics-photo looking northeast. (Photograph courtesy of Lahontan RWQCB)

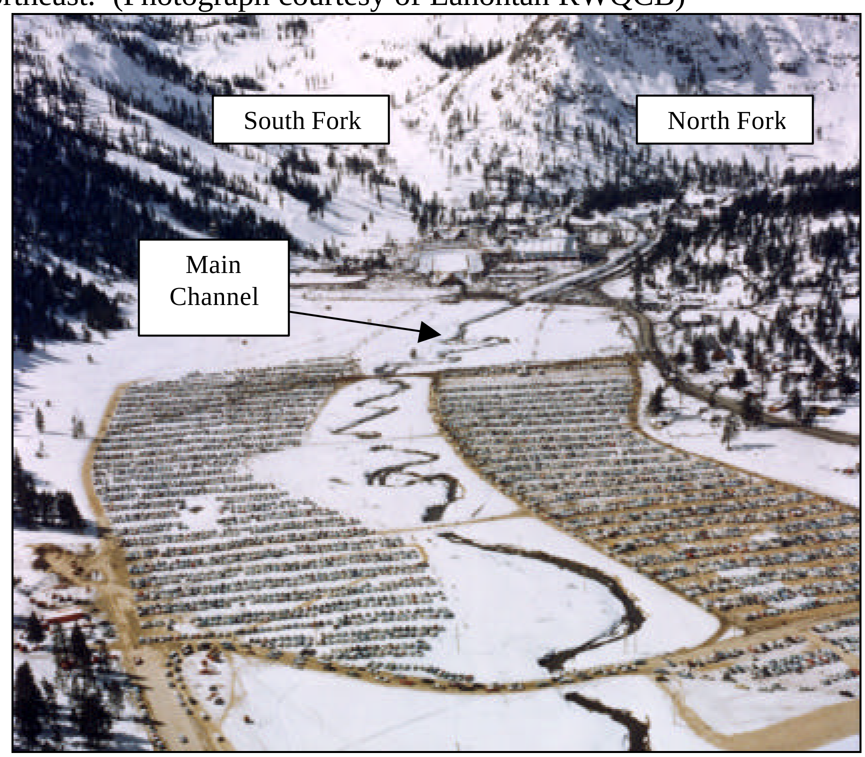


Figure 10. Squaw Creek meadow being used for parking during 1960 Olympics-photo looking west. (Photograph courtesy of Lahontan RWQCB)

Figure 11. Present day view of Squaw Meadow looking northeast. Golf course is identified by the striped golf greens, sandtraps, and two large sediment retention ponds.

3. DATA COLLECTION AND ANALYSIS METHODS

The main focus of this study is to analyze hillslope sediment sources and active processes operating on mountain slopes with respect to erosion, deposition and potential input to stream systems. Many watershed studies commonly utilize flow records on gauged streams to develop sediment budgets and to analyze fluvial processes; however, the development of flow duration curves, mean annual discharge, and peak daily, monthly, or annual discharge was not possible for Squaw Creek because it is an ungauged watershed with little hydrologic data other than intermittent discharge and (recent) suspended sediment measurements from other studies (e.g., Hecht and Jett, 1988; McGraw et al., 2001; Kuchnicki, 2001). Therefore, existing data including maps, technical reports from previous investigations in the watershed, and repeat aerial photography (Appendix C) and imagery were utilized to assist in the evaluation of the physical characteristics and processes operating in the watershed. Historical evidence (largely derived from written and oral accounts of historical conditions and land uses, including photographs, drawings, surveyor's notes, etc.) related to watershed processes was also utilized in the analysis. The assessment of Late Quaternary watershed processes was based on field observations and mapping of the Quaternary geology, geomorphic mapping, aerial photographic mapping, and use of a Geographic Information System (GIS) which provides a longer-term perspective into the future behavior of the watershed.

The study utilized field data sheets and notes; site photographs; working draft maps; channel condition data summaries including channel cross sections and longitudinal profiles; fluvial geomorphic data; general sedimentology; field verified vegetation and land use layers, and an integrated GIS database of relevant field tabular data and maps to develop a watershed assessment. Areas sensitive to erosion and areas having elevated sediment yields, based on the field data and analysis, were digitized and integrated into a digital format compatible with the study GIS database.

3.1 GIS Spatial Data

The Squaw Creek watershed GIS database includes existing DRI and public domain data sets and newly created digital data. These data were utilized extensively for spatial analysis, description of the watershed features, and drainage basin morphometry. Data were projected into Universal Transverse Mercator (UTM) zone 10, datum NAD27 for this study.

Existing data layers of the Squaw Creek watershed were used to assist in the analysis of watershed processes and spatial identification of sediment sources. Data layers used for analysis include 10 meter resolution Digital Elevation Models (DEMs), 1998 Digital Orthophotoquads (DOQs), scanned topographic maps, hydrology, soils, geology, and roads. These were modified and details enhanced based upon field reconnaissance, historic aerial photographic analysis, and field data analysis. Additional digital information was created as well, based on field mapping and observations. This included vegetation, fluvial geomorphology of the meadow portion of the creek, historic (1939) and present land use and land disturbance, hillshade, topographic contours, stream orders, and hillslope erosion susceptibility modeling, which are described in Appendix D. ArcView version 3.2a GIS software was used to create and analyze data layers.

Using 1998 digital orthophotoquads (DOQs), 1997 aerial photography (scale 1:16,000), and field observations, an ArcView polygon feature shapefile of land use and land cover in the Squaw Creek watershed was created. Sixteen categories were developed for the watershed; manually interpreted based on texture, tone, color, shape, field reconnaissance, and watershed knowledge; and then digitized into the GIS to produce the coverage to assist in the spatial evaluation of potential sediment sources. Descriptions of the categories and associated attributes are provided below in Tables 2 and 3.

Table 2. Descriptions of land use categories, including percent of area covered by each land use or land cover type. Squaw Creek consists of the entire watershed.

Category: Land Use	**Percent of Watershed Area**			**Description**
	Squaw Creek	**North Fork**	**South Fork**	
Bridge or culvert	0.02	0.0	0.1	Engineered stream crossing structure
Golf Course	2.2	0.0	0.0	Land covered by fairways, rough, greens, and sand traps
Graded Ski Run	6.1	1.8	11.6	Ski runs created through removal of vegetation, recontouring of slopes, and soil grading; may overlap roads
High Density Urban	2.6	0.0	2.6	Development resulting in highest degree of impervious surface
Low Density Urban	4.9	0.0	1.1	Residential development
Transportation Corridor	0.5	0.0	0.0	Primary paved roads

Table 3. Descriptions of land cover categories, including percent of area covered by each land use or land cover type. Squaw Creek consists of the entire watershed.

Category: Land Cover	**Percent of Watershed Area**			**Description**
	Squaw Creek	**North Fork**	**South Fork**	
Alpine Meadow	2.3	1.1	0	Areas exhibiting typical wetland/meadow vegetation
Bare Rock	23.6	28.8	43.1	Exposed bedrock with little or no vegetative cover
Chaparral	4.7	0.2	13.3	Open areas dominated by montane chaparral vegetation (manzanita, sagebrush, ceanothus)
Forbs And Grasses	2.2	0.0	9.5	Areas of typical upland grass and herbaceous vegetation
Landslide	0.7	0.0	0.0	Large-scale landslide scars

Category: Land Cover	Percent of Watershed Area			Description
	Squaw Creek	North Fork	South Fork	
Mixed Conifer	30.2	32.2	6.0	Areas dominated by conifer species (e.g., Jeffrey and lodgepole pine, white and red fir) with greater than 10% canopy cover
Mixed Conifer/Bare Rock	18.1	34.5	11.6	Exposed bedrock that includes conifer tree species with less than 10% canopy cover
SEZ (stream environment zone)	0.7	0.0	0.8	Primary stream courses
Water	0.5	0.1	0.0	Non-flowing water bodies
Woody Riparian	0.8	1.3	0.3	Stands of woody riparian species (willow, aspen, alder, dogwood) [see Appendix B for listing of species]

3.2 Data Collection Methods

Current physical watershed processes operating within the Squaw Creek watershed were monitored and analyzed in order to establish current conditions and determine the dominant and/or active processes. Field data collection and analysis focused on quantifying erosion rates and subsequent determination of the processes acting to initiate the movement of sediment through the watershed hillslope to stream channel sediment transport system. This aided in the determination of the dominant source areas contributing to suspended and bed-load sediment within the hillslope environment. As described in section 3.1 above, historic (1939) and current land use and vegetation were classified, identified, and mapped to assist with the analysis of sediment sources.

3.2.1 Subdivision of the field area for source studies

Sediment source studies typically begin by subdividing watersheds into units based on attributes such as geology and vegetation. For this study, the Squaw Creek watershed was divided into five sectors based on aspect, relief, geology, sub-watershed divides, and land use (Figure 12). Within each sector, field instrumentation such as erosion pins and modified sediment traps were installed to assess the rates of sediment movement. Appendix D describes the extent, geomorphology and general geomorphic processes, and geology of each sector.

3.2.2. Field Methods

Specific field methods used for characterizing the major sediment sources and in estimating erosion rates and developing a sediment budget are described below. In situ methods were used to measure erosion rates from different hillslope and stream channel components. Stream channel sediments were sampled and hillslope soil composition was determined from laboratory analysis to further characterize the nature of sediment sources. Repeat observations were used to estimate change through time and rates of erosion or deposition for different areas of the landscape. Monitoring techniques included:

- Photo documentation and reconnaissance
- Stream channel cross-sections
- Rill and gully transects
- Erosion pin transects
- Sediment fences to trap sediment transporting on slopes and roads

- Collection of material from channel bars and hillslope soil pits for sediment particle size analysis

The field season commenced in May 2001 and continued through the spring snowmelt peak runoff period during the 2002 field season. See Appendix D for a full description of the above methods.

4. RESULTS AND DISCUSSION: ASSESSMENT OF SEDIMENT SOURCES

The objective of the source assessment is to characterize the types, magnitude, and locations of sources of sediment loading to the entire Squaw Creek watershed, including the major north and south fork tributary sub-basins. This was accomplished through the use of analytical techniques, incorporation of existing data, field reconnaissance and data collection. By examining the system as a whole it was possible to also assess the timing of greatest sediment flux into the system. Through initial field reconnaissance and aerial photographic analysis, the dominant sediment sources for the watershed appeared to be related to anthropogenically disturbed areas, bedrock geology (type, distribution), geologic structure, surficial deposits (hillslopes, alluvial and colluvial debris fans, fluvial terraces), and in-channel condition and processes (sediment stored in bars, stream bed and banks, floodplain). Geomorphic process-response analysis was used to interpret the significance and degree of these factors within the watershed and their possible effects on the water quality (Ritter et.al, 1995).

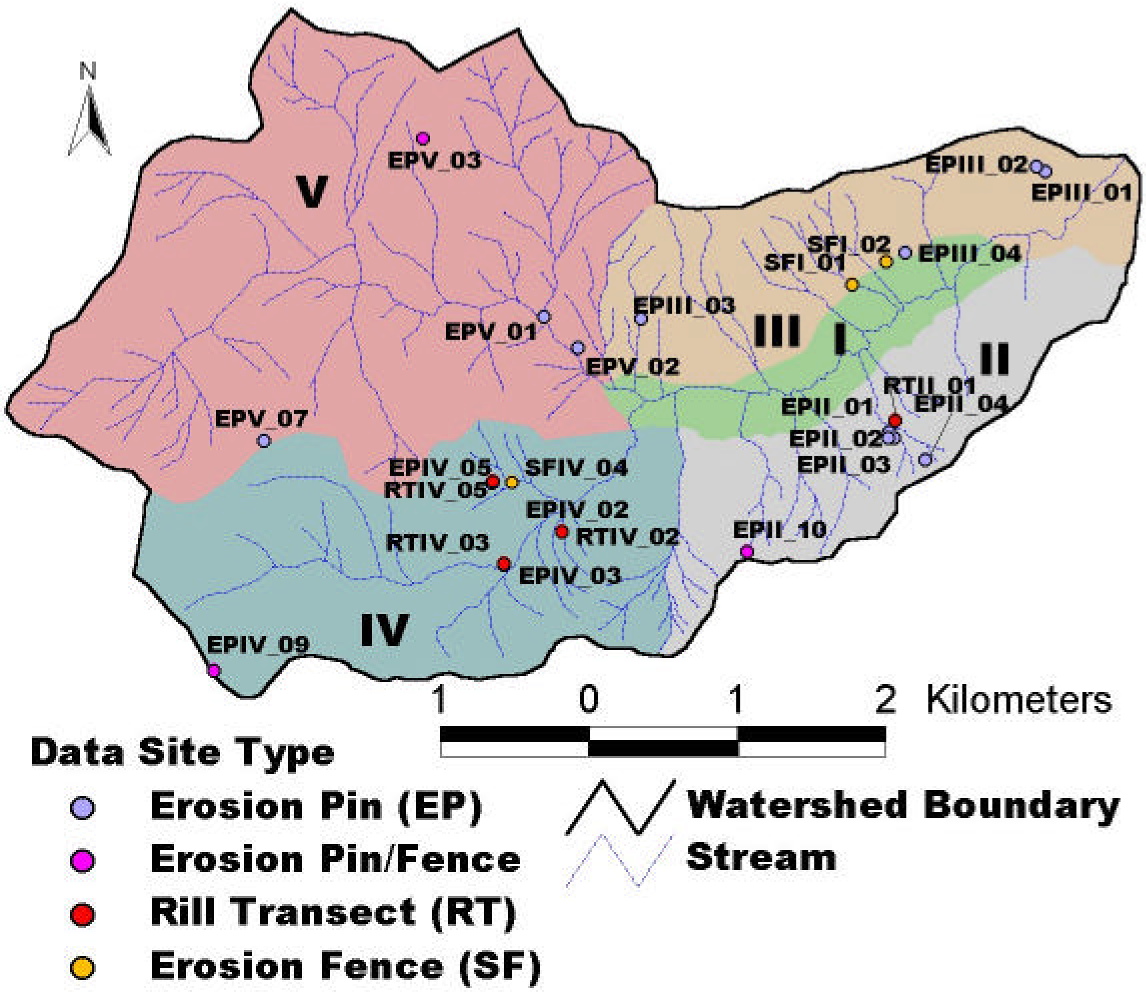


Figure 12. Map showing the division of the study area sectors and locations of hillslope erosion monitoring sites. Roman numerals denote sector identification number.

An assessment of the relative rates of sediment production and susceptibility to erosion was made based on mapping from aerial photographs, imagery, field investigations and data collection, and comparison with empirical studies from similar areas.

An analysis of sequential year aerial photographs (1939 – 1998) and development of GIS data layers showing disturbance and landscape modification were conducted in order to assess the anthropogenic landscape alterations and the potential effect on the watershed hydrologic and geomorphic responses. This was used to determine the type and location of natural and anthropogenic-related sources of sediment, changes in loci of erosion and deposition, and changes in sediment transport.

Other factors considered include the influence of vegetation on sediment contributions from bedrock, surficial deposits (including hillslopes), and in-channel sources and indicators of episodic high sediment discharge into the system (Morgan et.al, 1986) based on erosion data collected during field studies.

4.1. Morphometric Analysis

Basin morphometry is simply defined as the geometric characteristics of a watershed's master channel and its tributary network. These quantifiable sets of geometric properties define the linear, areal, and relief characteristics of a watershed and are used to predict and describe geomorphic processes, estimate erosion rates, and assess sediment yield. These measurable geomorphic properties of basins are factors of watershed hydrology, geology, and climate and can therefore reveal relationships between watershed hydrology, geology, surficial processes, and the movement of water and sediment within a watershed (Ritter et al., 1995).

Basin morphometry was calculated to aid in the characterization of the Squaw Creek watershed and allow for comparisons of the north and south forks of Squaw Creek. Drainage basin morphometric analyses were completed both manually and using the Squaw Creek DEM with ArcView Spatial Analyst. A summary of geomorphic analyses for the entire watershed as well as the north and south forks is provided in Table 4.

Table 4. Summary of geomorphic analyses and morphometric relationships for Squaw Creek and the north and south fork subwatersheds§.

Morphometric Property	Squaw Creek Basin	South Fork (Sector IV)	North Fork (Sector V)	North Facing Valley Wall (Sector II)	South Facing Valley Wall (Sector III)
Area [km^2 (mi^2)]	21.12 (8.15)	4.70 (1.82)	9.29 (3.60)	4.04 (1.56)	2.63 (1.02)
Basin Order (Straher)	5	4	4	2	2
Basin Length [km (mi)]	7.9 (4.9)	3.6 (2.2)	4.3 (2.6)	--	--
Basin Shape	0.34	0.36	0.52	--	--
Bifurcation Ratio	2.84	1.83	3.17	--	--
Max. Relief: [m (ft)]	900 (2,953)	809 (2,654)	854 (2,802)	550 (1,804)	460 (1,509)
Avg. Relief [m (ft)]	730 (2,395)	644 (2,112)	512 (1,680)	300 (984)	312 (1,024)
Relief Ratio	0.11	0.20	0.17	--	--
Drainage Frequency* [N/km^2 (N/mi^2)]	12.87 (33.37)	8.70 (22.53)	15.02 (38.89)	12.38 (32.05)	7.95 (20.59)
Drainage Density [km/km^2 (mi/mi^2)]	4.02 (6.50)	2.93 (4.72)	4.58 (7.37)	5.01 (8.06)	3.45 (5.55)
Hypsometry [% basin area above 2,300 m (7,500 ft)]	37	58	53	--	--

§ Squaw Meadows (Sector I) is not a drainage basin by definition and was not analyzed for morphometric properties

-- not applicable

* Drainage frequency is defined as the number of stream segments (N) per unit area, based on the Shreve stream classification method (Ritter et al., 1995).

4.1.1 Linear Parameters

Linear parameters include the length of streams of any order, the relief, the length of basin perimeter, and other similar measurements that allow size comparisons of topographic units or sub-basins within a given watershed. Many of the linear parameters are described by dimensionless numbers, which are often derived as ratios of different linear aspects of a watershed. These measurable aspects include: length ratios (R_L, ratio of the average length of streams of a given order to those of the next higher order) which can be used to determine the average length of streams in an unmeasured given order [L_0] and their total length; bifurcation ratios (R_b, the ratio of the number of streams of a given order to the number in the next higher order using Strahler classification) which allow for rapid estimates of the number of streams of any given order and the total number of streams in the basin and is an indication of underlying geology (e.g. when geology is homogenous, R_b commonly ranges from 3.0 – 5.0); (Ritter et al., 1995). Linear parameters for the Squaw Creek watershed are provided in Table 4. Figure 13 depicts stream orders for the watershed using the Strahler classification methods.

4.1.2 Basin Characteristics

The vertical dimension of a drainage basin includes factors of gradient and elevation, which have implications for sediment production, and are characterized by relief measurements. Relief measurements include the maximum basin relief (the highest elevation on the basin divide minus the elevation of the mouth of the trunk river), the divide-averaged relief (average divide elevation minus the mouth elevation), and the relief ratio. The relief ratio is defined as the maximum basin relief divided by the longest horizontal distance of the basin measured parallel to the major stream and indicates the overall steepness of the basin (Ritter et al., 1995).

