Sediment Source Assessment: Squaw Creek Watershed, Placer County, California

Thomas F. Bullard
Timothy Minor
Rebecca Maholland

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Abstract

Squaw Creek is an impaired waterway for excessive nonpoint source sedimentation on the Environmental Protection Agency's (EPA's) 303(d) list and was recommended for watershed analysis to (1) identify potential problem areas and (2) develop a Total Maximum Daily Load (TMDL). Sediment sources in the watershed were evaluated from a geologic and process geomorphology perspective to identify and characterize sources of sediment and mechanisms of sediment transport as well as to quantify rates of hillslope and in-stream erosion in order to develop a sediment budget. Sagehen Creek, a relatively undisturbed watershed located approximately fifteen miles north of Squaw Creek, was chosen as a reference watershed to aid in development of sediment load allocations

Squaw Creek is a small (approximately 8.2 square mile [21.1 km^2]), subalpine and alpine watershed located about six miles (9.6 km) northwest of Lake Tahoe, California between the towns of Tahoe City and Truckee. The main stem stream channel is divided into north and south subwatersheds. Both of these have similar relief, although the south fork is generally smaller, steeper, and exhibits greater mean elevation than the north fork. Despite differences in size, existing data indicate that the smaller south fork contributes approximately twice as much runoff per unit area. Watershed geology is dominated by andesitic rock types, granite, and glacial deposits. Land use in the watershed is largely recreational, commercial, and residential. During the past 50 years, natural vegetation has been removed from hillslopes in the south fork; and these areas have been developed into ski slopes with associated maintenance roads. A minor degree of ski area development also has occurred in the north fork.

Analysis of erosion rates on disturbed and undisturbed hillslopes with different geologic parent materials and under differing vegetation conditions clearly indicates that the principal sources of sediment are related to land use impacts on hillslopes and stream channels. Andesitic and granitic bedrock exposures and bedrock channels contribute to sediment as well, but these are relatively insignificant amounts. Erosion rates on undisturbed hillslopes were found to be lower than on disturbed hillslopes by as much as a factor of three. Most material eroded on undisturbed hillslopes remains in storage on the

slopes or at the toe of slopes and typically does not enter streams at elevated rates. Roads in the watershed were found to both produce sediment and concentrate runoff and sediment load to the stream network. Nearly all roads connect either directly or indirectly with streams and therefore act as extensions of stream networks and effectively increase watershed drainage density. In the south fork, the presence of dirt roads has increased drainage density approximately 250%. This increase in effective drainage density means that the length of hillslopes to streams, and therefore to potential long-term storage sites for eroding material, is dramatically reduced. In addition, the increase in effective drainage density means that sediment from hillslopes is transported more rapidly to streams. Roads circumvent natural hillslope sediment transport processes and accelerate erosion; produce sediment through rills and gullies; and alter the magnitude, timing, and peak discharge of streams. All of these impacts have detrimental effects in the downstream reaches of the watershed.

Severe modifications of the south fork stream channel (e.g., flow rerouting through roadside ditches and culverts, reinforcing stream banks with rock rip rap) increase the velocity of stream discharge, which can be problematic during spring snowmelt runoff and large precipitation events. This is also evident in the meadow area where discharge has increased velocity and is causing accelerated bank erosion due to channel straightening as the creek enters the low gradient meadow from hillslope tributaries. Measurements of long-term channel migration indicate that stream bank erosion has increased substantially during the past 60 years when channel straightening occurred. As much as 2,000 to 3,000 tons of sediment per year have eroded from the banks in the meadow reach since 1940. Studies by other researchers indicate that the long-term average is similar to erosion of stream banks during normal precipitation years.

Direct measurement of rates, comparison to values in the literature, field observations, and professional judgment were utilized to develop a sediment budget based on relative percentage of sediment produced by different sources. Compared with values of the reference watershed (Sagehen Creek), reductions can be proposed that will decrease sediment in Squaw Creek.

Sagehen Creek has similar characteristics to Squaw Creek yet has experienced very little human disturbance. The geology of Sagehen Creek is most similar to the south fork of Squaw Creek: dominantly andesitic with an extensive cover of glacial deposits. The geology of Sagehen Creek indicates its high sensitivity to disturbance, making it an excellent reference site for the disturbed Squaw Creek watershed. Sagehen Creek stream gauging records cover approximately 50 years, and suspended sediment data are available for the past 30 years. Thus, daily sediment loads for the two watersheds can be compared to a certain degree. Furthermore, because the network of roads in Sagehen Creek is less dense, the reference watershed can serve as a template for reducing the number of dirt roads in Squaw Creek. Suspended sediment data suggest that Squaw Creek produces significantly more sediment than Sagehen Creek, although Squaw Creek is slightly smaller. Reducing the density of dirt roads in the south fork of Squaw Creek by a factor of approximately 3.5 should result in a significant decrease in sediment discharge.