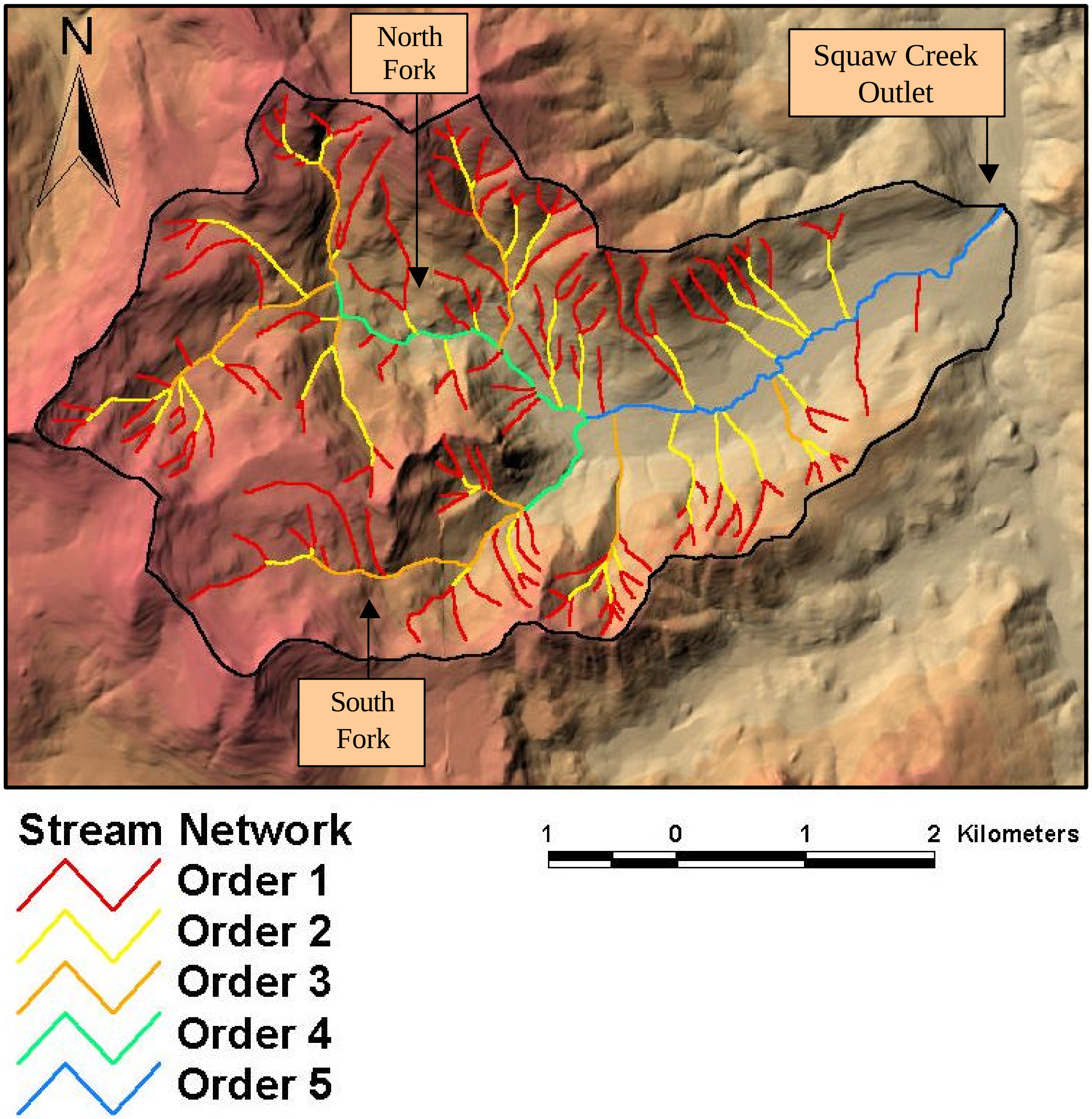


Figure 13. Strahler stream orders for the Squaw Creek watershed.

The maximum relief values for the watershed and sub-watersheds are indicative of high mountain watersheds and the sensitivity of the watershed to climatic factors. The relief ratio provides more valuable information regarding the relationship between the different forks of Squaw Creek and their respective erosional susceptibilities. Parker (1977) notes that sediment yield tends to increase with increasing relief ratio. In comparing the relief ratio of the entire watershed to the north and south fork sub-basins, it is apparent that the sub-basins are likely to yield high sediment relative to other portions of the watershed. Similarly, the south fork is slightly steeper as indicated by its relief ratio value of 0.20 and is therefore interpreted as being prone to yielding slightly higher amounts of sediment per unit area over the north fork based on relief ratio (Table 4).

4.1.3 Drainage Frequency and Density

Areal geometric properties of basin morphometry include drainage density and frequency, which can provide insight into the behavior of different parts of a watershed and the potential for erosion and production of sediment. Drainage frequency is defined as the number of stream segments per unit area based on the Shreve method of stream network ordering (Ritter et al., 1995). Drainage density, which is controlled in part by geologic and climatic factors, is a morphometric relationship that provides a measure of the spatial distribution of streams, both ephemeral and perennial, in a watershed and is related to sediment production and tributary connectivity to hillslopes. Drainage density (D) is defined as the average length of streams per unit area and reflects the spacing of the drainage ways and the interaction between geology and climate (Ritter et al., 1995).

The drainage density can indicate the relative distance overland flow on hillslopes must travel to channels, and therefore the relative connectivity that exists between hillslope erosion and the stream network. Given the much lower drainage density (and frequency) of the south fork compared to the north fork sub-basin, the south fork hillslopes should be less connected to the stream network than the north fork, and therefore produce and transport less sediment on an annual basis to the stream system.

Additionally, watersheds with higher drainage density tend to intercept more surface flow and therefore generate greater runoff and sediment yield than basins with lower drainage density (Parker, 1977). However, two studies indicate that the south fork generates significantly more runoff and sediment as the north fork. Hecht and Jett (1988) suggest that land use impacts in the south fork may be responsible for generating an increase of nearly twice as much runoff per unit area as the north fork of Squaw Creek. McGraw et al. (2001) report results from modeling that indicate the south fork produces 15% of the sediment load of Squaw Creek and the north fork produces 20%. This translates to the south fork producing twice as much sediment per unit area compared to the north fork. Finally, a comparison of the drainage density and frequency values for the north and south facing valley walls is indicative of the inter-relationships between aspect, precipitation, vegetation cover, soil properties, and bare surface area exposed by landslides, such that the north-facing slope has a higher drainage density than the south-facing valley wall. This is due to north-facing slopes being more likely to receive and maintain greater amounts of snowfall that produce more runoff during the spring.

4.1.4 Hypsometry

The hypsometry of a drainage basin represents a relief and morphometric relationship that relates elevation to area and provides a quantitative measure of the areal distribution of relief within a watershed. The relationship is typically represented as a cumulative curve of the percent of landmass (a/A_b) lying above a given elevation within the drainage (h/H) (e.g., Strahler, 1957) and possesses values between zero and one, which allows for comparisons between watersheds (Ritter et al., 1995). Kelson and

Wells (1989) showed that bedrock geology controlled both the extent of glacial erosion and the relative percentage of a watershed lying above a certain elevation, and that the hydrology and sediment transport in the drainage were all reflected in the basin's hypsometry.

Hypsometric curves graphically depict the distribution of basin area relative to height above the lowest datum. Beginning at the mouth of a basin, area is at a maximum and relief is at a minimum. Moving upward in a basin from the mouth, relief increases, but area decreases. Therefore, if the majority of basin area lies at low elevations the area proportion will decrease more quickly than the height proportion and will produce a concave hypsometric curve, typical of dissected and eroded landscapes. However, if the majority of basin area lies at high elevations the height proportion will decrease more quickly than the area proportion and produces a convex hypsometric curve. Thus, the hypsometric curve for any given drainage basin will eventually be concave over time.

Measurable differences in the hypsometry of the north and south forks are apparent in the Squaw Creek watershed (Table 4). Hypsometric curves were produced for the entire basin draining the Squaw Creek watershed (Figure 14), the basin draining the north fork of Squaw Creek (Figure 15), and the basin draining the south fork of Squaw Creek (Figure 16). The curve representing the entire Squaw Creek watershed as a whole has a concave shape, indicating that the majority of basin area lies at comparatively low relief; that is, the majority of basin area lies at lower elevations, while the majority of relief is gained mainly in the headwaters of the basin. In the case of the north and south forks of Squaw Creek, an examination of the convex form of the hypsometric curves produced for each indicates that area is gained slowly when progressing towards the respective watershed divides, but relief increases dramatically and therefore the majority of both basin areas lies at comparatively high elevation. This means that these areas receive high amounts of precipitation in the form of snow and a longer period of spring runoff, compared to lower elevation areas.

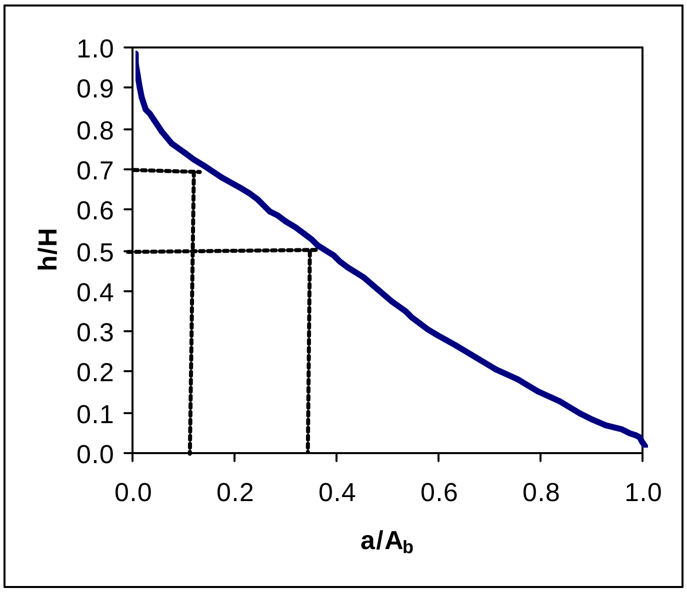


Figure 14. Hypsometric curve for the Squaw Creek watershed.

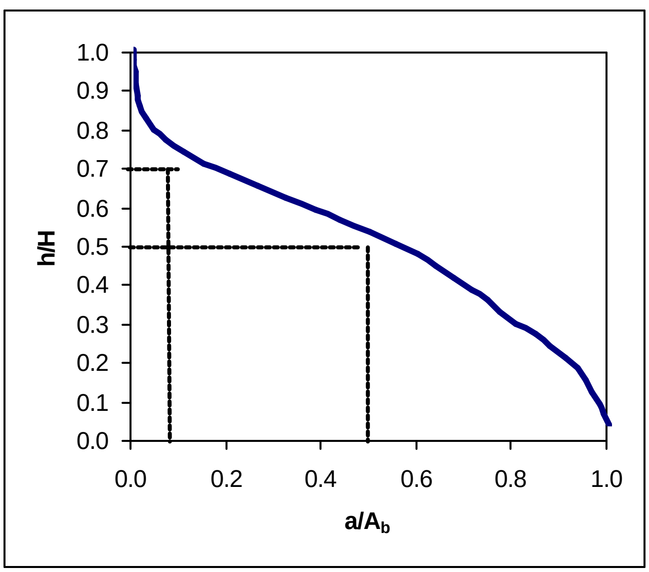


Figure 15. Hypsometric curve for the north fork subwatershed.

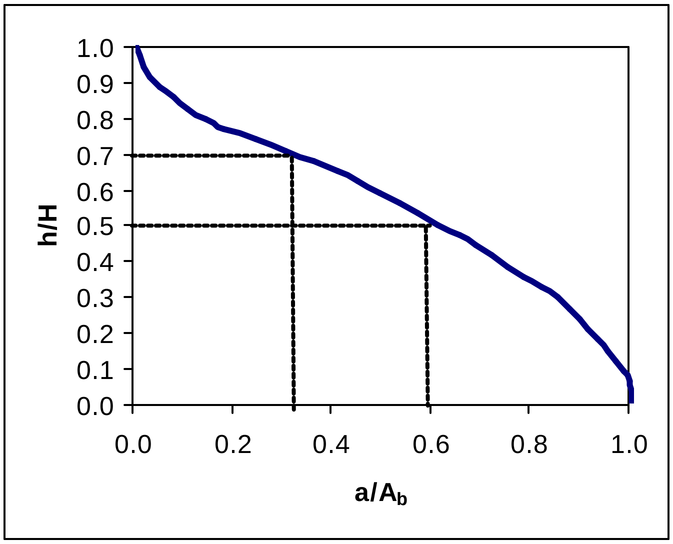


Figure 16. Hypsometric curve for the south fork subwatershed.

Comparing the south fork and north fork hypsometric curves yields additional information as to the similarities and uniqueness of each basin. In general, the curves appear similar, thus indicating that each of the sub-watersheds is deeply incised, with narrow valleys and broader upland areas, which is typical for convex curves. The curves for the north and south forks are generally convex-up, but have a slight S-shape to the curves that points out differences between the two basins. The north fork watershed has a more convex-up shaped curve with a sharper tail (top left hand corner) that indicates a greater percentage of area lying at lower elevations than does the south fork. The north fork hypsometric curve also indicates a broader upland area but a sharper climb in elevation gain closer to the basin divide. In other words, the south fork sub-watershed has a greater percentage of area located at higher elevations and slightly less pitch in the terrain at its highest elevations. This indicates that the south fork sub-watershed is likely to receive more snow and therefore have a larger snowpack, making it more susceptible to erosion. The broad upland area that encompasses a greater percentage of the north fork's total area also contains a greater percentage of vegetative cover, as well as many sinks (or sediment storage sites) that naturally occur and circumvent or dissipate hillslope runoff and erosion.

The fact that a greater percentage of the south fork of Squaw Creek lies above 2,300 m (7,500 ft) may be a basis for the amount of winter snowfall that accumulates there and in the resultant runoff behavior from that portion of the watershed. Winter precipitation in the form of snow is significant in the Squaw Creek watershed where the vast majority of the drainage area lies above 2,130 m (7,000 ft) because snow is stored above ground and may be released as water under very different conditions from rainfall during periods of warm weather, particularly during spring. Nolan and Hill, (1991) report the long-term average annual snowfall for Tahoe City is 5.4 m (17.7 ft). This amount of snow accounts for approximately 50% of the total winter precipitation at lower elevations (below 2,400 m [7,900 feet]) and 90% of the winter total for higher altitudes (above 2,400 m [7,900 feet]), with snow accumulations greatest on north-facing slopes. During non-winter season periods, precipitation amounts are relatively small, resulting from infrequent summer convective thunderstorms. For Squaw Valley, Hecht and Jett (1988) report that the mean annual precipitation measured at the Squaw Valley Fire Station is approximately 1.5 meters on the valley floor, nearly 4 m less than falls in the higher elevations. Taken together with its steeper, upper watershed and higher accumulations of snow, the south fork may have characteristics of rapid and high velocity runoff in contrast to the north fork, which because of the broad, montane valley and higher percentage of forest cover, may tend to absorb and attenuate runoff. All of these factors have, therefore, had an impact on the hypsometric curves produced for the Squaw Creek watershed and the respective north and south fork sub-watersheds.

4.1.5 Longitudinal Stream Profiles

Longitudinal stream profiles (long profiles) were constructed for the north fork, south fork, and the meadow reach of Squaw Creek (Figure 17) by plotting the horizontal distance of the stream channels against the elevation. Long profiles, or slope profiles, are reflections of the major geomorphic factors within a watershed, which consist of climate, rock type, structure, time, and process. Ritter et al. (1995) describe four main components of the long profile, all or some of which may be present: an upper convex segment, cliff face segment, straight segment with constant slope and angle, and a concave segment at the hillslope base. In mountainous areas with thin soils such as the Squaw Creek watershed, weathering-limited slope profiles are common and are determined by the characteristics of the parent rock (Ritter et al., 1995).

Figure 17 shows that the profile for the south fork of Squaw Creek is steeper than the north fork. This suggests that the south fork has naturally higher stream power than the north fork. The shape of the profiles also illustrates the "stepped" nature of the north fork. Where the south fork generally maintains the same stream slope gradient until reaching the confluence, the north fork passes through several lower-gradient areas prior to meeting the south fork. These areas serve as depositional sediment storage sites and energy dissipaters, reducing overall stream power. The meadow reach below the confluence of the north and south forks is fairly flat until it reaches the terminal moraine, where it then continues on to its confluence with the Truckee River.

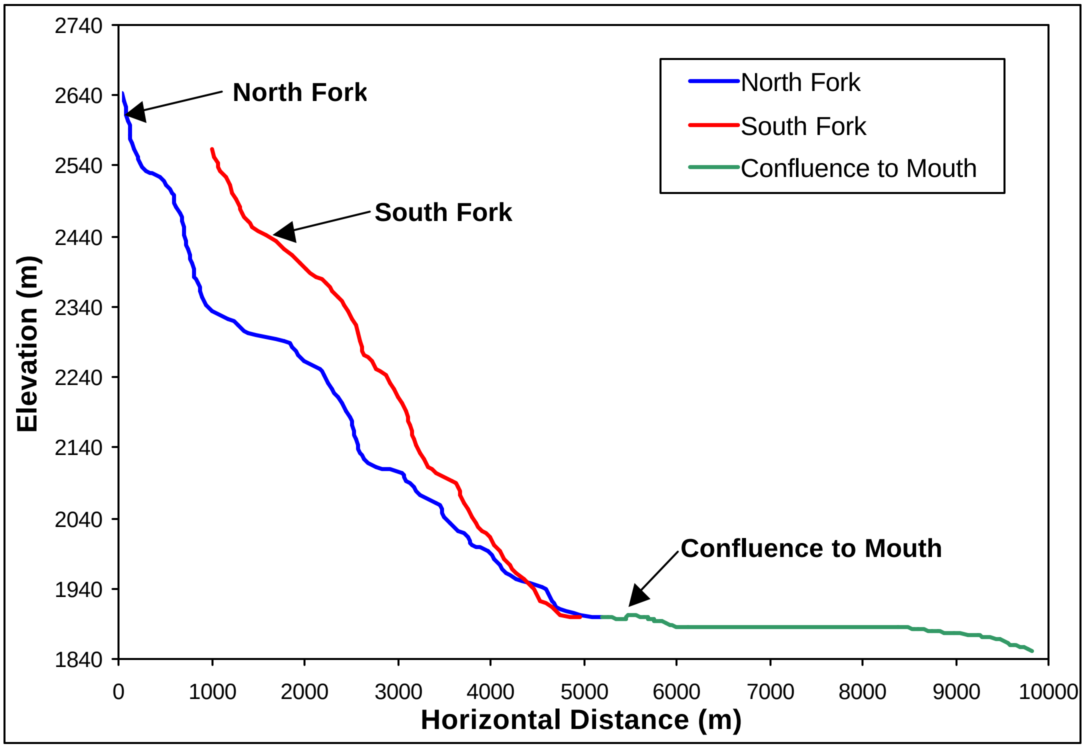


Figure 17. Long profiles for north fork, south fork, and meadow reach of Squaw Creek.

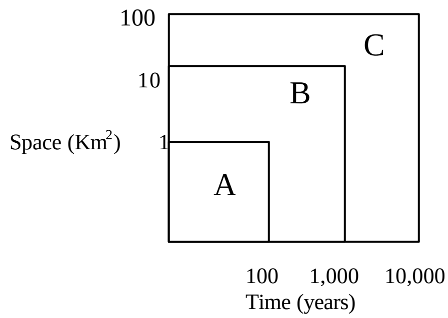
4.2 Hillslope Sediment Sources

Much of the Squaw Creek watershed area is comprised of hillslopes, which serve as the original source of all sediment in the basin. In the hillslope environment, geologic factors such as rock type and structure influence the production of sediment available for transport and the characteristics of the sediment (e.g., particle size). Transport of sediment to the main trunk is accomplished via the tributary stream network and through direct inputs, such as landslides.

Hillslope sediment supply is influenced by geomorphic variables that operate at differing time scales on or within a watershed and include both internal and external variables. Internal variables are unique to a watershed and its local environment and include soil infiltration conditions, surface roughness of hillslopes; and drainage density and configuration. External variables are more regional in nature and include precipitation characteristics, alluvial-fill geometry, and bedrock type and continuity. External variables influence such processes as rilling, gullying, and headcutting. Internal variables influence processes such as soil creep, debris and mudflows, sheetflow, and rilling (Wells and Rose, 1981). Table 5 lists the internal and external variables generally affecting hillslope sediment supply. Greater numbers of these variables are related to shorter examination timeframes and smaller study areas, whereas longer time periods and larger areas involve fewer, more regional variables. An examination of the internal and external variables is therefore necessary in providing a spatial and temporal assessment of sediment supply in a watershed.

Table 5. Variables affecting hillslope sediment supply (modified after Wells and Rose, 1981).

	INTERNAL	EXTERNAL
A	- Hillslope geometry, gradient, composition - Surface roughness - Drainage density and frequency - Surface and subsurface biomass - Infiltration conditions - Sediment yield and runoff per unit area	- Sediment yield and runoff (total) - Basin fill geometry - Bedrock heterogeneity - Precipitation intensity, duration, and timing
B	- Vegetation density - Hillslope relief and gradient - Drainage network - Rates of weathering and soil development - Degradation and aggradation rates	- Valley slope - Drainage area - Channel pattern and geometry - Bedrock Geometry - Climatic perturbations
C	- Vegetation density - Degree of soil development - Degradation and aggradation rates	- Base level change - Climatic change - Bedrock geology



For this study, hillslope sediment supply and erosional process analysis focused on variable classes A and B. Examination of the internal variables involved the investigation of distinct areas within the watershed by dividing the basin into study sectors that allowed for a more refined analysis. External variables were watershed-based and allowed for more general descriptions of basin characteristics. Integration of the internal variables into the context of external variables therefore provided a basis for developing an efficient methodology for the evaluation of hillslope erosional and sediment transport processes.

4.2.1 Influence of Bedrock Geology on Hillslope Sediment Production

Physical and chemical weathering processes break down bedrock which eventually become sediment particles available for transport; thus a consideration of the relative erosion potential characteristics of the rock types present in Squaw Valley provides a means by which to evaluate areas of potentially high erosion hazard. Bedrock sources were identified and assessed through a combination of field mapping, aerial photographic mapping and review of existing maps for the Squaw Creek watershed. Analysis of aerial photographs from 1939 (scale 1:24,000), 1987 (scale 1:30,000), and 1997 (scale 1:16,000) and field investigations verified and updated the bedrock and Quaternary geologic map first created for the area by Birkeland (1962). Data collected for bedrock units included descriptions of major rock units and geologic structure, an assessment of the relative susceptibility of rock types (macroscopic mineralogy, relative degree of weathering, position in the landscape and watershed) to erosion and the relative contribution of sediment production based upon visual observations and a review of previously published research.

Geologic units were differentiated using air photo recognition techniques (e.g., Ray, 1960; Siegel and Gillespie, 1980) that included tone/color, texture, shape, and size, and then verified by field reconnaissance. Sediment sources were identified by the smooth texture with a lack of vegetation and higher albedo (i.e., reflectivity) areas associated with sandy and silty deposits. Differentiation between the natural and anthropogenic sediment sources is primarily based on the 1939 and 1997 photos. Areas present in both sets of photos that show no significant change in size or shape and are associated with factors such as steep slopes (talus deposits) and/or contacts between rock units are considered pre-1939 and defined as natural sediment sources for the watershed. Sediment sources that were not present in both sets of photos and are linked to non-natural features, due to land development, such as roads, waterbars, and ski slopes are considered potential anthropogenic sources of sediment for the future, current and possibly recent historical supply of sediment.

Nolan and Hill (1991) provide insight into the effects of bedrock geology on erosion susceptibility through studies of several similar watersheds in the adjacent Lake Tahoe basin. The authors note that in General Creek, which is highly glaciated similar to the north fork of Squaw Creek, hillslope erosion in the upper portions of the basin is relatively low due to the fact that much of the weathered soil material was removed by glacial processes. As a result, much of the upper watershed consists of bare rock and minimal soil available for erosion and transport. In contrast, metamorphic and volcanic rocks present in the Blackwood Creek watershed, comparable to the south fork of Squaw Creek, produce thin, nutrient deficient (and therefore sparsely vegetated) soils. Such soils are susceptible to erosion via sheetwash and rilling and may increase runoff to the stream network as well. Nolan and Hill (1991) make an important note, however, regarding both watersheds. Although the General and Blackwood Creek watersheds contain different underlying bedrock components, both exhibit U-shaped valleys characteristic of glacial activity. The resulting wide, flat valley floors (analogous to Squaw Valley) effectively disconnect hillslope sediment transport mechanisms from the main stem of the stream in a completely natural setting.

Examination of the respective mineralogies of the rock types provides a further means by which to evaluate erosional susceptibility. Andesite bedrock commonly has a mafic groundmass (microscopic, iron-rich mineral assemblage) composed of olivine and plagioclase. The phenocrysts are typically augite, plagioclase, hornblende, and pyroxene. The alteration of andesite is commonly observed throughout the Squaw Creek basin and is identified as being either bleached (extensive weathering rind) or colored brightly in reds and yellows (Birkeland, 1961). Granite and granodiorite are typically coarser grained and mainly composed of quartz, potassic feldspar, plagioclase, biotite and hornblende. When comparing the mineralogy of the andesite to the granite, the andesite is compositionally more mafic (contains dark, ferromagnesian minerals) whereas the granite is compositionally more felsic (contains abundant amounts of quartz and feldspar). Mafic minerals are inherently less stable than felsic minerals and therefore weathering reactions proceed more quickly in mafic igneous rocks, such as andesite, relative to felsic igneous rocks, such as granite (Boggs, 1995; Hibbard, 1995).

The most important bedrock sources of sediment are those prone to producing fine-grained sediment because fine-grained material is more easily transported by hillslope processes such as overland flow, soil creep and dry slide (Young and Saunders 1986, Ritter et al., 1995). In the Squaw Creek watershed, rock units consisting of volcanic rocks and glacial deposits (generally heterogeneous mixes of coarse debris and fine silt) are the primary sources for fine sediment. Volcanic rock types, which are rich in easily weathered, dark ferromagnesian minerals, commonly weather by chemical and physical interactions down to fine-grained clay particles (Miller and Donahue, 1995). Areas of granitic bedrock typically produce coarser material, including grus, talus, sands, gravels, and cobbles when weathered (Hecht and Jett, 1988; Boggs, 1995) and only contribute fine material indirectly in the glacial valley walls that include both andesitic and granitic derivatives. In general, the south fork of Squaw Creek contains a higher percentage of volcanically derived bedrock (andesitic), whereas the north fork contains a greater percentage of plutonic bedrock (granitic) by area (Figure 2).

4.2.2 Measured and Observed Hillslope Erosion Rates

Young and Saunders (1986) suggest a process for obtaining sediment movement rates: develop instrumentation, measure rates of change using the instrumentation, and then spatially and temporally extrapolate the data obtained. This approach was used in the Squaw Creek watershed to assist in the identification of the dominant geomorphic processes operating within the watershed in reference to hillslope erosion. Selection of erosion monitoring sites and estimations of the types and distribution of processes were made from aerial photographic analysis and initial field reconnaissance, taking into account factors such as climate, vegetation cover, land use, and geologic setting. Subsequent GIS analysis and erosion data collection through use of erosion pins and sediment fences allowed for interpretation of the different processes operating within the Squaw Creek watershed, estimations of relative magnitudes and dominance, and assessment of seasonal periods of domination for particular processes involved in hillslope erosion. Representative areas of dominant land use and land cover types within the watershed were selected for measurement using a stratified sampling scheme and included:

- Exposed rock slopes
- Undisturbed mixed conifer hillslopes
- Erosion associated with graded ski runs
- Undisturbed slopes having chaparral cover

Sediment movement was measured at all data collection transect sites periodically which spanned a time frame with little to no precipitation. The data collected were used to calculate erosion rates representing different types of land use, land cover, and geology.

Relative sediment movement rates for each hillslope site were determined and extrapolated across similar areas in the watershed. To determine the overall average movement occurring at a site for the sampling period, the change (+/-) in pin measurement height between visits was calculated. Positive values for change in pin height indicated deposition at the point, and conversely, negative values indicated erosion. The absolute values of the calculated change values were then summed to indicate the overall movement at the pin for the sampling period. The absolute value was used to: 1) recognize that deposition at a pin is a result of erosion from some point above, so summing the absolute values of the change values provides an estimate of the overall movement on hillslopes, and; 2) ensure that the rate of movement at a site is depicted accurately such that instances of erosion and deposition occurring at the same pin do not negate each other. An average movement rate by site was then computed by summing the overall movement obtained for each pin and then dividing by the number of pins, yielding a movement rate for the sampling period (Wells and Gutierrez, 1982). Finally, precipitation data collected daily by the Squaw Valley Fire Department was utilized to extrapolate sampling period data and obtain an annual movement rate for each site.

Monthly precipitation records from 1993 to present were used to calculate the average annual amount of precipitation and included rain totals and snow totals converted to snow water equivalent values. Snow water equivalent values were computed by assuming an 8:1 ratio of snow depth to rain depth (NOAA, 2002). To determine the average annual erosion rate, it was assumed that precipitation was the primary agent of initiated sediment movement, so the total movement at a site was the result of the total precipitation occurring during the sampling period. Using this assumption, annual rates of movement are obtained by relating the precipitation that occurred during the sampling period to the average annual expected precipitation (annual average precipitation calculated from taking the average of annual precipitation values from 1964 to 1993). The equation below illustrates the computation process used to derive annual movement rates:

$M_A = (M_{SP} / PPT_{SP}) * PPT_A$

M_A	Annual movement rate, m/year
M_{SP}	Sampling period movement rate, m/sampling period
PPT_{SP}	Total precipitation for the sampling period, inches
PPT_A	Average annual precipitation, inches

A table of the computations used to calculate erosion rates for each erosion pin transect site is provided in Appendix E. By using the data collected at erosion pin transect sites, erosion fences, and geomorphic field reconnaissance, the conclusions were drawn from the data for different representative land use, land cover, and geology categories, as described below.

Exposed rock slopes (Sites EPIV-9, EPV-1, EPV-2, EPV-3) - Transect locations EPIV-9 and EPV-3 are both located on actively eroding andesitic hillslopes consisting of coarse angular talus and fine-grained silty sediment. EPV-1 and EPV-2 are located on granitically derived coarse sandy regolith with some established vegetation. Erosion rates obtained for these bare rock and soil monitoring sites indicate that these sites are low to moderate producers of sediment, excepting bare granite in undisturbed areas such as the north fork, which displayed few signs of active, measurable erosion.

Undisturbed mixed conifer (Sites EPII-2, EPII-4, EPIII-1) **-** The lowest erosion rates generally are associated with forested areas. These lower rates provide evidence of the importance of overstory canopy cover as well as litter and duff covering the soil, which have the effect of reducing rain drop impact, increasing infiltration, and limiting rill initiation (Morgan et al., 1986).

Erosion associated with graded ski runs (Sites EPII-1, EPIV-3, EPV-7) - Erosion measurements from graded ski runs exhibit variability in erosion rates but generally are moderate to high sediment producers. Field observations support the high erosion rates on the graded or disturbed portions of ski runs. Graded ski runs exhibit high potential for rill and gully formation (Figure 18).

Figure 18. Rill and gully formation on graded ski run in Sector V, approximately 40 to 50 cm deep (photo courtesy of Lahontan RWQCB).

The site measured to have the highest erosion rate in relation to erosion on ski runs (EPIV-3), is located on moderate slopes (17° compared to slopes of 30° to 35° at other sites), sparsely vegetated with grasses and shrubs, and is located upslope of a primary dirt road (Figure 19). Another, smaller road is located above the site with a roadside drainage ditch approximately 30.5 m (100 ft) north of the edge of the sample site. This site not only had the most erosion and deposition in relation to land use impacts, but also is one of the few sites with well-developed rills, suggesting that roads exert a significant impact on increasing sediment movement on hillslopes by concentrating runoff and aiding the formation of rills and gullies.

Figure 19. Ski run site, EPIV-3. Slope angle is approximately 17º. Photo was taken just below the dirt road that is located above the site, looking east.

Another ski run (EPII-1) had calculated erosion rates near values estimated for natural bedrock and bare soil sources. This value appears to be due in part to the high degree of compaction at the sample site, which retards soil movement during short duration, low intensity precipitation events. However, more intense storms may initiate rilling and gullying, as evidenced by the severe gullying just east of the site. Additionally, compacted soils have lower infiltration capacities and although the ski run itself may not erode during low intensity storms, the increased runoff caused by the compacted conditions may create problems downslope and downstream.

Undisturbed slopes having chaparral cover (Sites EPIII-2, EPIII-3) - Undisturbed chaparral environments might be expected to have low rates of soil movement.

However, one of the chaparral sites (EPIII-2), located adjacent to a mixed conifer forest transect, exhibited moderate levels of movement, despite the presence of mature shrubs and grasses. Morgan et al. (1986) provide a possible explanation for the observed values. Citing other related studies which reached similar conclusions, the authors reported that below 50% canopy cover, soil detachment rates were equal to those obtained for bare soil, and that most of the detachment occurred during the onset of precipitation events. The Morgan et al. (1986) study and data collected for this project suggest that because of the vegetative morphology of most shrubs (generally open-branches and small leaves) and resulting low canopy cover and minimal litter and duff layers that chaparral environments will yield moderate rates of soil movement. The noticeably high rate of erosion for the other chaparral site (EPIII-3) is not completely a function of vegetative cover, but rather may additionally be a result of the location of the site itself. It is part of a natural gully drainage at the contact between andesite bedrock and the lateral moraine deposit, conditions which are conducive to soil movement. Being that the site is situated on the edge of the incised drainage on a drier, southern aspect hillslope, erosion rates may be locally elevated.

In addition to erosion pin data, other methods were utilized to assist with the assessment of hillslope erosion rates and sources of sediment and are discussed below. Following precipitation events during 2001, all erosion fence structures on the hillslopes were revisited and only one, SFII-10 showed evidence for substantial sediment movement. This site is approximately 9.1 m (30 feet) below a waterbar (a sediment and runoff diversion structure transverse to the centerline of a road) installed on a maintenance road (Figure 20). Following precipitation events, the erosion fence was filled with fine sand and silt indicating that the roads are producing and transporting significant amounts of sediment. Sediment collected by erosion fence structures downslope of culverts draining the residential subdivision in Sector III (sites SFI-01 and 02) indicates that active transport of fine-grained sediment occurs from road drainage diversions to the meadow and subsequently Squaw Creek. In particular, subnival flow below the culvert outlets was observed reaching the creek during the winter of 2002, indicating that sediment movement occurs at any time of the year (Figure 21).

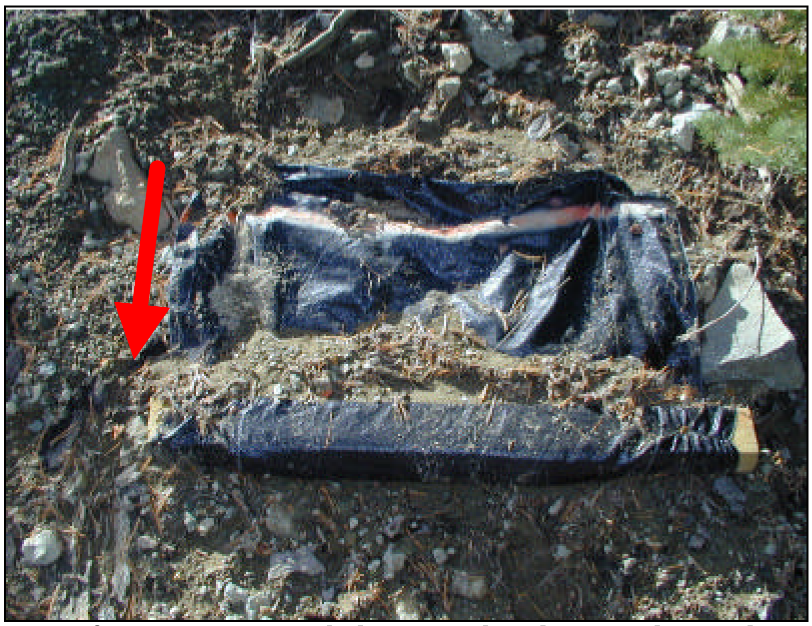


Figure 20. Erosion fence site SFII-10 below waterbar draining dirt road. Red arrow indicates downslope direction. Erosion fence is approximately 60 cm long and 9 cm high.

Finally, several sites were marked with a large, orange "x" spray painted on the ground to aid in re-location of potential monitoring sites and as observational tools for monitoring sediment movement (Goudie, 1981; Gardner, 1986; Thorne, 1998). Sediment movement is suggested by the distortion and disappearance of the orange "x." Between the time of installation and the first measurement, nearly all evidence of the "x" was removed from all such marked sites, indicating that even during periods of low or lacking precipitation, hillslope sediment movement is actively occurring.

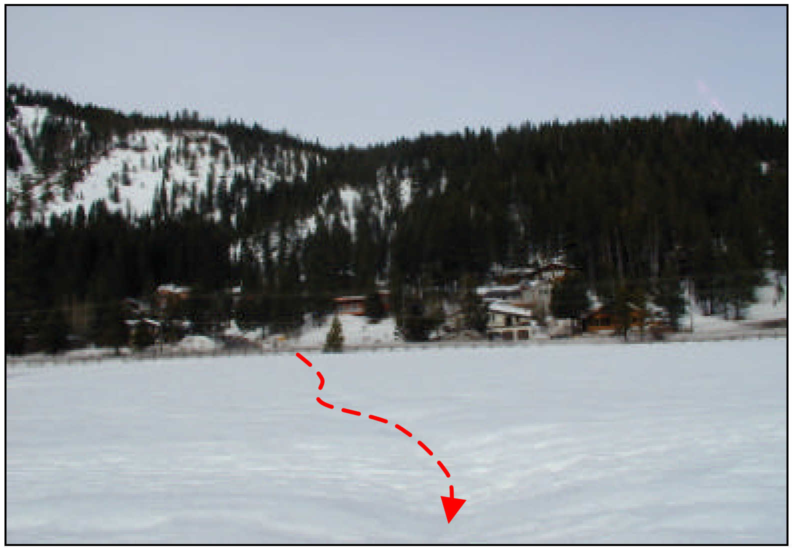


Figure 21. Red dashed line shows direction of subnival flow reaching Squaw Creek draining from subdivision culverts. Flow was observed entering meadow from culvert, following flow path under snow (identified by depression of snow along dashed line), and exiting into Squaw Creek.