Reducing the density is best accomplished by removing roads and culverts, replacing culverts with over crossings, and rehabilitating affected slopes. In paved road areas, roadside drainage should be improved through the use of Best Management Practice techniques developed to decrease the negative effects of certain land use practices on erosion.

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Disclaimer

The statements and conclusions of this report are those of the contractor and not necessarily those of the State of California. The mention of commercial projects, their source, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products. The source analysis portion of the Squaw Creek Total Maximum Daily Load relies on the most accurate and appropriate characterization of the natural system that was feasible under the constraints of time, cost, and existing data.

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1. Introduction

This report presents the results of a sediment source assessment conducted for the California Regional Water Quality Control Board, Lahontan Region (LRWQCB) in support of a forthcoming Total Maximum Daily Load (TMDL) for sediment in Squaw Creek, Placer County, California. The principal objectives of the study were as follows:

1) Conduct a comprehensive sediment source assessment
2) Identify and characterize the linkage between sources and water quality targets
3) Establish sediment loading and allocations for the north and south forks of Squaw Creek and for the meadow reach of Squaw Creek from the upper parking areas to the terminal moraine of Pleistocene glaciation

By meeting these objectives, the assessment seeks to refine the existing TMDL problem statement (see Appendices A and B) and address resolution of controllable watershed disturbances considered to adversely affect beneficial uses defined by LRWQCB. In addition, this assessment provides an estimate of the sediment budget for the watershed and an analysis of human-induced changes in sediment production, transport, and storage in the basin. Analysis of changes in the sediment budget related to human activities is used to identify priority sites for erosion control and prevention projects throughout the watershed. Finally, findings of the study form the basis for a subsequent TMDL implementation plan.

The sediment source assessment was approached in the following manner:

- Current watershed processes were evaluated to characterize baseline conditions. This evaluation was conducted using maps, photography, remotely sensed data, and field observations of geomorphic processes.
- Historic and Late Quaternary processes were assessed through field observations and interpretations as well as mapping of the Quaternary geology and geomorphology. This provided a longer-term perspective for understanding potential future behavior of the watershed than is possible from historic data alone.

- Bedrock, surficial geologic deposits, and in-stream sediment sources and responses to change in sediment load were identified.
- Biologic factors affecting sediment loading (e.g., vegetation type and cover) were evaluated and integrated with a biologic assessment carried out under a separate contract by Dr. Herbst of the Sierra Nevada Aquatic Research Laboratory (SNARL).
- The current Squaw Creek watershed was compared to a reference site to assist in establishing target values for sediment discharge. This was accomplished by following the U.S. Environmental Protection Agency protocol (EPA, 1999a) for reference watershed comparisons.
- A geographic information system (GIS) database and spatial data generation were developed.
- Source contributions were assessed through direct measurement, field observations, and existing data to develop an estimated sediment budget to assist in establishing target conditions and load allocations.

1.1 Overview of sediment source analysis

Analysis of sediment sources commonly includes identification and ranking, observing and documenting processes and rates, and estimating sediment yield from suspected sources. Estimates of sediment yield are frequently based on measurements at drainage outlets and modeling of watershed characteristics using readily available computer programs. Models rarely are able to account for spatial variation in process rates that result from the geologic and geomorphic framework, however. These processes have been shown to exert profound influences on the hydrology and sediment transport behavior of fluvial systems within mountain watersheds (e.g., Kelson and Wells, 1989). Because the behavior of a watershed is governed in part by antecedent geologic and geomorphic conditions, it is important to have a working understanding of the geomorphic history, which provides a longer-term view of the trends in fluvial (streams and rivers) system behavior and potential changes that may occur should the system be disturbed. Understanding the natural behavior of a fluvial system, as interpreted from deposits, can provide valuable information for use in restoration planning. This understanding commonly begins with the processes involved in sediment movement.