4.2.3 Active Geomorphic Processes

Typically, watershed studies focus on in-stream sources of sediment while indirectly estimating the contribution from the hillslope denudation. Denudation is defined as the general lowering of the ground surface by removal of sediment from within a drainage area (Young and Saunders 1986) and is accomplished through the mobilization of colluvium on a hillslope through erosional processes and subsequent transport of sediment down slope (Reid and Dunne, 1996). Rates and types of active processes can be affected by variations in temperature and precipitation that impact weathering (e.g., freeze thaw, frost wedging) and transport processes. Processes such as dry ravel and slide, soil creep, and frost heave all dominate during relatively dry years with little precipitation, whereas wetter years initiate processes of mass movements (landslides), debris flows, gully formation, gully-wall erosion, and headcut erosion in relation to sediment supply to the stream. Thus, even during dry periods, active erosional processes are taking place on the hillslopes surrounding the valley which impact sediment supply and transport in the stream network. Figure 22 illustrates the generalized erosional processes that operate in a hillslope environment. Active transport processes operating on hillslopes in the study area are described below, as determined from geomorphic field reconnaissance and field instrumentation.

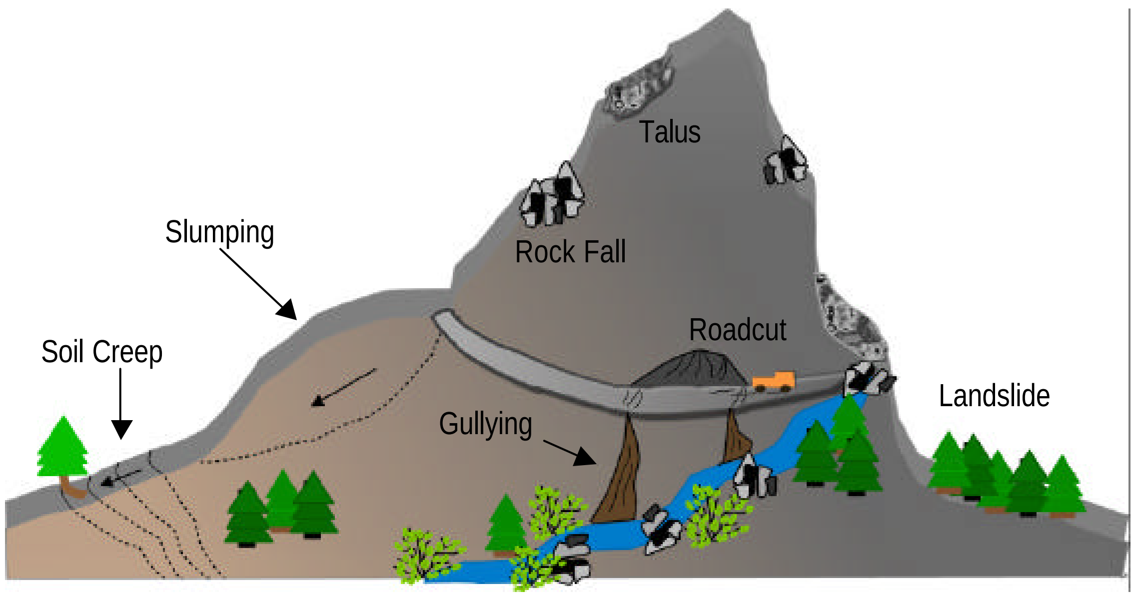


Figure 22. Generalized hillslope erosional processes.

Soil Creep - Soil creep is an active, widespread geomorphic process in the watershed relative to sediment transport on hillslopes. Soil creep is the process by which regolith is transferred down slope through expansion and contraction of the uppermost portion of the soil column. With this process, denudation commonly takes place at the very top of the slope. An examination of several studies by Young and Saunders (1986) found that creep is affected by particle size (smaller particles move faster than larger), soil moisture content (wet sites creep faster than dry), and the mechanism of heave that is produced by soil swelling and freezing and by freeze/thaw activity (Ritter, 1995). This last mechanism is important in relation to the Squaw Creek watershed because in mountains freeze-thaw processes dominate soil creep (Boggs, 1995; Ritter et al., 1995; Allen, 1997). Slope angle, soil texture, and vegetation play secondary roles in heave mechanisms (Young and Saunders 1986). Heave may have implications for this study because sites located higher in the watershed typically receive more snow than lower elevation areas, and therefore have higher soil moisture content and a related increased likelihood of freezing. This is evidenced by observations of numerous erosion pins that were pushed out of the ground over the winter by these processes. Young and Saunders (1986) report soil creep rates of approximately 15 mm/year, which is on the same order of magnitude of calculated erosion rates for this study.

Overland Flow and Sheetwash - Small-scale sediment fans composed of granitic grus (deposits of coarse-grained, angular rock fragments) were noted throughout the watershed where granite outcrops are common and are evidence of active erosional processes, such as sheetwash erosion. This appears to be a common occurrence for the transport of relatively coarse debris down the hillslope in addition to more typical creep processes, which are active throughout the watershed. Coarse-grained material appears to remain on the slopes or at the base of steep slopes where it acts as an effective sediment trap for fine-grained slope materials (e.g., Caine, 1986; Gardner, 1986).

Overland flow occurs as saturated overland flow in the spring when the soil profile is saturated from snow melt, and Hortonian flow in drier seasons. Hortonian flow, or surface wash, occurs when rainfall intensity supercedes surface soil infiltration capacity and surface runoff is initiated. Factors that affect infiltration capacity and subsequent rates of erosion due to runoff include differences in rainfall intensity, vegetation cover, soil erodibility, slope, and slope length (Young and Saunders 1986). The processes of overland flow have been shown to initiate rilling and gullying once surface flow becomes unstable through concentration of flow. Studies have shown that erosive surface sheetflow is fundamentally unstable and therefore when it occurs, it is likely to form networks of rills and gullies with increased soil erosion (Savat. and De Ploey, 1982; Dunne and Aubry, 1986; Young and Saunders 1986).

Rills and Gullies - As described above, overland flow tends to concentrate on compacted surfaces with low infiltration capacity such as disturbed hillslopes, dirt road surfaces, and along the margins of dirt roads, leading to the development of rill and gully networks in these areas (Brunton and Bryan, 2000). Rills are typically a few centimeters deep and wide, although, some master rills have developed into larger gullies that are capable of producing significant amounts of sediment (Seginer, 1966; Selby, 1982). Processes of gullying and rilling are visibly prominent on ski runs and roads in the study area. During field reconnaissance and data collection efforts, observations and evidence of water flowing along roads and on road surfaces mobilizing sediment during rainstorms (rill and gully formation, plumes of sediment in drainage ditches) was most notably apparent in the south fork of Squaw Creek.

Frequent road grading prohibited the establishment of rill transects to estimate rates of erosion. However, observation of rills developed on roads and ski runs demonstrates the direct effect that land use has on the evolution of rills and gullies. Studies of sediment volumes derived from gullies in the Blackwood and Edgewood Creek watersheds in the Lake Tahoe basin by Nolan and Hill (1991) support this assertion. All gullies inventoried in the two watersheds were formed as a result of drainage concentration, which in most cases was associated with roads. Within the Edgewood Creek watershed in particular, the permeable granitic-derived soils are not prone to developing gullies under undisturbed conditions, which was similarly noted during field reconnaissance for the granitic soils of the north fork of Squaw Creek. Additionally, comparisons of suspended sediment budget data for Edgewood and Logan House creeks in the Lake Tahoe basin indicate that sediment supply and in-stream storage has increased as a result of erosion from gullies and road cutslopes in these streams (Nolan and Hill, 1991).

Mass-Wasting - Large scale mass wasting is most apparent on the south facing exposure in the northern lateral moraine in the form of historic landslides, but smaller-scale mass wasting processes (e.g., slope failure on cut banks) are also visible in road cuts elsewhere. It is not clear as to why large scale mass wasting has occurred in the northern valley wall and not in the southern valley wall, as soils, geology, and angle of slope are similar for both areas, although aspect may have had an effect on vegetation establishment on the southern valley wall. A relatively large slide occurred several thousand years ago in the vicinity of Hidden Lake (Jones, 1981), which is a small sag pond formed within a landslide mass in Tioga age glacial till near the northeast end of the watershed. More recently, smaller landslides are observed in the Hidden Lake area, which were attributed in part to poor construction activities (Jones, 1981), and small debris slides on the south side of the valley east of the Resort at Squaw Creek that occurred during the winter rain-on-snow event of 1997. The large area of irregular topography on the northern margin of the valley floor (currently partially covered by residential housing) most likely represents an ancient landslide mass. The currently active processes on the landslide scar appear to consist of shallow, slumps at the head of the slide, shallow translational slides and debris flows that are funneled into a main drainage that traverses the residential area and is finally transported to the north edge of the meadow via culverts. Coarse material is deposited at the edge of the meadow, but much of the fine-grained, suspended material is delivered to Squaw Creek by water flowing from the culverts through the drainage ditch structures that were installed during the 1960 Olympics for meadow parking (Figure 10).

When landslides occur, they contribute a significant amount of sediment to stream networks compared to all other erosional processes acting in the watershed. However, because landslides are typically rare, sporadic events, they are not considered to be the dominant source of sediment compared to continuously active erosional processes, such as soil creep. Young and Saunders (1986) suggest that slope form supports this assertion; that is, if landslides were the dominant process, hillslopes would have a hummocky ("bumps and hollows") morphology. In the Squaw Creek basin, like most watersheds in the Sierra Nevada, slopes generally have a smooth, concave-up form suggestive of active geomorphic processes such as creep and overland surface flow.

Other mass-wasting processes observed in sub-alpine environments that are aided by gravity and weathering include rock falls on the upper slopes of the watershed that form talus cones, debris flows, and rock slides. While common, these processes do not readily produce and transport coarse and fine grain sediment, but rather the large fragments of rock are the initial stages of bedrock degradation.

Particle size analysis - The particle sizes of sediment available for transport from the hillslopes and stream channel were analyzed by the Soil Characterization and Quaternary Pedology Laboratory at the Desert Research Institute (Appendix F). Samples were obtained in the vicinity of established erosion pin transects, in stream channels, and in sediment capture devices to determine both the sizes of available sediment and the caliber of sediment being transported on hillslopes. Particle size analysis of the samples showed that, in general, sediment available is larger than 2 mm (delineation between sand and gravel), although Nolan and Hill (1991) noted that the majority of sediment likely to be transported in watersheds within the Lake Tahoe basin is finer than 2 mm. In most sites in the Squaw Creek basin, approximately 50 to 70 percent of the sediment available for transport is greater than 2 mm. Of the remaining 30 to 50 percent of sediment, typically 75 to 80 percent is sand and only about 20 percent is silt and clay. However, in natural and artificial sediment traps and on certain types of hillslopes, there was less than 50 percent gravel and between 30 and 45 percent silt and clay. Bar samples in Squaw Creek are dominantly sand and gravel with very small percentages of silt and clay, indicating that most silt and clay is likely transported through the system in the washload. Hecht and Jett (1988) also document that suspended sediment discharge for Squaw Creek is dominated by silts, clays, and fine sands. Particle size distribution graphs are contained in Appendix F.

4.3 Road Sediment Sources

The presence of road networks represents a potential primary mechanism for significant increases in sediment delivery to streams (Grace et al., 1996; Sun and McNulty, 1997) and is considered to be more important than impacts such as deforestation (Swanson and Dyrness, 1975). Roads and their associated attributes (the road corridor), such as drainage ditches, road surfaces, cut banks, fill slopes, stream crossings, and culverts, as well as sand applied during winter months, all contribute to stream sediment through two main mechanisms: increased runoff and increased sediment yield (Foreman and Alexander, 1998). Roads and road corridors function both as sediment sources and as delivery mechanisms for runoff and sediment by concentrating flows and increasing overall watershed drainage density, leading to higher watershed peak flows and therefore increased stream erosive power. Interruption of other hydrologic processes by roads include subsurface flow conversion to surface flow through road cuts, increase and elongation of first order streams from concentrated flows off of roads, engineered structure failure (e.g., culverts and bridges), and compaction and redistribution of the soil matrix through cut and fill construction techniques and use. These interruptions can all lead to dramatic increases in landslide frequency and in-stream sediment supply (Swanson and Dyrness, 1975; Foreman and Alexander 1998; Jones et al., 2000). Brown (1994) notes that the extent and degree of impacts from roads is related to vegetation and cover, soil types, topography, and the level and type of use associated with the road corridors.

The impacts associated with a road network are related to the spatial relationship between the road corridors and hillslope position (ridges, mid-slope, valley bottom) and connection of road segments to stream drainages. Road segments situated on high ridges in upper watershed areas may experience significant erosion impacts related to the deeper snowpacks that occur in these areas. The snowpacks supply more available water for erosive work during melt periods, but because these roads are generally not directly connected to streams by virtue of their position in the watershed, their contribution of sediment to streams is limited. Roads located in mid- and lower portions of a watershed, however, typically cross stream reaches more frequently and therefore are directly connected to the stream network (Jones et al, 2000). Roads located in these areas may be oriented parallel to the main reaches of the stream, allowing the associated rills, gullies, and culverts to effectively transport sediment directly to the stream (Figure 23). Mid- to lower-slope road cuts also are more likely to intercept shallow subsurface water flow, causing the flow to become surface runoff in addition to runoff from the road itself (Wemple et al., 1996) (Figure 24). Similarly, road drainage ditches function in the same connective capacity as road segments, transporting and generating sediment from road surfaces and associated ditches, cut banks, and debris slides directly to stream networks (Jones et al., 2000).

Figure 23. Gully formed on road surface concentrates and directs runoff and sediment to an adjacent stream channel in Sector IV. Red arrow indicates direction of flow.

Figure 24. Interception of shallow groundwater on cutslope contributes to increased flow in ditches and road surfaces.

Road density is frequently used as an overall index of the impacts of roads in a watershed because negative effects (e.g., higher runoff, increased sediment delivery to streams) increase with increased density (Foreman and Alexander, 1998). The Squaw Creek watershed exhibits a particularly high density of roads in certain portions of the basin (Figure 25). The road density for the overall watershed is 3.62 km/km^2 (5.78 mi/mi^2), with the highest density occurring in the south fork sub basin: 10.03 km/km^2 (16.17 mi/mi^2) (Table 6). Using the logging road density from Madej (2000) for a North coast watershed of 5 – 7 km/km^2, the latter value for the south fork of Squaw Creek is approximately three times greater than a typical managed (logged) watershed. For comparison, road density values for Heavenly Valley ski resort in the Lake Tahoe basin were calulated using a GIS. Heavenly Valley's road density values are estimated to be 3.75 km/km^2, which is notably less than those found in the ski area portions of Squaw Creek. Foreman and Alexander (1998) note that increased peak flows in streams may be evident at road densities of 2 – 3 km/km^2. These figures would indicate that the road densities in the south fork of Squaw Creek and on the north-facing valley moraine wall are large enough to create a negative impact on the stream network.

Table 6. Density of dirt roads by area and density of dirt roads by area above 2,300 m (7,550 feet) elevation.

Location	**Road Density: km/km^2 (mi/mi2)**	**Road Density: km/km^2 (mi/mi2) above 2,300 m (7,550 feet) elevation**
South Fork Sub-basin	10.03 km/km^2 (16.17 mi/mi^2)	8.65 km/km^2 (13.93 mi/mi^2)
North Fork Sub-basin	0.56 km/km^2 (0.89 mi/mi^2)	0.61 km/km^2 (0.97 mi/mi^2)
North Facing Valley Wall	6.73 km/km^2 (10.83 mi/mi^2)	6.02 km/km^2 (9.69 mi/mi^2)

The drainage density (D_d) of a basin is defined as the summation of the stream lengths (ΣL_S) over the basin area (A): $D_d = \Sigma L_S/A$ (Wemple et al., 1996). Drainage density has been used as an indicator of the efficiency of a stream network such that higher drainage density values indicate greater discharges, erosive power, and sediment transport within the watershed. Wemple et al. (1996) and Jones et al. (2000) have shown that the overall drainage density of a watershed or subwatershed is increased via road network connectivity with the stream network because roads function as extensions of the drainage network. The increase in drainage density, termed the “effective drainage density”, results in higher peak flows, increased delivery of runoff to streams, and in-stream erosion. Drainage density increases ranging from 21% to 50% for several roaded study areas were noted by Wemple et al. (1996). These values would be somewhat higher if gullies (a by-product of the road corridor) that feed into the stream network were included in the analysis. A comparison of drainage densities for sub-basins in the

Squaw Creek watershed adjusted for road connectivity (effective drainage density) and under an undisturbed regime is represented in Table 7.

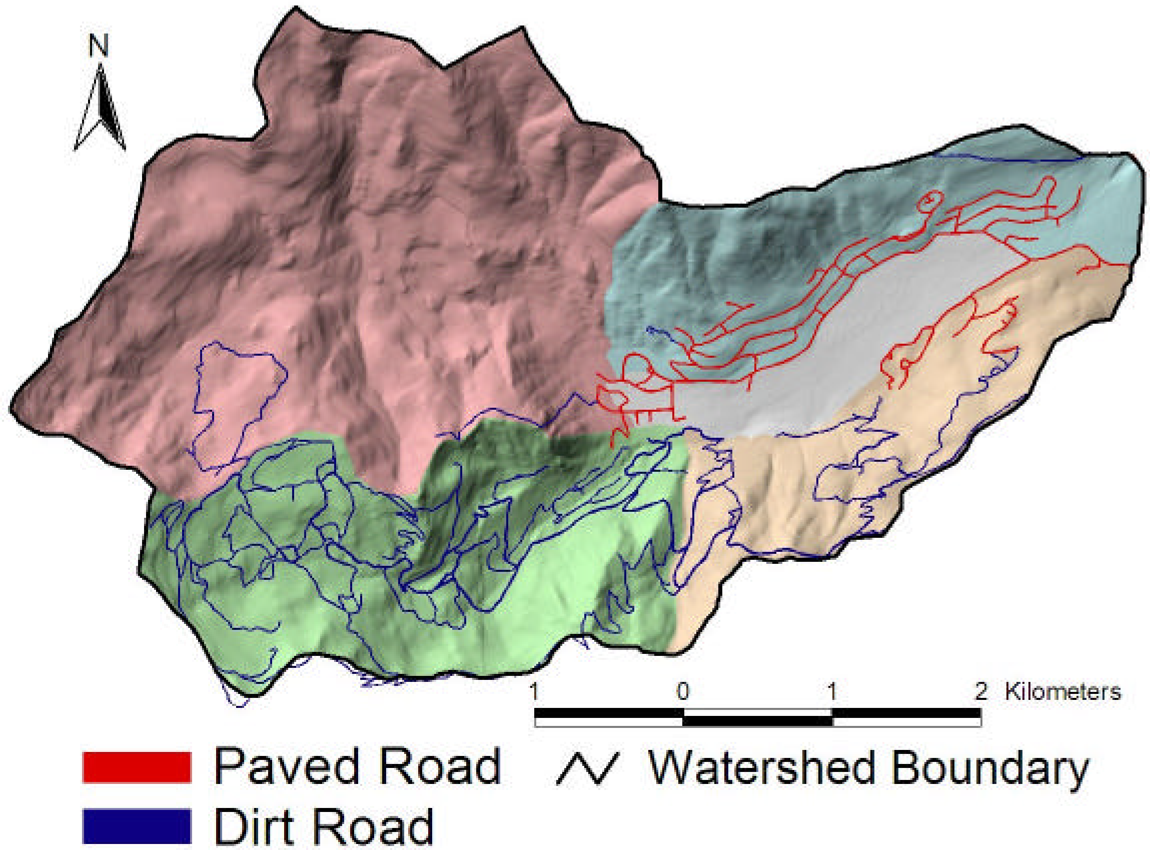


Figure 25. Distribution of primary and secondary dirt and paved roads in the Squaw Creek watershed overlain on study sector map.

In studies conducted by Jones et al. (2000) and others, steep forest landscapes were found to have an increase in the frequency of debris slides, debris flows, and landslides associated with road networks located within the watershed when compared to similar watersheds that were forested and undisturbed (roadless) (Wemple et al., 1996). These mass movements are considered to be the major source of sediment in some mountain streams (Fredricksen, 1970; Madej 2000). Varnes (1978) found that small

Table 7. Stream network drainage density and effective drainage density adjusted for dirt road connectivity to streams.

Location	Drainage Density: km/km^2 (mi/mi^2)	Effective Drainage Density: km/km^2 (mi/mi^2)	Increase in Drainage Density
South Fork Sub-basin	2.93 km/km^2 (4.72 mi/mi^2)	10.24 km/km^2 (16.48 mi/mi^2)	250%
North Fork Sub-basin	4.58 km/km^2 (7.37 mi/mi^2)	5.06 km/km^2 (8.14 mi/mi^2)	10%
North Facing Valley Wall	5.01 km/km^2 (8.06 mi/mi^2)	8.61 km/km^2 (13.84 mi/mi^2)	70%
Squaw Creek Watershed	4.02 km/km^2 (6.50 mi/mi^2)	7.6 km/km^2 (12.3 mi/mi^2)	90%

scale, shallow translational slides are associated with roadcuts and steep slopes having thin mantles of colluvium. It is possible that the translational slides may be influenced by natural processes, such as frost heaving, caused by differential expansion of clay minerals.

Rills and gullies formed on unvegetated cut and fill slopes associated with roads are found to induce slope failures and provide direct sediment input to streams. Midslope road crossings of first through third order streams, as classified by Strahler (Ritter et al., 1995), were found to have significant occurrences of debris flows, which indicates the significant impacts that road stream crossings have (Jones et al., 2000). Jones et al. (2000) therefore propose that cumulative effects resulting from road stream crossings increases at downstream locations of areas with high densities of these crossings. Using a GIS, a total of 66 drainage crossings were identified in the Squaw Creek watershed that have the potential to affect the hydrologic routing within Squaw Creek sub-basins.

Peak flow, or peak discharge, is defined as the maximum volume flow rate passing by a particular location in a stream during a precipitation event or specified timeframe. Increases in peak flow can bring about alterations in stream channels, such as channel width enlargement, channel incisement, rapid soil movement, bed and bank erosion, and bank failure (Hancock et al., 1998; Madej, 2000). It has been observed that road networks connected to streams cause increases in peak flows through hydrologic rerouting of hillslope water that would naturally be infiltrated through soil, resulting in the aforementioned channel impacts (Foreman and Alexander, 1998; Jones et al. 2000). Paired watershed studies in the Idaho Batholith by Wemple et al. (1996) strongly support these observations by showing a statistically significant change in peak flows as a direct result of the presence of roads. Increases in peak flow are accomplished by road network connectivity through roadside drainage ditches which reroute precipitation runoff generated from compacted road surfaces and intercepted shallow subsurface water from roadcuts. Compacted road surfaces cause a decrease in infiltration capacity and soil permeability and an increase in surface runoff resulting in accelerated water erosion, removal of vegetation, and increases in the production of fine sediment (Brown, 1994; Foreman and Alexander, 1998; Jones et al., 2000). Drainage water may then be rapidly delivered to stream networks, causing not only increases in magnitude, but increases in the frequency of peak discharge as well (Wemple et al., 1996; Jones et al., 2000; Madej, 2000).

Culverts present unique issues related to watershed erosion. Runoff from road surfaces, ditches, and cutslopes is concentrated by rerouting through culverts, thus increasing its erosive power. This can lead not only to increases in delivery of sediment to the stream network where culverts are directly discharging into streams, but gully formation and incision can occur below culvert outlets which then deliver additional sediment and flow (Megahan et al., 1986). The amount of sediment increase can be significant from these gullies; Megahan et al. (1986) reports deposition quantities of up to 15 times greater from gullies resulting from culvert discharge over that of runoff from only the road surface. Steep slopes (>40%) in particular warrant attention as they are significantly more prone to gullying and may thereby add sediment and create another mechanism by which roads are connected to the stream network (Wemple et al., 1996). In addition to the physical effects of hydrologic rerouting, sediment delivery increases can result from culvert failure. Plugged or undersized culverts may cause stream flow to divert around the structure and erode road fill material and cause rilling or gullying. Similarly, failed culverts above stream networks may divert and discharge flow onto unprotected hillslopes causing rilling and gullying (Megahan et al., 1986; Madej, 2000).

With consideration of all these factors, quantification of sediment yields from road corridors can be problematic despite their importance as a primary source to stream networks, particularly in high-traffic watersheds such as Squaw Creek. However, several sources provide comparisons of sediment load in disturbed (roaded) and undisturbed systems that can be used as guides in assessing the relative contributions of sediment from roads. In a study of logging roads constructed in a forested watershed, Fredrickson (1970) reported that sediment output was 250 times that of the undisturbed condition following road construction, decreasing to two or three times during subsequent years. Logging road construction in the Idaho Batholith, consisting of steep granitic terrain and shallow coarse-textured soils similar to portions of the Squaw Creek watershed, resulted in accelerated surface erosion and sedimentation hundreds of times greater than undisturbed watershed rates (Megahan et al., 1986). Megahan et al. (1986) also reported road erosion rates of 50 m^3 ha^{-1} for constructed logging roads in the No Name Creek basin in Idaho. Using the Universal Soil Loss Equation (USLE), Sun and McNulty (1997) predicted a loss of 1 to 50 metric tons/ha/year from managed roads. Swanson and Dyrness (1975), in a study of right-of-way slide erosion along roads, found that right-of-ways associated with roads eroded thirty times faster than comparable forested sites.

Most discussion related to impacts of road networks in forested settings focus on unimproved (dirt) roads. However, paved roads also have the potential to contribute to accelerated levels of erosion in a watershed. There are a number of paved roads located within the Squaw Creek watershed, primarily in the residential subdivision and the main roads leading to commercial areas. Paved roads comprise approximately 21.2 km (13.2 miles) of the road network in the Squaw Creek watershed and nearly 1% of the total surface area of the watershed. Paved roads do not themselves contribute to erosion, but rather provide impervious cover that restricts infiltration and concentrates runoff and associated sediment transport. The runoff may then increase erosion in roadside ditches and adjacent unpaved surfaces, such as road shoulders. Field observations indicate that nearly all paved road runoff is collected in ditches and directed through culverts into the meadow or directly into Squaw Creek itself. In particular, fine-grained material appears to be frequently transported into Squaw Creek utilizing remnant ditches created to drain the meadow for parking during the Olympics. Paved roads also represent a source of sediment due to road sanding operations during winter months, with approximately 360 tons of sand per year being used in the Squaw Creek watershed. Some sand applied in winter is mechanically removed through sweeping, although records are not maintained.

Additional road-related parameters were computed for the Squaw Valley watershed road network to provide a means to compare with erosion rates associated with roads in other study areas (Table 8).

Table 8. Total road length and road surface area in Squaw Creek watershed by road type.

		Road Surface Area (km^2[mi^2])		
Road Type	**Length**	**Squaw Creek**	**North Fork**	**South Fork**
Dirt – Single Track	41.9 km (26.0 miles)	0.255 (0.098) *[1.2]	0.082 (0.032) *[0.3]	0.187 (0.072) *[3.4]
Dirt – Double Track	13.2 km (8.2 miles)	0.161 (0.062) *[0.8]	0 (0) *[0.0]	0.114 (0.044) *[2.4]
Total Dirt Roads	55.1 km (34.2 miles)	0.416 (0.160) *[2.0]	0.082 (0.032) *[0.3]	0.301 (0.116) *[5.8]
Paved – Primary	6.9 km (4.3 miles)	0.063 (0.024) *[0.3]	0 (0) *[0.0]	0 (0) *[0.0]
Paved – Secondary	14.3 km (8.9 miles)	0.114 (0.044) *[0.5]	0.001 (0) *[0.9]	0.003 (0.001) *[0.1]

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

4.4 In-stream Sediment Sources

In-stream channel sediment sources and responses to changing sediment loads were assessed and qualitatively described utilizing previously reported data in addition to data collected for this study. Fluvial geomorphic assessment focused on geomorphic parameters commonly used in fluvial studies, such as those described by Thorne (1998), including: stream channel character; stream migration patterns; longitudinal profiles; sediment stored in the channel bed and bars and floodplain, and; the degree and manner in which stream channels respond to and recover from watershed activities, particularly elevated sediment loading. Field data included: channel cross-sections; channel bed sediment data (e.g., grain size distributions); percent of fines (from grab samples); channel characteristics (pattern, width/depth ratio, sinuosity); evidence of past and current channel aggradation; and assessment of current channel conditions in steep tributary stream reaches.

In undisturbed watersheds, erosion, transport, and deposition of sediment are natural in-stream processes, though relative rates from each may be altered by land use (Coleman and Scatena, 1986). In Squaw Creek, accelerated erosion of the stream banks appears to be occurring, resulting in higher levels of sediment in the stream. Evidence of bank erosion includes numerous undercut, cantilevered bank sections, and in-stream terrace-like features in the stream created by failed bank material (Figure 26). Measurements of stream cross sections established in 2001 (Appendix G) show the undercut nature of the meadow reach of Squaw Creek and indicate the potential for introducing significant volumes of sediment to the stream. It is important to note that accelerated bank erosion is typically the result of more than one influence, including both natural and anthropogenic sources. Air photo analysis shows that many of the natural processes occurring within the watershed have been active since the post-glacial period and are indicative of high elevation and relief, small, glaciated watersheds.

4.4.1. Bedrock Channels

Within the Squaw Creek watershed, both the north and south forks contain considerable portions of bedrock streams (Figures 27 and 28). Although Howard (1998) notes that few observations or direct measurements of bedrock channel erosional processes have been observed, these channels were considered for their contribution of sediment to the stream network primarily because of their connectivity to hillslope processes (e.g., Tinkler and Wohl, 1998). For this study, bedrock channels are defined as sections of stream consisting of at least 50% exposed bedrock within the channel.

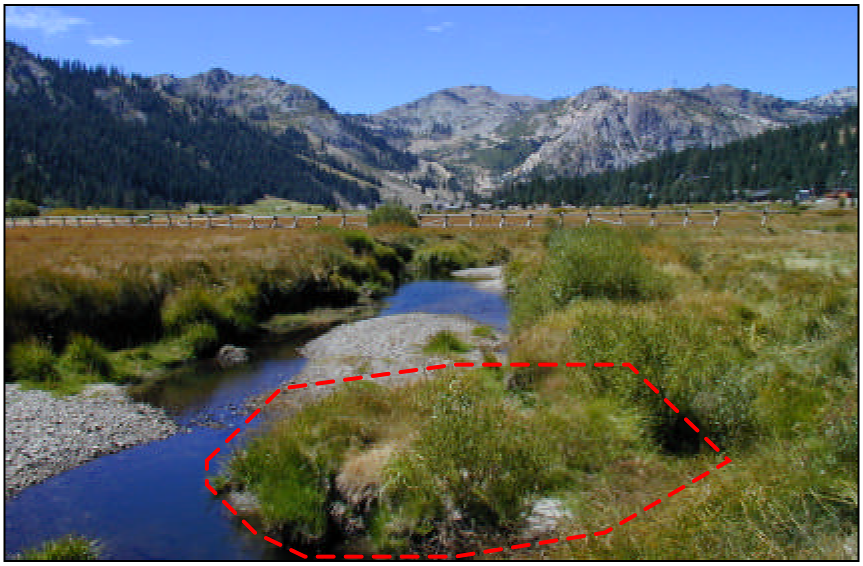


Figure 26. Dashed red line indicates location of in-stream terrace formation created by failed bank material.

Bedrock channel morphology reflects the interactions between erosive processes and bedrock resistance and can be used to infer dominant erosional processes occurring within the channel (Wohl 1998). Bedrock channels are eroded by three primary fluvial mechanisms: 1) corrosion, or chemical weathering and solution; 2) corrasion, or abrasion by sediment in transport along the channel, and/or; 3) cavitation and other forces associated with flow turbulence (Wohl 1998). The latter two are the dominant bedrock channel erosion processes in watersheds such as Squaw Creek, although chemical weathering can cause an increase in the rates of these processes by weakening the bedrock (Howard, 1998; Hancock et.al., 1998; Wohl, 1998). Rates of channel erosion are also adjusted by mass wasting processes operating within the system, including debris flows, rockfalls, and avalanches that supply additional sediment to the channel network (Howard 1998).

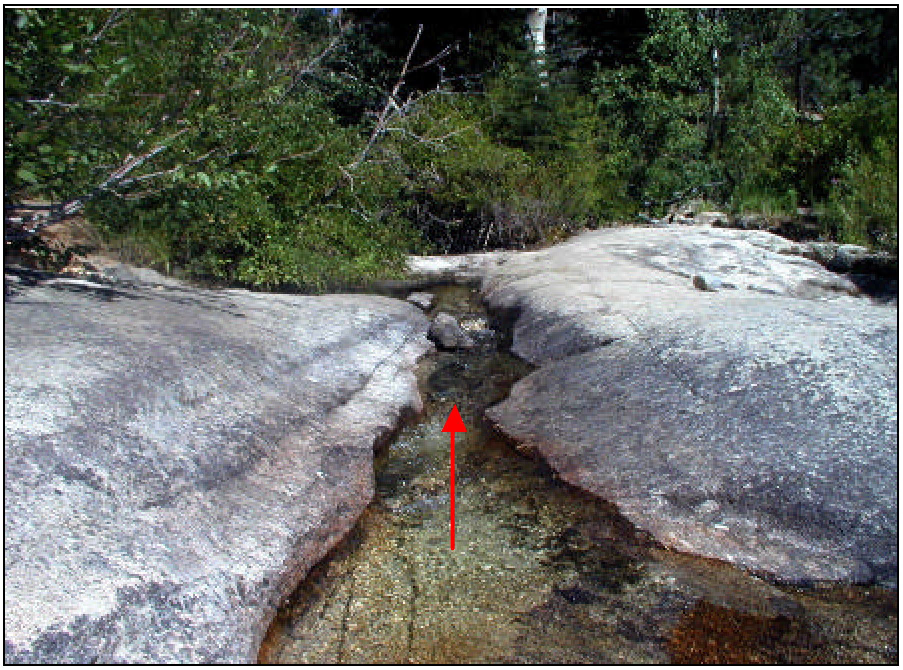


Figure 27. Bedrock channel in north fork subbasin. Red arrow indicates flow direction.

Figure 28. Bedrock channel in south fork subbasin.

Corrasion, or abrasion, is the erosion of bedrock channels and is facilitated by entrained bedload and suspended sediment. Incision rates from abrasion are regulated by the overall amount of sediment present within the system. Insufficient sediment supply results in low incision rates. An overabundance of sediment causes a veneer of alluvium to cover the channel bedrock, shielding it from abrasive forces and decreasing erosion rate. Therefore, a sufficient supply of sediment must be present for abrasion to take place, but not in such quantities as to restrict access to the bed (Pazzaglia et al, 1998; Sklar and Dietrich, 1998; Hancock et al., 1998). In the Squaw Creek watershed, abrasion processes appear to function under normal sediment regimes in the north fork and portions of the south fork. Wohl (1998) reports abrasion rates ranging from 0.25 to 3.9 mm per year, the latter being associated with granite, schist, and gneiss, and which may be an appropriate value for bedrock channels in Squaw Creek. However, the primary dam on the south fork acts a sediment trap that restricts the transport of coarse sediment to that portion of the stream below it (identified as a bedrock channel), resulting in reduced erosion of the bedrock from abrasion. Therefore, the amount of sediment produced from bedrock channel erosion is small.

Cavitation, formed in turbulent flow regimes, is a process that occurs when velocities in small regions of flow are sufficiently high that a localized temporary drop in pressure below the water vapor pressure is created, forming bubbles. The water vapor bubbles collapse once they are subjected to higher pressures, resulting in a microjet burst of water that acts as a miniature water hammer. The force exerted by the microjet can lead to surface pitting and cracking, and ultimately erosion of the bedrock channel. Investigations of flows in natural channels indicate that cavitation may be an important process under conditions of turbulent, sediment-impoverished flow (Tinkler and Wohl, 1998; Hancock et.al., 1998), as is the case below the dam on the south fork of Squaw Creek. Channels that exhibit coarse, even jointing, such as the granite that dominates bedrock channels in the north fork of the creek, experience similar hydraulic process-driven erosion similar to cavitation. The joints create inner channels that concentrate flow into a circular jet that excavates deep plunge pools and result in erosion of the bedrock channel (Tinkler and Wohl, 1998), as can be seen in the representative bedrock channel in the north fork of Squaw Creek (Figures 29 and 30).

Figure 29. Bedrock channel, north fork of Squaw Creek, showing granite bedrock with preferential flow along jointing.

Given the low rates of bedrock incision relative to other sources, and the presence of impacts in the watershed that tend to reduce corrasion forces, sources of sediment from bedrock within the Squaw Creek watershed are most likely negligible in comparison to other sources.

Figure 30. Plunge pool, north fork of Squaw Creek.

4.4.2. Alluvial Channels

Stream channels and the banks are known to be important sources of sediment. Sediment derived from these processes constitutes a major portion of the sediment budget for a watershed, measuring in the tens of millions of tons per year in larger watersheds (Darby and Simon, 1999). The meadow section has the potential to be a large contributor of sediment to Squaw Creek as a result of bank erosion during high stream discharge events associated with peak spring snowmelt. This is consistent with other studies in the Lake Tahoe basin (Nolan and Hill, 1991) that found that in-stream sources constituted approximately 95% of the suspended sediment to Lake Tahoe.

Darby and Simon (1999) describe destabilized geomorphic channel forms that aid in the interpretation of the evolution of disturbed channels through time:

Stage I: Premodified
Stage II: Constructed
Stage III: Degradation

Stage IV: Degradation and widening
Stage V: Aggradation and widening
Stage VI: Quasi-equilibrium

Squaw Creek below the confluence of the north and south forks is most aptly described as dominantly being in stage IV with some portions grading from stage III or grading to stage V given the location and properties of a particular reach. This is evidenced by the frequent slumping banks (indicating channel widening) and disconnectivity of the stream with the floodplain indicated by the lack of regenerating riparian vegetation and increasing encroachment of successional riparian forest species (lodgepole pine) at the edges of the meadow. This concept is important because increased sediment from bed and bank sources not only directly impacts sediment loading within the stream, but can result in channel aggradation and further instability downstream (Bravard, et al., 1999; Darby and Simon, 1999).

The major active processes associated with elevated streambank erosion are lateral corrasion (bank scour) and bank failures, which are principally the resultant effects of channel incision and subsequent widening (Duijsings, 1986; Bravard, et al., 1999). Causes of stream channel incision include channelization, dam construction, climate and land use change. Because several land use activities which are typically associated with stream incision are present in the Squaw Creek watershed and there is strong evidence that the main stem of the stream through the meadow is incised and is currently in the widening phase of geomorphic recovery process, the effects of incisement and bank failure are discussed below relative to the watershed.

An incised channel is defined as a stream that is vertically degraded through the process of bed-level lowering in response to a disturbance that causes one or more of the following: a sediment starved reach upstream of incisement; increased annual discharge or peak discharge; concentration of flow, or increased channel gradient. The disturbance may be an increase in flow energy, shear stress, and/or sediment transport capacity (stream power) (Schumm, 1999; Darby and Simon, 1999) resulting from any number of activities, including removal of vegetation, channelization (which increases stream gradient), and drainage density increases. The primary causal agents of channel incision are provided in Table 9.