1.1.1 Sediment entrainment and transport

Processes responsible for initiating brief periods of sediment motion are known as entrainment. Entrained sediment experiences active transport in stream systems and is known as sediment load. Entrainment occurs as a result of shear stresses exerted on particles in the streambed and by impact of moving particles against particles at rest. Sediment transport refers to the actual movement of particles from one point to another.

Sediment transport in fluvial systems typically occurs as either bedload or suspended load. Bedload refers to coarse sediment (i.e., sand and gravel, but may include cobbles and boulders) that is transported by rolling or sliding along the stream bed. Most large sediment particles in streams do not move continuously during average discharge conditions. Rather, they move in short bursts over short distances separated by longer periods of time when they are at rest (Knighton, 1998). Suspended load typically consists of very fine particles (i.e., silt and clay) carried in suspension.

The manner in which sediment is transported is dependent upon the flow regime. For example, coarse particles—which for brief periods can be transported in suspension at higher discharges—may become part of the bedload or come to rest and be stored on the streambed when discharge decreases during seasonal or diurnal discharge fluctuations (Richards, 1982; Knighton, 1998). For fine particles, the volume of water, velocity, and turbulence limit the maximum suspended sediment concentration. In general, finer-grained particles are transported in the water column for great distances downstream (Knighton, 1998). Depending upon concentration, the suspended load can be the most visible component, often heralding violations of water quality standards related to non point source sediment.

1.1.2 Sediment sources

Anthropogenic activities can initiate geomorphic imbalances in watershed system dynamics and result in a variety of impacts including accelerated erosion and sediment transport processes. Agriculture, forestry, mining, urban and recreational development, and other human activities are known to affect the sources, rates, and magnitudes of sediment production, delivery, and yield (e.g., Reid and Dunne, 1996; EPA, 1999a). For example, removal of vegetation cover—such as that accompanying timber harvest, intense grazing, road building, or winter recreation ski trails—can alter the hydrologic characteristics of slopes by increasing overland flow, which typically results in increased rill and gully formation (Harr et al., 1975; Swanson and Dryness, 1975). Similarly, vegetation removal in the riparian zone reduces the influence of vegetation on dissipation of energy during high discharge and overbank events and leads to increased erosion of stream banks.

Forest roads are documented sources of erosion and sediment that affect both hydrologic (surface runoff) and geomorphic processes (erosion). Reduced infiltration, increased rates of runoff, and accompanying increased sediment production are common occurrences on compacted road surfaces (Reid and Dunne, 1984; Duncan et al., 1987; Grayson et al, 1993). Depending on road location and geometry, roads can intercept overland flow on hillslopes and divert the water into drainage collection systems. Increased runoff and sediment from roads is routed to channels with a corresponding alteration in peak flow magnitude and timing of sediment delivered to streams (Fredriksen, 1970; Harr et al., 1975).

Roads also can contribute to slope failures through removal of lateral or underlying support or through overloading with weight or water directly to the head of the slope (Selby, 1982; Swanson and Dryness, 1975). Slope failures commonly increase the volume of sediment entering small tributaries.

In undisturbed watersheds, geomorphic variables and processes are in a form of equilibrium (Ritter et al., 1995). Disruption of the equilibrium condition of a geomorphic system (e.g., watershed) can result in changes in sediment storage and movement. This concept was first put forth by Gilbert in the late 1800s (Hunt, 1988) and subsequently refined by numerous researchers (e.g., Mackin, 1948; Schumm, 1973, 1977; Bull, 1991). The general concept of geomorphic equilibrium states that landforms within a stable landscape system (e.g., watershed) will retain their character as long as geomorphic thresholds are not exceeded sufficiently to cause disequilibrium in the system (Ritter et al., 1995). If the system variables change in a manner that upsets the equilibrium condition (e.g., a change in climate that provokes increased sedimentation and aggradation), geomorphic processes will tend to adjust to the new conditions and the system may slowly return to former conditions during a period of variable duration, called the relaxation period (e.g., Bull, 1991). If a geomorphic threshold is crossed, the system will slowly adjust to establish a new equilibrium condition (Schumm, 1973; Ritter et al., 1995). These are important concepts to consider prior to initiating surface-disturbing activities within a watershed.

1.2 Study limitations

Given the relatively short time period to conduct the study and the desire for a geomorphic-process-based investigation, the direct measurements covered a short duration in time. As a result, these measurements may not capture the range of variation in sediment movement through the system. Compounding this issue is the fact that the study period occurred during two of the driest years on record during which little sediment appeared to be moving into the tributary streams. Despite these dry conditions, however, the dynamic watershed processes were observed. A second and related consideration is that Squaw Creek is an ungauged watershed, and the long-term record of stream discharge and sediment load is very limited. Two short studies (i.e., Woyshner and Hecht, 1987; McGraw et al., 2001) provide some gauging and sediment data, although these are not continuous records.

Reservoirs and detention basins are commonly used to provide estimates of sediment yield (Reid and Dunne, 1996). In the Squaw Creek watershed, several small reservoirs primarily intercept coarse fractions of sediment load; however, accurate records of sediment removed from the reservoirs are not maintained. In addition, the original configurations of detention basins typically are not known. Many of the detention basins have been reconfigured over time such that the original volumes have changed and accurate dimensions are not known. In addition, maintenance schedules are irregular, records of the volume of material removed are not reliable, and the success and efficiency of sediment removal efforts are not known. Similarly, sediment removed from culverts is not recorded. Therefore, measured sediment yield data are limited and also under-representative of the amount of sediment produced in the watershed. As such, available sediment yield data from Squaw Creek can only provide rough estimates.

Modeled sediment loads using 1996 and 1997 data are available, however; and a watershed erosion model calibrated to 1996 data (McGraw et al., 2001) can be used to provide general constraints on sediment yield.

2. Squaw Creek Watershed Overview

Squaw Creek is a small (approximately 8.2 square mile [21.1 km^2]), subalpine, and alpine watershed located about six miles (9.6 km) northwest of Lake Tahoe in Placer County between the towns of Tahoe City and Truckee (Fig. 1). The characterization developed for this assessment includes climate factors, geology, soils, vegetation, geomorphic processes, sediment sources, sediment movement, as well as spatial and temporal variability in the system (where appropriate).

2.1 Climate

The climate of the Squaw Creek watershed is similar to many high-altitude alpine settings and is characterized by rapidly changing weather conditions. Strong microclimate effects result from the great differences in elevation and aspect throughout the watershed. The proximity to Pacific frontal storm tracks results in frequent floods and droughts. Average annual precipitation within the watershed is approximately 32 inches (812 mm), and average temperature ranges from a minimum of 30°F (-1°C) to a maximum of 56°F (13°C) (WRCC, 2001). Precipitation is mostly in the form of snow from October to April. The long-term average annual snowfall is about 200 inches (5 m). At elevations above 7,000 feet (2,100 m), average annual snowfall may reach 240 inches (6.1 m). The eastern parts of the watershed receive slightly lower amounts of precipitation. Light intensity thunderstorms can occur throughout the year. Winds are mostly from the west and occasionally from the south (JARA, 1975). Wind velocity and direction patterns are similar to most mountain watersheds: light winds in the early morning with a down valley flow followed by an up valley flow in the afternoon as warm air rises. This pattern is countered, however, by the overall westerly wind flow. Temperatures are usually mild during the summer months, averaging 75°F to 80°F (24°C to 27°C) during the day with minimums between about 35°F and 45°F (2°C and 7°C). Winter minimum temperatures range in the teens but rarely drop below 0°F (–18°C).