Table 9. Causes of incision (modified after Schumm, 1999).

Geologic/Tectonic	**Hydrologic**
Uplift	Increased discharge
Subsidence	Increased peak discharge
Faulting	Decreased sediment load
Lateral tilt	
Anthropogenic	**Geomorphologic**
Dam construction	Stream capture
Sediment diversion	Base-level lowering
Flow diversion	Meander cutoffs
Urbanization	Avulsion
Dam removal, failure	Lateral channel shift
Roads, trails, ditches	Sediment storage (increased gradient)
Meander cutoff	Mass movement
Groundwater withdrawal	Groundwater sapping
Climatic	**Biologic**
Drier	Grazing
Wetter	Tracking/Trail Development
Increased intensity	

The process of incision follows a predictable, step-wise pattern. Generally, seasonal peak flows of streams convey an in-channel bankfull discharge equal to the 1 to 2 year flow recurrence interval. When incision occurs, the channel deepens and is capable of passing a greater discharge before overtopping its banks and spreading excess flow onto the floodplain. The increased discharge exerts higher shear stresses and transports greater amounts of sediment, both of which lead to increased bank erosion because: increased bank height (from lowered bed level) exceeds the strength of the bank sediments, less resistant (to erosion) sedimentological units (gravel and sand dominated) are exposed at the base of the bank as observed in Squaw Creek (Figure 31), or increased shear stress is exerted on the base of the bank (Bravard, et al., 1999; Darby and Simon, 1999). Also, as overbank deposition decreases over time due to channel incision, the concentration of suspended sediment in the water column increases and is transported out of the basin (Bravard, et al., 1999).

In discussing incision, it is important to differentiate between the natural erosion of the channel bed (scour) and incision resulting from disturbance. Bed scour is limited spatially and temporally to localized portions of the channel and is of short duration. Moderate undercutting of banks occurs and can provide important habitat for numerous cold-temperature fish species. Incision is not limited to specific areas, but generally affects the entire stream length over extended time frames and results in significant modifications to the morphologic and geotechnical character of the stream (Darby and Simon, 1999). In Squaw Creek, frequent undercut bank failure and in-stream meander development caused by aggradation of sediment in channel bars was observed. Such activity causes channel widening by diverting flows toward opposite banks (Darby and Simon, 1999). Undercutting and failure of banks and development of in-stream meander patterns from alternating channel bars is seen in the profiles of Squaw Creek stream cross sections in Appendix G.

Figure 31. Sediment deposits exposed in alluvial streambank showing more resistant clay-silt above and less resistant gravel and sand fluvial deposits below. Clay-silt and organic layers are representative of bog and lake environments. (Courtesy of B. Hecht)

Bank failures may be described as either planar or rotational. Rotational failures are the less common of the two, as they occur in high banks when the shear stress resulting from higher in-channel discharge exceeds the shear strength of the bank. Planar failures occur along weak planes in any location of the bank as a result of undercutting and are therefore more likely to occur earlier in the degradation process. Planar failures are generally associated with steep banks (Darby and Simon, 1999; Simon, et. al, 1999). Both types of failures yield large amounts of fine-grained sediment and contribute to channel widening through bank retreat (Simon, et. al, 1999). Actual rates of channel widening vary, ranging from less than 1.0 m yr^{-1} in cohesive streambank materials, to as much as 100 m yr^{-1} in non-cohesive streambank materials (Darby and Simon, 1999).

Failure of bank material is apparent throughout the meadow section of Squaw Creek (Figure 32). A combination of both rotational and planar failures have been observed and documented within the meadow section of Squaw Creek and are potentially significant supplies of sediment. Slumping (or bank failure) along Squaw Creek occurs through a number of different ways. In dry seasons, accelerated rates of stream bank erosion results from the formation of tension cracks in the valley fill sediments as drying occurs and a loss of cohesion occurs along the fracture plane, therefore causing planar failures of the bank material. Slab rotational failures result from the loss of vertical support caused by stream undercutting. During the dry season the problem is less apparent because of low flow conditions. However, during the spring months, thawing of the bank material results in lowered cohesion and failure into the stream (e.g., Reid, 1985). This problem can be exacerbated by seasons of high runoff that coincide with optimum thawing of bank sediments. High discharge will effectively erode the lowered cohesion sediments and transport them directly into the stream.

The presence of the dam on the south fork of Squaw Creek merits discussion in relation to incisement and bank failure (Figure 33). Dams limit both stream flow and sediment load in the stream below the dam, creating a sediment “starved” system. The common result is incision in sediment starved reaches (Hupp, 1999; Schumm 1999). This process is further aggravated in Squaw Creek by the channelized reach north of the large parking lot at the western edge of the meadow, which causes an increase in the velocity of the starved flow prior to entering the meadow section of Squaw Creek.

As incised rivers widen and enter the recovery phase, aggradation of sediment transported from eroding reaches above and other inputs can occur (stage 5) (Hupp, 1999; Darby and Simon, 1999). Evidence of this is present within Squaw Creek in the form of large channel gravel bars, geomorphology and cross-section locations in the

Figure 32. Example of cantilever bank failures in meadow portion of stream.

Figure 33. Dam in lower portion of south fork bedrock channel.

Squaw Meadows section of Squaw Creek. The aggraded bars represent a potential sediment source that may be mobilized during more extreme events. Estimates of sediment storage in channel bars were calculated using an average thickness of 0.61 m (2 ft), based on cross section measurements and field observations. The average thickness was then multiplied by the total mapped bar area, to give an estimate of the sediment stored. Using the standard of 1.5 g/cm^3 (1.7 tons/m^3) as the average bulk density of sediment, the total volume was converted to tons of stored sediment in bars. Table 10 provides a summary of these calculations.

Table 10. Estimates of total channel storage in meadow portion of Squaw Creek.

Estimate Measure	Amount
Total volume of sediment stored in channel deposits	17,350 m^3
Total sediment stored in channel deposits	29,500 tons

Channel cross-sections were established in the meadow portion of the stream during the 2001 field season and re-measured the following year. During years of below-average precipitation and mild spring runoff, changes in cross-sectional morphology are slight. However, bank undercutting and channel bed erosion processes remain active (Figure 34) as a result of stream incisement and lack of riparian vegetation. Channel cross-sections were also used to calculate width/depth ratios (w/d), which reflect channel sediment characteristics and provide insights into fluvial processes. W/D is found by dividing the top width of the bankfull channel by the depth of the stream measured at the deepest point at a cross-sectional area (FISWRG, 1998). Width/depth ratio defines channel shape and is determined by the characteristics of the sediment in the channel perimeter. Wide, shallow channels (low w/d) are typical of streams consisting of coarse-grained sediments in their perimeters, whereas narrow, deep channels (high w/d) tend to have perimeters composed largely of silts and clays (particle sizes < 0.074 mm) (Ritter, et al., 1995). Changes from a low to high w/d commonly indicate an increase in sediment load and aggradation or widening of the channel (bank failure) without increasing depth. A decrease in w/d frequently indicates incision in response to change in sediment load conditions.

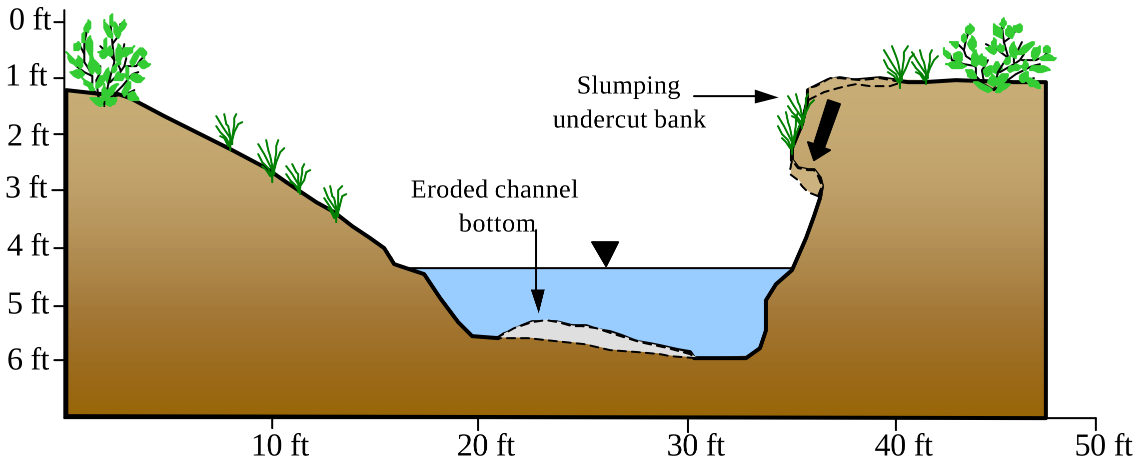


Figure 34. Cross section measurements showing bank undercutting and channel bed erosion. Bank on right shows slump development caused by undercutting.

Table 11. Width/depth values for the meadow portion of Squaw Creek.

Cross-Section Station	Width/Depth (W/D)
R1Xn-01	6.24
R1Xn-02	5.90
R1Xn-03	7.06
R1Xn-04	5.68
R2Xn-01	4.17
R2Xn-02	6.23
R2Xn-03	9.08
R2Xn-04	5.55
Average W/D	6.24

Long term stream channel migration in the meadow portion of Squaw Creek was determined from aerial photographs (1939, 1987, 1998) and from GPS stream mapping in 2001. Channel sinuosity, the ratio of stream length to valley length, was calculated for each period to determine change over time (Table 12) (Ritter, et al., 1995). Average annual channel migration was also calculated by taking the change in distance between mapped stream thalwegs for 1939 and 2001 at successive intervals along the length of the stream, determining the average distance the stream migrated, and dividing that number by 62 years. The average meander migration from 1939 to 2001 is 12 m (40 ft), and the average annual migration is 0.2 m (0.65 ft) and ranges from 0.3 to 0.7 m (0.95 to 2.3 ft) (Table 13).

Figure 35 shows the changes that have occurred in stream migration and meander pattern below the confluence of the north and south forks. Most apparent is the channelization of the stream just below the confluence to accommodate the existing parking lot as part of the preparations for the Olympics. The approximately 180 m (600 ft) trapezoidal channel is reinforced with rip rap in several locations and is set vertically and horizontally due to the presence of bridges at either end. The engineered trapezoidal channel effectively increases the velocity and volume of flow that enters into the meadow reach, increasing shear stresses on the banks and bed, thereby resulting in increased elevated bed and bank erosion. At the same time the trapezoidal channel was constructed, the confluence was modified. Both forks were straightened and the south fork was re-directed to the west, resulting in a shift in the location of the confluence to the west as well.

Overall, the stream has become straighter and has abandoned (or lost through modification) a bifurcated reach it once used. Over the past 60+ years, sinuosity in Squaw Creek has decreased, which indicates that the stream is becoming less stable, most likely due to incisement and subsequent adjustment. Sinuosity values for later time periods (1987 – present) show sinuosity values below 1.5, while the value for 1939 is 1.57. Although a specific geomorphic threshold value does not exist where streams are characterized as either straight or sinuous, the value of 1.5 is commonly used as the transition between straight and meandering streams (Ritter, et al., 1995). This suggests Squaw Creek has transitioned from a sinuous to a straight stream, resulting in increased channel slope, velocity, and shear stress that ultimately lead to increased bed and bank erosion, channel incision, and channel widening.

Table 12. Calculated channel sinuosity values.

Sinuosity			
1939	1987	1997	2001
1.57	1.44	1.43	1.41

Table 13. Calculated annual stream migration values, 1939 - 2001.

Channel Migration	Migration Value, m (ft)
Average Channel Migration	12 (40)
Average Annual Migration	0.20 (0.65)
Range of Channel Migration	0.3 – 0.7 (0.95 – 2.30)

*Width measurements taken perpendicular to flow at widest spot of polygon

Examination of the stratigraphy exposed in the stream banks provides insight into changes in depositional environments that have been active in the watershed. Stream bank stratigraphy was logged at the eastern edge, middle, and western edge of the meadow (Figure 36). The youngest (top) deposits consist of fine-grained silt and clay overbank material deposited during events that breach the channel banks and activate the floodplain. These floodplain deposits are underlain by black organic rich (peat) bog deposits indicative of the prior existence of marsh conditions where stagnant standing water was present. This black organic rich layer (bog deposit) represents a period of stability and is indicative of a wetland environment.

The bog deposit is underlain by coarse sand and gravel indicative of higher energy periods. These deposits are most prominent in the stream bank stratigraphy in the

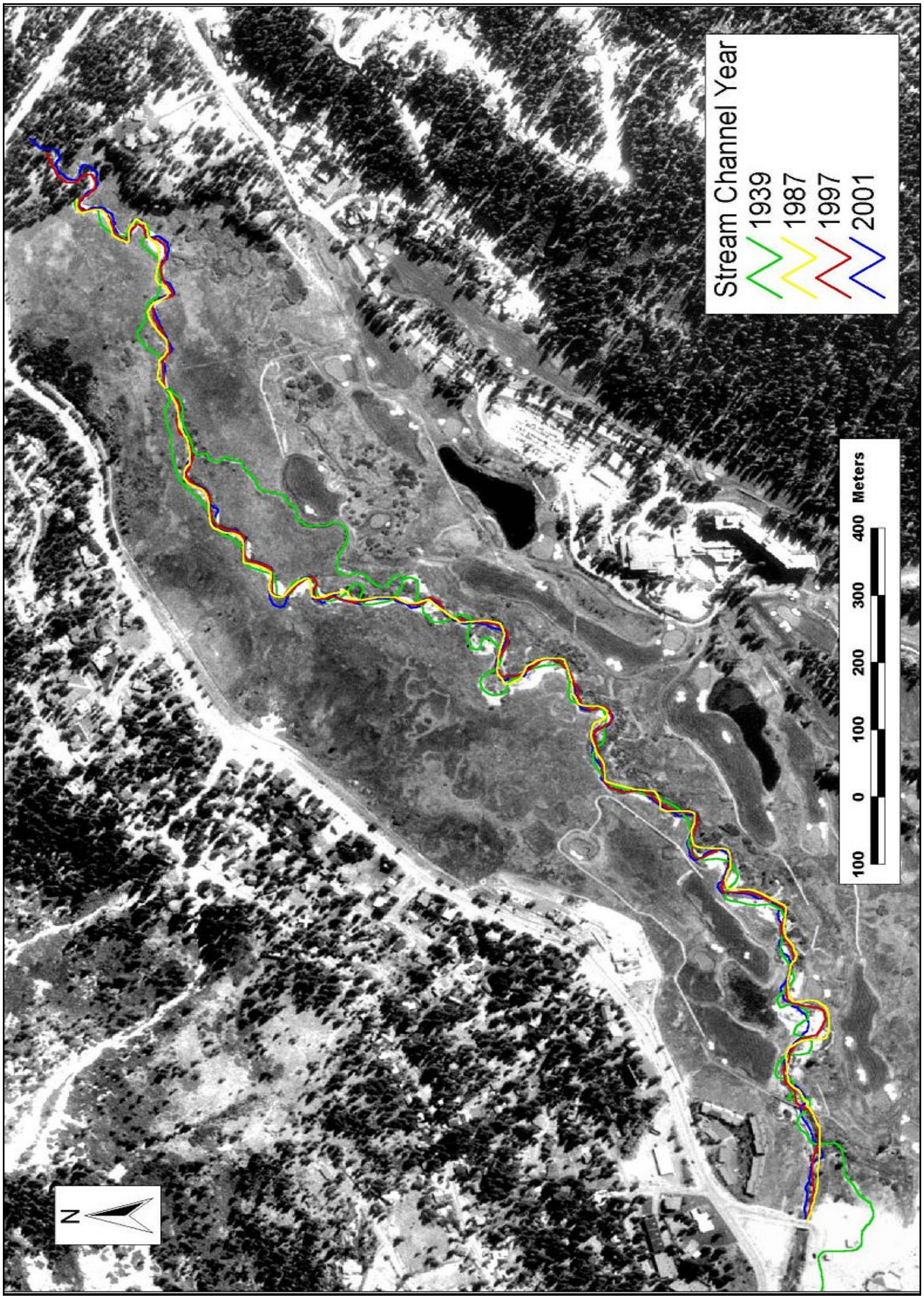


Figure 35. Changes in stream migration and meander pattern below the confluence of the north and south forks.

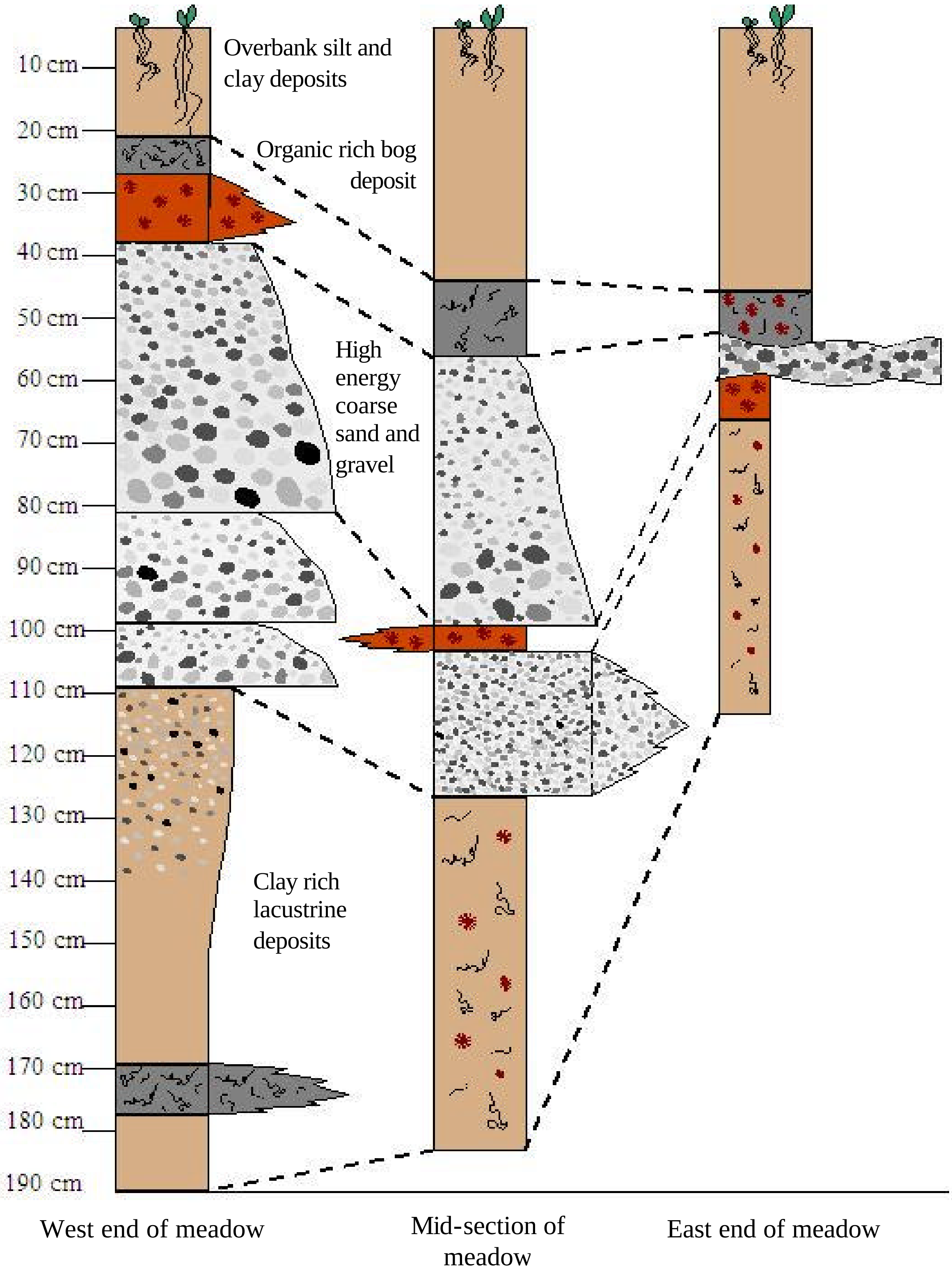


Figure 36. Correlated meadow deposits stratigraphic column for Squaw Creek.