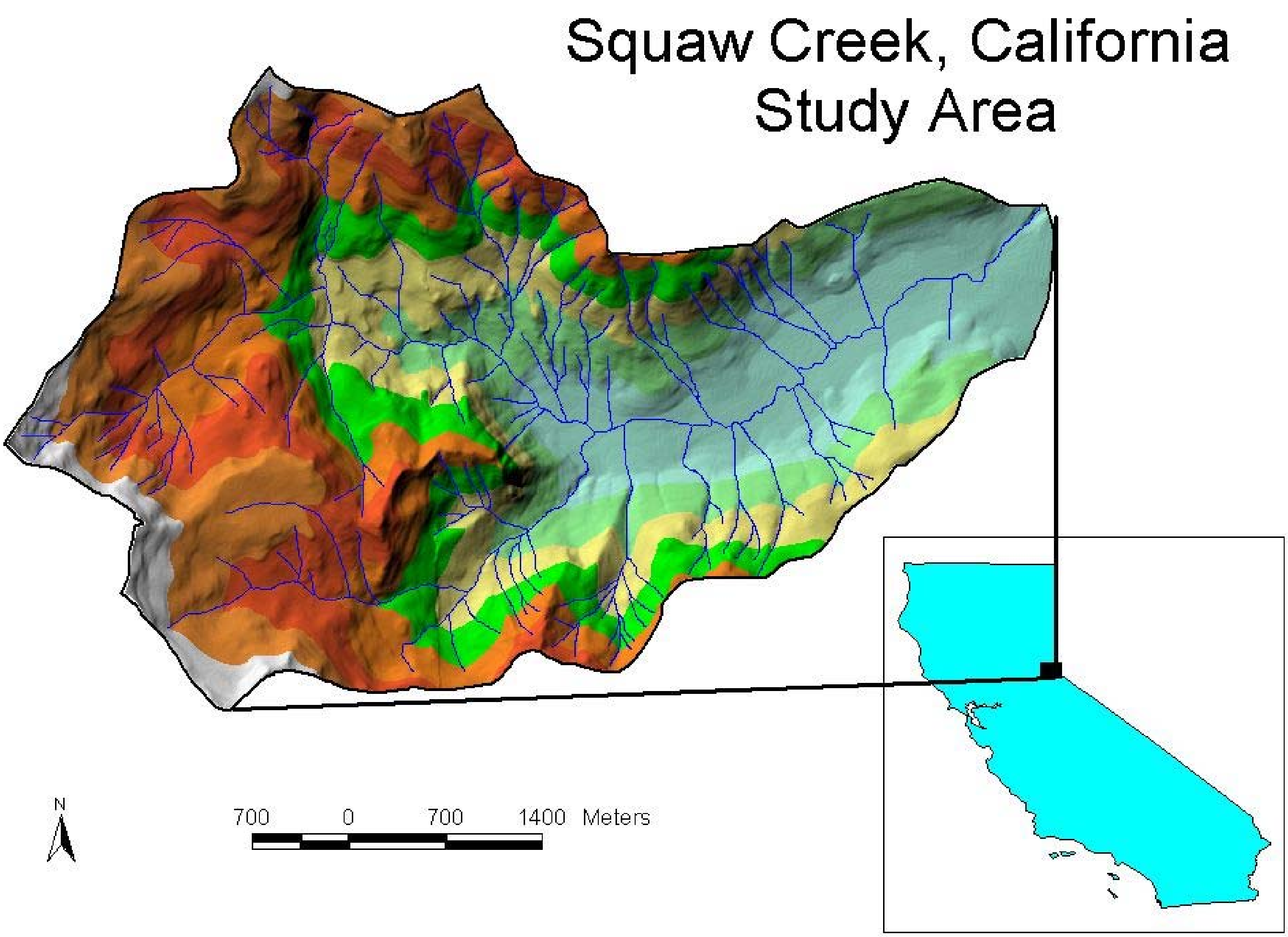

Figure 1. Location map of the Squaw Creek watershed.

2.2 Surface water hydrology

The climate and weather patterns of the region surrounding Squaw Creek exert a notable influence on the surface water hydrology, runoff characteristics, and movement of sediment within the watershed. Surface water hydrology in the Squaw Creek watershed is driven largely by snowmelt, which typically has a principal peak runoff associated with spring snowmelt. The magnitude of the peak spring runoff is controlled by total snowfall for the winter season, water content, and rate of melt. Much of Squaw Creek maintains a small base flow, the amount of which is dependent upon annual precipitation. The rate of movement of sediment within the watershed and the amount of sediment leaving the system are not constant. Bursts of activity occur depending on snowmelt and storms. For example, extreme runoff events capable of producing large discharges of water and sediment have been recorded during rain-on-snow events in the winter and early spring. In addition, intense thunderstorms have been documented to produce runoff characteristics similar to rain-on-snow events (e.g., Woyshner and Hecht, 1987).

Squaw Creek is an ungauged watershed. As a result, very little hydrologic data exist with the exception of intermittent discharge measurements made during other watershed studies (e.g., Woyshner and Hecht, 1987; McGraw et al., 2001; Kuchnicki, 2001). The record is too sparse and inconsistent to determine such long-term hydrologic characteristics as flow duration curves; mean annual discharge; and peak daily, monthly, or annual discharge. Data from previous studies were sufficient, however, to develop preliminary discharge-suspended sediment concentration (SSC) and turbidity relationships, (McGraw et al., 2001; Kuchnicki, 2001) and sediment loads (Woyshner and Hecht, 1987).

The Squaw Creek watershed can be divided into two prominent subwatersheds drained by north and south forks that meet at the west end of Squaw Valley at an elevation of 6,220 feet (1,895 m). The area of the north fork is approximately twice that of the south fork, but discharge for the two subwatersheds is almost identical (Table 1). Basing discharge on unit area during 1986–1987, twice as much water discharges from the south fork (Woyshner and Hecht, 1987).

Table 1. Comparison of physical characteristics and stream flow for the south and north forks of Squaw Creek (stream flow and water yield modified from Woyshner and Hecht, 1987).

	South Fork	**North Fork**	**Squaw Creek (watershed)**
Area	1.8 mi^2 (4.7 km^2)	3.6 mi^2 (9.3 km^2)	8.2 mi^2 (21.1 km^2)
Relief	2,665 ft (812 m)	2,786 ft (849 m)	2,904 ft (885 m)
Maximum Elevation	8,885 ft (2,708 m)	9,006 ft (2,745 m)	9,006 ft (2,745 m)
Stream flow (1986)	9,550 ac-ft	10,770 ac-ft	26,240 ac-ft
Stream flow (1987)	3,370 ac-ft	3,250 ac-ft	8,340 ac-ft
Water yield (1986)	29.32 x 10^6 L/ha	15.41 x 10^6 L/ha	16.47 x 10^6 L/ha
Water yield (1987)	10.35 x 10^6 L/ha	4.65 x 10^6 L/ha	5.23 x 10^6 L/ha

The upper reaches of the north and south forks of Squaw Creek are supplied primarily by snowmelt, but ephemeral streams and local seeps are found throughout the watershed. Seeps, or intermittent springs, in the north and south forks and elsewhere appear to be controlled by local geologic conditions, most notably the interface of surficial geologic deposits and bedrock.

Squaw Creek is channelized for about one-half mile from the confluence of the two forks to the eastern end of the main parking lot at the base of the mountain. Because of thick, coarse-grained alluvial sediments contained in the large fan formed at the junction of the mountain front and the valley floor, infiltration is common and a notable decrease in stream flow occurs through this section in periods of low summer flow. Squaw Creek then meanders from the parking lot to the terminal Pleistocene glacial moraine that defines the downstream end of the alluvial valley. In the reach from the terminal moraine to the confluence with the Truckee River, Squaw Creek has a steeper, boulder-controlled gradient. Much of the drainage from the south side of Squaw Valley is captured by small retention ponds and channelized or passed through culverts that lead directly to Squaw Creek. The golf course at the Resort at Squaw Creek has detention ponds designed to capture sediment and attenuate flow from the south side of the valley to Squaw Creek.

The overall stream network pattern is dendritic, although geologic structure exerts an influence in the north fork where a prominent north-trending fault passes. Both the north and south forks of Squaw Creek have steep gradients and bedrock-controlled channels. Stream patterns observed on the valley sides are slightly parallel but with an overall dendritic form.

2.3 Geology, geomorphology and geomorphic processes, and soils

2.3.1 Geology

The geology of the eastern Sierra Nevada, which contains the Squaw Creek watershed, is composed principally of Cretaceous intrusive granitic rocks of differing composition (mostly diorite and granite; Kg), Late Tertiary (Pliocene) basaltic andesite and pyroclastics (Ta), and minor amounts of Lower Jurassic metasedimentary and metavolcanic rocks (Tr-Jr) (Fig. 2). Quaternary surficial geologic units include abundant glacial deposits (lateral and terminal moraines), colluvial and alluvial fans at the junction of the valley side slopes and meadow floor, and fluvial deposits in meadow portions of the creek (Birkeland, 1961, 1962). Table 2 shows the relative percentages of geologic units in the watershed.

Table 2. Relative percentages of geologic units in Squaw Creek watershed, north fork of Squaw Creek, and south fork of Squaw Creek.

	Squaw Creek [A = 21.1^2 km]		**North Fork** [A = 9.3 km^2]		**South Fork** [A = 4.7 km^2]	
Geology	**Area mi^2 (km^2)**	**Area (%)**	**Area mi^2 (km^2**	**Area (%)**	**Area mi^2 (km^2**	**Area (%)**
Granite (Kg)	3.0 (7.8)	37	2.3 (5.9)	63	0.7 (1.9)	40
Andesite (Ta)	2.8 (7.2)	34	1.2 (3.1)	33	0.7 (1.9)	40
Metamorphic rocks (Tr-Jm)	0.1 (0.3)	1	0.1 (0.3)	3	--	--
Quaternary Geologic Units						
Glacial deposits (Qta, Qti, Qtil, Qtip)	1.6 (4.2)	20	--	< 1	0.3 (0.8)	17
Valley fill alluvium (Qal)	0.4 (1.1)	5	--	< 1	--	< 1
Alluvial fans (Qf)	0.1 (0.2)	1	--	--	--	--