Figure 37. Stream bank layers of fine-grained material showing alternating bands of lacustrine clay deposits (tan and white bands) and organic bog deposits (dark bands). The top layers contain charcoal and organic material, indicative of a stable, vegetated land surface. The presence of root casts and burrows further support the rich organic marsh environment during the formation of these deposits.

Figure 38. Stream bank exposure showing coarse-grained fluvial deposits overlain by fine-grained lacustrine and bog deposits.

west end of the meadow and are characteristic of a high energy fluvial environment (Figures 37 and 38). Fluvial deposition is likely to have occurred in the western end of the meadow because of the abrupt decrease in the stream gradient (and hence, energy) where the south and north forks enter into the low gradient valley. At the east end near the terminal moraine, which acts as the base level in the watershed, bank deposits consist more dominantly of fine-grained materials, especially clay, indicating a quieter lacustrine or backwater wetland environment.

The oldest (deepest) exposed deposits consist of fine grained silt and clay material consistent with a lower energy environment. These clay rich layers represent a more pure lacustrine phase.

Mapping of in-channel geomorphic features for the meadow portion of the stream was completed during the 2001 field season and are described in Appendix H. Whereas the stratigraphy indicates that fluvial processes were dominant historically in the western portion of the meadow and lacustrine dominant in the eastern end, geomorphic mapping of more recent features indicates a change in stream processes. The dominance of point bars in the eastern end indicates a progression of fluvial deposition of coarse-grained materials that previously occurred further upstream closer to the confluence of the north and south forks. The dominance of fluvial processes in the eastern end support the idea that an adjustment in stream process is occurring. Effectively, energy dissipation within the stream has been transferred from the western end to the eastern end as a consequence of an increase in stream power resulting from land use impacts.

Particle size analysis of channel bed and bar sediments (Appendix F) reflects the composition of hillslope sediments and show that fines are transported through the system. For example, approximately 50 to 70% of the sediment available for transport is coarser than 2 mm. The remaining hillslope sample sites consist of approximately 80% sand and 20% silt and clay. Samples collected from natural and artificial sediment traps on hillslopes contained less than 50% gravel and between 30 and 45% silt and clay, indicating that most of the fine sediment is transported to the stream network. Samples from channel bars in Squaw Creek are dominated by sand and gravel with small percentages of silt and clay. Thus, most fine sand, silt and clay is transported through the system as suspended and wash load. This is supported by suspended sediment discharge for Squaw Creek data reported by Hecht and Jett (1988).

Riparian vegetation is an integral component of the integrity of a stream system, both from a geomorphic and habitat perspective, providing significant controls on bank stability, near-bank flow hydraulics, in-stream temperature and turbidity (Hupp, 1999; Darby and Simon, 1999). Specifically, riparian vegetation affects fluvial stability in the following ways (Hupp, 1999):

- creates flow resistance on most fluvial surfaces;
- increases bank shear strength through root mass development;
- increases sedimentation on channel bars;
- increases sediment deposition and stability on banks and other low relief fluvial surfaces.

Riparian vegetation can be reduced or eliminated because of stream incision or grazing. Channel incision typically reduces riparian vegetation through the lowering of the subsurface water table below the root zone of most species. The loss of vegetation reduces the shear strength of banks and leads to bank failure. Conversely, a reduction in riparian vegetation can lead to bank failure and subsequent incision as well via reduction of root mass and shear strength (Hupp, 1999; Darby and Simon, 1999). The most common mechanism for the removal of riparian vegetation in Sierra Nevada meadows is through grazing (Montgomery, 1999; Murphy and Knopp, 2000). Sheep and cattle grazing are documented as occurring in the Squaw Creek watershed from the period of 1860 through 1980 (Poulsen, 1984) (Figure 39), which is likely to have caused a decrease in riparian vegetative cover and, in concert with increased discharges from upper watershed disturbance, incisement of the meadow channel.

Hupp (1999) suggests there are successional stages of plant community establishment associated with the recovery phases of vertical channel degradation and channel form evolution. These "suites" of vegetation (Table 14) assist in evaluating the current channel evolution phase of various portions of Squaw Creek.

Figure 39. Historic photograph - Documentation of cattle grazing in Squaw Creek meadow (courtesy of Lahontan RWQCB).

Table 14. Vegetative indicators of channel evolution (modified for Squaw Creek watershed after Hupp, 1999)

Pioneer Species (Suite 1) Late Stage IV	**Intermediate Species (Suite 2) Stage V**	**Hardwood Species (Suite 3) Stage VI**
Species: *Salix, Acer, Lupinus, Achillea*	Species: More mature *Salix, Alnus, Cornus; Carex*	Species: *Populus,* age-diverse *Salix*
Ruderal (native or non-native "weed"), unstable sites	Stable conditions	Mature, stable condition
Shade intolerant	Moderately shade tolerant	Shade tolerant
Fast-growing, short-lived plants	Slow-growing, long-lived plants	Slow-growing, long-lived plants
Extensive asexual reproduction	Rare asexual reproduction	Rare asexual reproduction
Abundant short-lived seeds	Long-lived seeds	Short-lived seeds
Wind and/or water dispersal	Wind and/or water dispersal	Animal dispersal
Seed release in late spring	Seed release in late summer	Seed release in late summer/fall

In Squaw Creek, the western portion of the meadow exhibits aggradation of sediment and some early colonization of willow (*Salix*), lupine (*Lupinus*) and yarrow (*Achillea*) on channel bars. This would indicate that this part of the meadow channel is in the later part of stage IV channel evolution. The eastern portion of the creek contains less aggradation, little vegetation establishment, and near-vertical banks, in general, suggesting that this portion of the creek is still in the early phase of stage IV or late phase of stage III (vertical degradation). This may be compared to the less impacted Sagehen Creek, which appears to have not incised to an appreciable degree as evidenced by the connectivity to its floodplain and a continuous riparian corridor of hardwood vegetation along with occasional, slightly undercut banks stabilized by a vegetative root structure.

4.5 Erosion Susceptibility Model

GIS modeling of both pre-development (1939) and current hillslope erosion susceptibility was utilized to aid in the evaluation of land use impacts to Squaw Creek. Areas of relative high and low erosion susceptibility within the watershed were identified using a GIS, field data and observations, aerial photographic analysis, applicable parameters related to sediment movement processes, and information from other studies.

Using the GIS, weighted erosion models were developed that incorporated the effects of roads, geology, soils, slope, land use, and land cover relative to erosional susceptibility for 1939 and 2002 (see Appendix I). The resulting erosion susceptibility models (Figures 40 and 41) for 1939 and 2002 suggest that changes in land use practices are responsible for the change in erosion susceptibility.

Comparison of the two erosion susceptibility models illustrates several points. First, many of the areas that are designated as high erosion susceptibility in 1939 are also present in 2002 with little change to the polygon shape, in particular, the steeper northern slopes of the north fork. These areas are naturally prone to erosion mostly due to their steep slopes. Other areas have become less prone to erosion over time, such as the south-facing lateral moraine on the north side of the valley. This is due to the succession of the vegetation community on the hillside from dominantly chaparral shrub

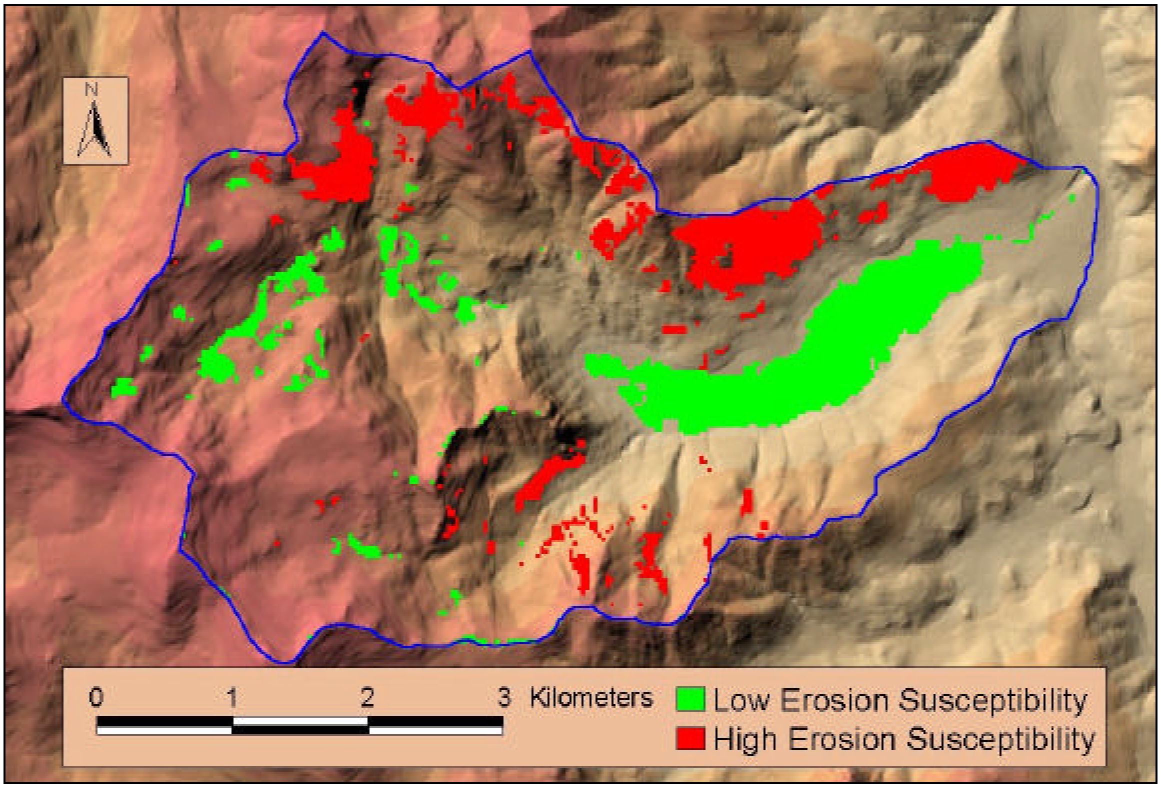


Figure 40. Erosion susceptibility model for 1939.

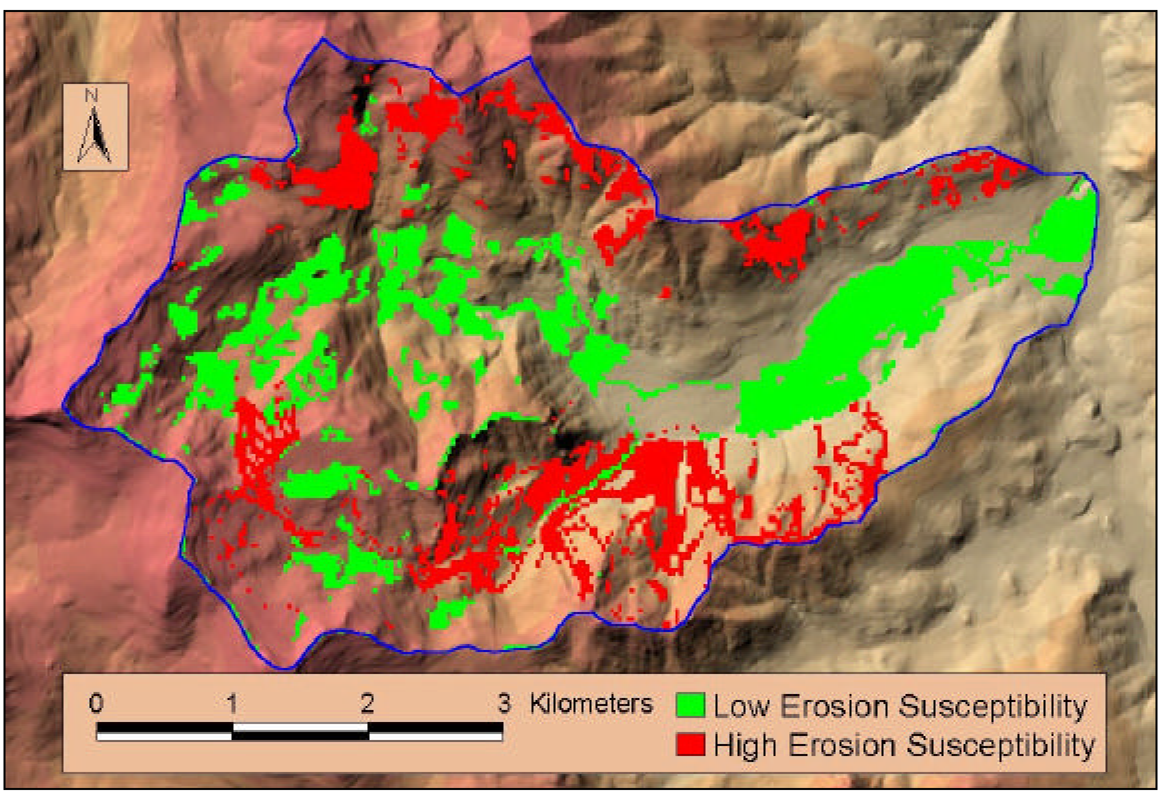


Figure 41. Erosion susceptibility model for 2002.

to mixed conifer forest. The increase in area covered by trees provides an increase in the duff and litter layer, which in this study was found to be important in reducing soil erosion.

The models highlight the significance of land use impacts in hillslope erosion susceptibility. For example, depositional zones, such as meadows, have low hillslope erosion susceptibility by definition. The western portion of the meadow through which the main stem of the stream flows was designated as low in 1939, but fell into the moderate category in 2002. This is a result of a large, impervious surface parking lot installed in that portion of the meadow, although this development did not result in a high susceptibility rating, it did result in a net loss of low susceptibility area. The most dramatic change between the models, however, is the increase in high susceptibility areas in the south fork and portions of the north-facing lateral moraine on the south side of the valley resulting from land use changes. Due to the presence of dirt roads and graded ski runs in this area, large areas of previously moderate erosion susceptibility were converted to areas of high erosion susceptibility.

4.6 Sediment Budget

Lehre (1981) defined a sediment budget for a basin as "a quantitative statement of relations between sediment mobilization and discharge, and of associated changes in storage". There are three requirements for the construction of a sediment budget: 1) recognition and quantification of transport processes (streambank erosion, streambed erosion, and hillslope erosion), 2) recognition and quantification of storage elements (streambed storage and colluvial storage), and 3) identification of linkages among transport processes and storage elements. A common approach is to compare measured sediment output from a drainage basin with measurements of sediment-transport processes and storage changes within the basin. Ideally, sediment input plus or minus sediment storage equals sediment output. The variety and widespread distribution of sediment sources and sediment deposition sites make it impossible to directly quantify rates at which all sediment related processes operate. In basins larger than a few hectares in size, it is generally impossible to measure erosion and deposition along all channels or erosion from all hillslopes. Because of the need to generalize rates and types of erosional processes in unsampled areas of a basin, nearly all sediment budgets should be considered estimates. Development of sediment budgets requires merging available data with carefully derived conceptual models of erosion and sediment transports in a given basin.

Nolan and Hill (1991) provide a similar definition: Drainage-basin sediment budgets are quantitative expressions of the relations between rates of sediment mobilization and sediment storage within a drainage basin during a defined period of time and sediment discharge from the basin during the same time period. Sediment budgets are based on the assumption that the law of mass balance applies to sediment during the time period included in the sediment budget, that is, sediment mobilization (input to the channel system from erosion of hillslopes and channel banks and beds) equals sediment discharge (output from the channel system at the basin mouth) after changes in storage are considered. A generalized sediment budget would satisfy the equation:

$$QS = MS - SS$$

Where,

QS = sediment discharge

MS = mobilized sediment

SS = stored sediment

Basin morphometric analysis, field observations, and field measurements of mobilized and stored sediment typically form the base of the sediment budget, in conjunction with fluvial sediment discharge measurements at the mouth of the basin (Nolan and Hill, 1991). In this study, mass values for mobilized and stored sediment were determined from hillslope erosion rates, stream channel cross-sections, volumetric measurements of sediment traps, geomorphic mapping, and stream migration mapping (Table 15).

A GIS was used to estimate hillslope contributions to the sediment budget using the 2002 weighted erosion susceptibility model and the land use/land cover theme. Volumes per acre of sediment per year, based upon erosion rate data collected in the field, were multiplied by the number of acres for a given polygon and multiplied by a delivery ratio. The delivery ratio was determined by the following equation:

$$SDR = 0.627\ (\text{Slope})^{0.403}$$

where Slope = % slope of main stem channel (Reid and Dunne, 1996).

Different delivery ratios were calculated for each of the subwatersheds and applied to the erosion polygon volumes. To account for the fact that a portion of hillslope erosion is stored as sediment on hillslopes, while the rest is delivered to the stream network, volumes of sediment were then only considered to reach the stream on an annual basis if they were within 10 meters of a drainage. Drainages include both stream networks and road networks, which are identified as connected to streams. Using the above calculations and assumptions, it is estimated that natural and anthropogenically-influenced hillslope processes contribute 28,890 tons of sediment per year to the stream network, while 668,410 tons of the mobilized sediment remains in storage on hillslopes.

To determine the average annual contribution from channel banks, an average stream depth of 1.60 m (5.25 ft) from channel cross section measurements was multiplied by the area lost due to stream migration in the meadow section from 1939 to 2001. Bank erosion from other channels in the watershed were not included in this calculation because they are primarily bedrock or boulder-controlled and as such have not lost channel bank material due to migration. Over the 62 year period, the volume of sediment was calculated to be 141,561 m^3, or an average annual volume of 2283 m^3. The volume was then converted to total tons of sediment per year by multiplying it by the average bulk density of the soil, 1.50 g/cm^3 (1.7 $tons/m^3$) (Miller and Donahue, 1995). This yields a total mass contribution of 3,800 tons of sediment per year from channel banks. These bank erosion rates are similar to the annual bedload discharge of 2,200 tons reported for 1986 by Hecht and Jett (1988), which they attributed primarily to bank failures.

To determine contributions from in-stream deposits (storage sites), areas were computed from geomorphic mapping of the alluvial channel bars and depositional terraces that were digitized into the GIS. The areas were then multiplied by the average thickness to obtain the volume of sediment in storage that is potentially available for mobilization (17,400 m^3). By multiplying the volume by the average bulk density of the soil, 1.50 g/cm^3 (1.7 $tons/m^3$), the potential mass input from in-stream deposits is 29,500 tons per year.

Contributions from dirt roads were estimated from sediment collected from an erosion fence sample site below a waterbar that conveyed runoff from a road surface segment. The amount of sediment collected during the study period is assumed to estimate the amount of sediment from dirt road surfaces specifically since the sample site is near the top of a ridge and therefore any sediment being transported by runoff would come from the road surface. However, the effect of roads on erosion rates in other areas is not reflected in this calculation. Using the soil bulk density to convert the volume of sediment to sediment mass and dividing that value by the contributing dirt road surface area, a mass per unit area value was computed. This value was then multiplied by the total dirt road surface area in the watershed to estimate that dirt roads contribute approximately 8,590 tons/year to the basin sediment budget.

Road cuts which were not covered by the GIS buffering operation and that had large, observable volumetric losses were mapped, digitized, and assigned estimated volumes. It was assumed that most of the roads associated with these roadcuts were constructed approximately 40 years ago and that losses of cut bank material occurred uniformly over time. Contributions from large road cuts were estimated to be 817 tons/year.

Paved roads from subdivisions concentrate runoff which accelerates the erosion of adjacent bare areas, erodes dirt roadside ditches, and transports that material to the stream network. The amount of sediment mass from paved roads in subdivided developments was estimated by multiplying the contributing paved road surface area by the volume of sediment collected at erosion fence sampling sites at the mouths of culverts draining subdivisions on the north side of the valley. The annual sediment mass delivered to Squaw Creek is approximately 43 tons/year.

Road sanding operations occur during the winter months within the Squaw Creek watershed and represent a sediment source. Although mass values were not available for the Squaw Creek watershed, the County of Placer, California reported the approximately 720 tons of road sand was applied during 2002 throughout the area (Boswell, pers. comm). Given that Placer County is responsible for sanding 27.4 km (17 miles) of paved road, half of which are located in the Squaw Creek watershed, it is assumed that 320 tons of sediment is available for delivery to the stream network via roadside ditches and culverts on an annual basis.

Rills and gullies not only provide an efficient means by which to transport sediment to the stream network, they also act as sources of sediment as well. Most rills in the watershed were observed to have formed on dirt roads. Since the contribution of sediment from roads encompasses the presence of rills on road surfaces, a separate computation for road surface rills is not necessary for the sediment budget. Numerous gullies were observed forming on ski slopes and off of road cuts and therefore are not included in road contribution calculations. Estimates of contributions of sediment from gullies were made by extrapolating the change in cross sectional area from gully cross sections, multiplying that by the length of the gully, and using the soil bulk density of 1.5 g/cm^3 to obtain a mass of 4,400 tons of sediment per year. Using the SDR for the subwatersheds containing the major gullies, it is estimated that 1,900 tons are contributed to the stream system from gully erosion annually.

The results of the sediment budget analysis indicate that while the majority of mobilized hillslope sediment remains in storage, hillslope erosion still provides the primary source for sediment to the stream network. Further, the presence of roads plays a significant role in the production and delivery of sediment to channels, supplying nearly a third of the sediment from the hillslope contribution. Stream bank erosion is a significant contributor as well, as are the larger gullies that are present on some ski slopes. Finally, in addition to hillslope storage, channel bars provide significant storage sites for the coarse-grained sediment from both in-stream and hillslope sources. Figure 42 illustrates the interconnection between these processes. Figure 43 provides an overview of the relative percentage that each mobilized source and storage type contributes to the sediment budget. These values derived for the sediment budget, are within the same order of magnitude as those reported for the watershed by Hecht and Jett (1988) and Kuchnicki (2001), and watershed modeling completed by McGraw et al. (2001).

Table 15. Summary of annual sediment contributions to basin sediment budget from different sources to Squaw Creek. *Represents % contribution of sediment source.

Sediment Source Squaw Creek Basin	Total Sediment (tons/year)	% Total	*South Fork (%)	*North Fork (%)
Hillslope Delivery	+20,300	57%	32%	39%
Dirt Roads	+8,590	24%	63%	07%
Road Cuts	+817	2%	71%	0%
Gullies	+1,900	5%	--	--
Paved Roads/Subdivision	+43	0.1%	--	--
Road Sanding Operations	+320	0.9%	--	--
Alluvial Channel Banks	+3,800	11%	--	--
Subtotal	35,770	--	--	--
Channel Bars (storage)	- 29,500	--	--	--
SEDIMENT BUDGET	**6,270**			

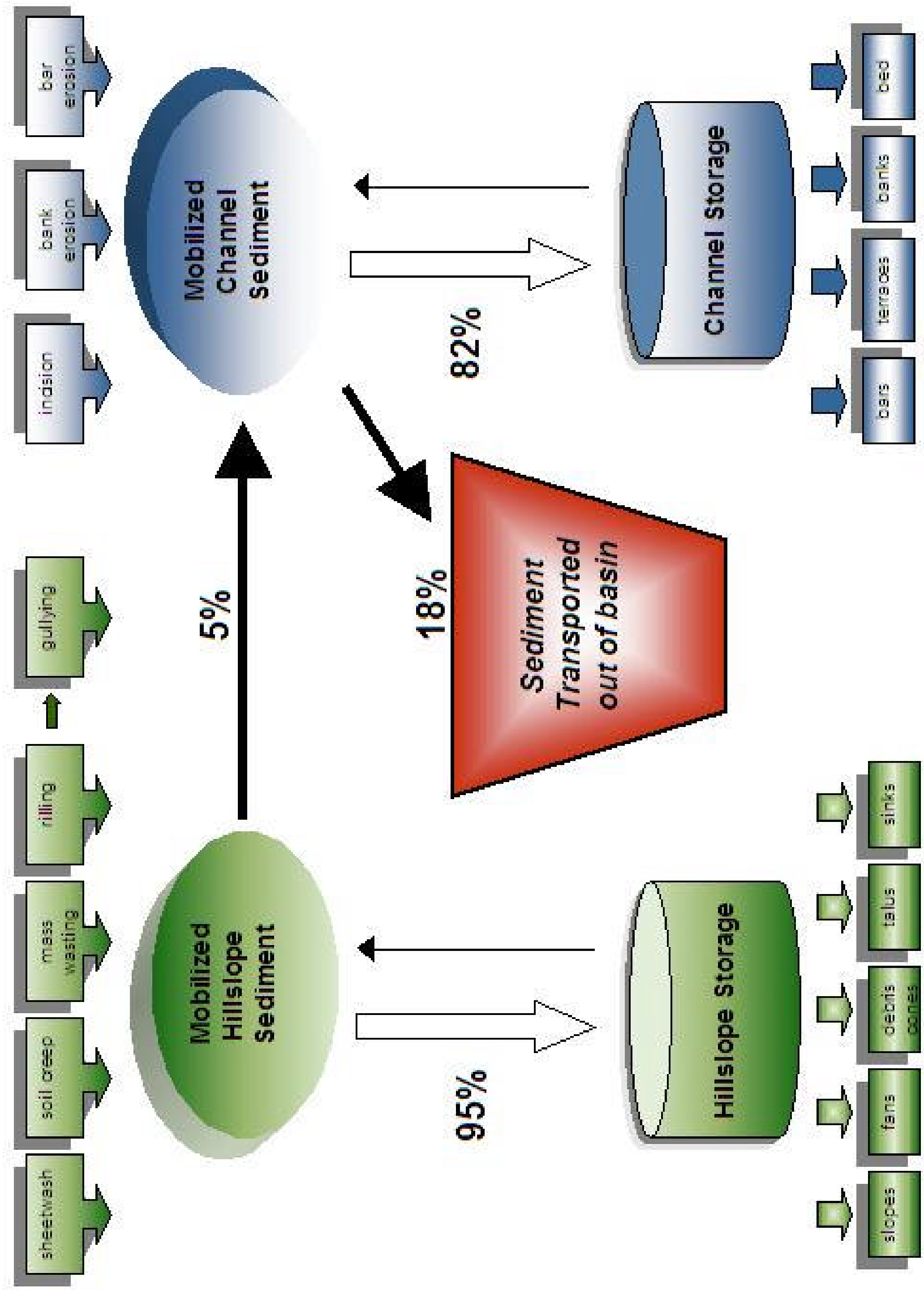


Figure 42. Flowchart of sediment budget for Squaw Creek watershed.

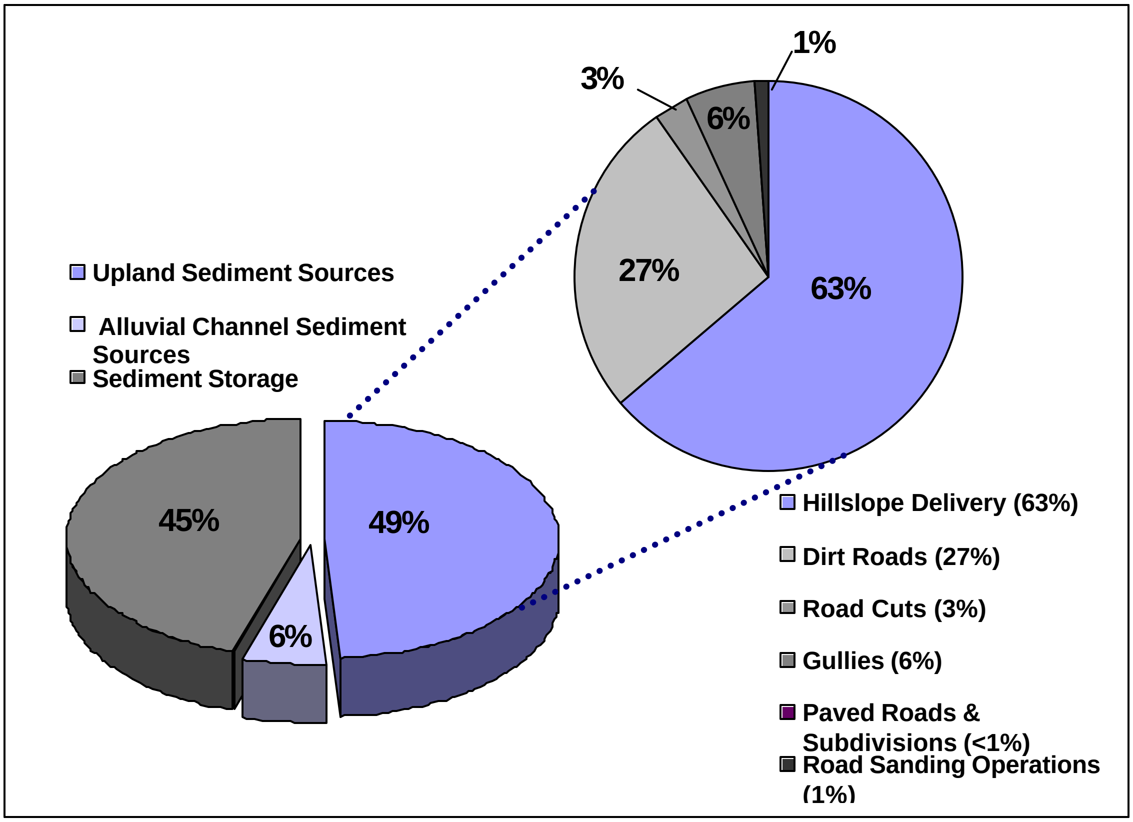


Figure 43. Relative source and storage contributions to the Squaw Creek sediment budget.

5. SUMMARY AND CONCLUSIONS

The purpose of this study was to evaluate and document dominant sediment sources impacting sediment loading to the main channel of a small, high relief sub-alpine drainage basin. To accomplish this, analysis and assessment of both natural and anthropogenic influences on the geomorphic processes active in the drainage basin were completed and compared with published literature.

Morphometric parameters of the watershed were computed in order to quantify geomorphic characteristics to provide a basis by which to compare measured and observed erosional processes. Relief ratio shows that relative to the north fork, the south fork is steeper and by nature more prone to yielding slightly higher amounts of sediment per unit area. However, the undisturbed drainage density for the south fork suggests that it would naturally transport somewhat less sediment to the stream network versus the north fork on an annual basis.

Over the past 60 years, sinuosity in the lower reaches of Squaw Creek has decreased from 1.57 to 1.41. This suggests that the stream is becoming less stable. Sheep and cattle grazing are documented as occurring in the watershed from the period of 1860 through 1980 (Poulsen, 1984), which is likely to have caused a decrease in riparian vegetative cover. This loss of vegetation in combination with increased discharges caused by upper watershed disturbance, and incision of the meadow channel were all contributors to the loss of sinuosity through increased stream bank erosion.

The erosion pin data provide useful insight into current processes and the relative erosion rates associated with various land uses and geology found throughout the watershed. Generally, the lowest movement rates are associated with forested areas. Low rates associated with forested sites are most likely due to the presence of overstory canopy cover, litter and duff covering the soil, which retards rain drop impact and rill initiation (e.g., Morgan et al., 1986). Unforested areas (e.g., chaparral, bare rock and soil) exhibit higher erosion rates, which are compounded by the impacts of land use. Roads can create high sediment yields through a variety of mechanisms and erosional problems are compounded by the intersection of various landuses (e.g. roads crossing graded ski runs). It is important to note that erosional processes, such as soil creep, dry slide, and rilling and gullying, were and are active and dominant in all portions of the watershed during both the characteristically dry period (summer and fall) of a low precipitation year and during the spring runoff period, although greater rates might be expected during rain-on-snow events. Additionally in the hillslope environment, in areas where there isn't a defined drainage system, snow melt related erosion is no more significant than summer or fall related precipitation. This is in contrast to in-channel erosion, which is dominantly impacted by snow melt peak runoff.

Bedrock geology was examined to determine the relative contribution of sediment related to rock type. Although bedrock channels dominate the north and south fork, sediment derived directly from bedrock channel erosion is negligible relative to other sources in the watershed. Bedrock type on hillslopes however is important to consider in assessing potential sediment sources. Most important are those that are prone to producing fine-grained sediment, such as andesite, because fine-grained material is more easily transported by hillslope processes such as overland flow, soil creep and dry slide. Bar samples collected during the study in Squaw Creek are dominantly composed of sand and gravel with very small percentages of silt and clay. This indicates that most silt and clay is transported through the system in the washload.

Road corridors (roads and related features, such as road cuts, fill slopes, and flow conveyance ditches), serve to both generate and deliver runoff and sediment to the stream network. This is accomplished through the concentration of flow from an increase in the overall watershed drainage density, which leads to higher peak flows and subsequently, increased stream erosive power. Downstream, increased stream erosive power results in accelerated bank erosion and incision, affecting both fluvial processes and stream habitat values. Specifically in the south fork, road connectivity has resulted in an increase in effective drainage density from 2.93 km/km^2 to 10.24 km/km^2, an increase of approximately 250%. The sediment budget and erosion susceptibility modeling both indicate that roads are a significant contributor to sediment delivery to the stream network. Modelling also illustrates that roads and graded ski runs increase hillslope erosion susceptibility.

It is estimated that the total amount of sediment available on hillslopes in the watershed is approximately 670,000 tons of sediment, based on field erosion measurements, land use and land cover, and modeling with GIS. Of the mobilized sediment, approximately 95% remains stored on hillslopes, leaving approximately 32,000 tons for transport to the stream network via roads, rills, gullies, and sheetwash on hillslopes. Approximate 8,590 tons of the transported sediment comes from dirt road surfaces. In-channel sources contribute 3,800 tons of sediment from stream bank erosion. Other sediment sources (gullies, paved roads, road cuts, sanding operations) contribute another 6,880 tons of sediment to the watershed. Of the calculated 35,770 tons of sediment input, approximately 82% goes back into storage in the form of channel bars, and the remaining 6,000+ tons per year is transported out of the watershed. Young and Saunders (1986) note that the influence of humans can accelerate denudation by 2, 10, or over 20 times. However, there are inherent difficulties in the collection and interpretation of geomorphic and sediment transport data related to spatial and temporal sampling and disturbance from equipment use. Despite these issues, observations, direct measurements, and modeling efforts indicate that in the Squaw Creek watershed, land use impacts have increased sediment loading to the stream network.

6. RECOMMENDATIONS AND SUGGESTED STUDIES

The Squaw Creek watershed has been impacted by a number of different land use and land management activities over time. To better assess, quantify, and ultimately provide sound management direction to reduce further impact to the watershed and identify restoration and monitoring opportunities, additional studies should be conducted and higher quality data collected. This includes:

- Obtaining recent, higher resolution aerial photography and/or digital imagery;
- Establishment of suspended sediment and flow gauges at several strategic locations within the Squaw Creek watershed, such as on each fork above the confluence, below the confluence, and below the meadow;
- Conduct basin-wide systemic rill and gully surveys and measurements;
- Conduct a study of rill initiation and gully head migration and retreat;
- Complete an intensive level I NRCS ssurgo/statsgo soil survey for the watershed, which will create the opportunity to utilize several established watershed modeling programs;
- Conduct a botanical survey for the perennial pepperweed (tall whitetop), an invasive plant which was noted high in the watershed and has the potential to further impact stream function by crowding out native riparian vegetation in stream corridors, resulting in degraded wildlife habitat and accelerated streambank erosion;
- Radionuclide particle tracer study to obtain more refined data on hillslope erosion rates and contributions to suspended sediment load;
- Tag coarse sediment fragments (e.g., painting) to monitor transport rates.

One particular approach that is applicable to the study of erosion and deposition within a basin that may offer potential for describing the sediment delivery processes is the use of the isotope Cesium-137 (^{137}Cs). As a result of nuclear weapons testing between the middle 1940's and the early 1970's, ^{137}Cs and other radionuclides (e.g., ^{210}Pb) were released into the atmosphere and subsequently re-deposited on the earth's surface as radioactive fallout. Cesium-137 moves from the stratosphere back to the troposphere and then back to the earth's surface (fallout). This cycle is strongly related to local precipitation patterns and rates (Walling et al. 1986, Ritchie and McHenry 1990, De Roo 1991). Once introduced into the soil system by dry fallout or in precipitation from the atmosphere and through-fall or turnover from vegetation, ^{137}Cs is adsorbed strongly on clay and organic particles and is therefore concentrated primarily in the surface soil layer. This approach was explored as an option for the Squaw Creek watershed during the development of this study, but due to time and funding constraints, was not utilized.

A number of Best Management Practices (BMP's), should be implemented within the watershed to reduce further impacts to the stream. These include:

- Reducing the overall number of dirt roads within the watershed through decommissioning. Increased benefits will be realized if decommissioning efforts include topographic restoration (restoring the contour of the hillslope), targeting roads that cross channels, armoring roadside ditches with rock and revegetation efforts, and stabilizing roadcuts with rock rip-rap and vegetation to stabilize the soil.
- Outsloping of flat grade maintenance roads where topography allows to reduce the potential for rill and gully development and to disperse runoff.

- Improving revegetation efforts on ski slopes and decommissioned roads by emphasizing native plant use, breaking up compacted topsoil to allow for infiltration, mulching with pine needles, and cross-contour ripping.
- Decreasing or eliminating the number of culverts that daylight directly into stream channels, and instead utilize sediment detention basins, dispersing runoff in low erosion areas (e.g., flat, forested areas), and other similar BMP's.
- Residential areas would benefit from installing curb and gutters to collect urban runoff and dispersing runoff in the meadow through the construction of micro-topographic ridges will reduce fine-sediment inputs to the stream.
- Removing rock rip rap in the meadow portion of the stream in the vicinity of the golf course and other areas. Hard engineering structures such as rock rip rap provide spot protection for banks, but do not always reduce stream energy. Rock rip-rap in the meandering section of Squaw Creek has instead increased and redirected stream energy to a point further downstream, resulting in increased bank erosion at that point. Rip rap could be replaced with root wads, creation of in-channel floodplain and riparian vegetation planting, or other bioengineering structures. Earlier attempts to use willow plantings as part of the meadow restoration and recreation enhancement project were unsuccessful, as evidenced by the large number of dead willow stakes, but would likely be successful in the future if willows are planted deep enough so that rooting structures have access to subsurface water year round.

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