Metamorphic rocks: Jurassic and Triassic (Tr-Jm) metasedimentary and metavolcanic rocks (Birkeland, 1961; Burnett, 1971) are exposed in very small outcrops at the crest of the watershed divide of the north fork of Squaw Creek. Outcrops are small and typically unvegetated. The rock units in the study area comprise only about 1% of the watershed and represent a very minor component of the bedrock.

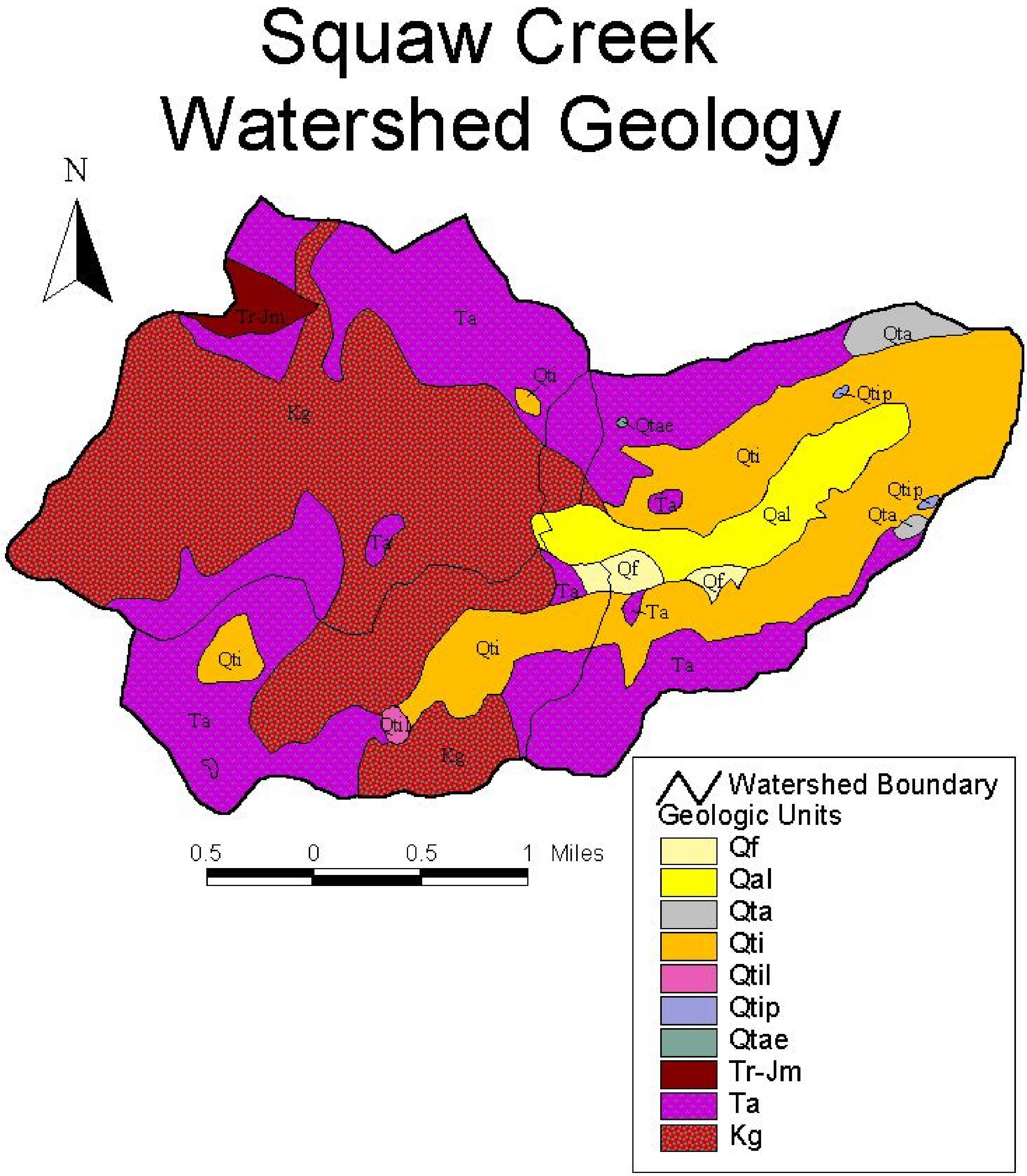

Figure 2. Generalized geologic map showing principal rock units in the watershed. Symbols used for rock units are described in the text.

Granitic rocks: Cretaceous granite and granodiorite (Kg) are exposed along the western margins and parts of the upper watershed. Granitic rocks underlie approximately 37% of the watershed. The formation of the granite mapped in Squaw Creek represents a portion of the Sierra Nevada batholith, which is the exhumed core of the magamatic arc associated with the former convergent plate margin along the Pacific coast of North America. A prominent fault system extending 400 miles (643 km) from south-central to north-central California (Saucedo and Wagner, 1992) separates granitic units from younger volcanics exposed farther to the east. Vertical displacements along the fault system have elevated the granitic rocks several thousand feet.

Volcanic rocks: Volcanic activity occurred during the Tertiary period in the Sierra Nevada principally as andesitic flows (map unit Ta). Volcanic rocks underlie about 34% of the watershed. The volcanic rocks are comprised predominantly of highly weathered andesitic flows and breccias and mixed pyroclastics (Birkeland, 1961; Saucedo and Wagner, 1992). These units form resistant ledges and prominent cliff faces and palisades on the southern side of the watershed near Squaw Peak. The volcanic rock units near the Watson Monument marking Emigrant Pass have a characteristic volcaniclastic texture that forms rugged cliffs that shed large amounts of coarse and fine-grained debris.

Quaternary geologic units: The Quaternary geologic units in the watershed are dominated by glacial deposits. Other Quaternary geologic units include alluvial fans and valley-fill alluvial deposits. Mass wasting deposits are identifiable in the watershed but are typically too small to depict at the scale mapped or were not differentiated from other Quaternary geologic units.

Glacial deposits. Glacial deposits formed during multiple glaciations in the latter part of the Pleistocene (Birkeland, 1962, 1963). These glacial units comprise approximately 20% of the mapped geologic units in the watershed and are located mostly in the lower parts of the watershed. Very few glacial deposits were mapped in the north fork of the watershed, whereas glacial deposits cover nearly 20% of the area of the south fork. Pleistocene glaciers carved out individual valleys during their expansion phases, creating the elongated U-shape of

Squaw Valley, which has the characteristic morphology of alpine glacial valleys. Glacial till, associated with the Tahoe (Qta) and Tioga (Qti and Qtil [late stade]) glacial events have been mapped within the Squaw Creek watershed (Birkeland, 1961). Deposits are primarily associated with lateral moraines, although till is thought to comprise a large part of the fill in the meadow section of Squaw Valley. Some ponded areas (Qtip) behind Tioga-age moraines are found along the margins in the distal part of Squaw Valley.

Tioga age glacial till—composed of boulders and cobbles within a fine, silty matrix—is extensive in the south fork of the watershed (almost 20%) and extends approximately 600 feet (200 m) up the sides of the valley. Glacial deposits are less apparent in the north fork of Squaw Creek, possibly reflecting differences in the relative percentage of granite in the two subwatersheds. Glacial erosional features, which include glacially striated granite bedrock and roche moutoneé, are prominent down valley from the Shirley basin.

Alluvial fans. Alluvial fans (map unit Qf) are found along the southern portion of the valley at the mouths of several tributary streams that feed into Squaw Creek. The fans are interpreted to be Holocene in age 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. 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. Construction activities and installation of subsurface culverts exposed sediments in the proximal fan deposits revealing coarse-grained gravel and sand as well as evidence of buried soils (indicating periods of nondeposition; Fig. 3). The coarse-grained nature of the fans undoubtedly influences surface hydrology where Squaw Creek crosses the fans. This is evidenced by the loss in discharge in reaches in the vicinity of residential housing at the base of the mountain. Small fans (less than 100 m^2) are found throughout the watershed and represent local sites of sediment storage.

Valley-fill alluvium. The sediments filling the lower meadow section of Squaw Valley (Qal) represent a mixture of fluvial and colluvial deposits, including landslide deposits that overlie glacial till near the base of the valley. Drilling logs and generalized descriptions from

Figure 3. Photographs showing coarse-grained gravel and sand of proximal alluvial fan deposits beneath the main parking lot at Squaw Valley. (Photos courtesy of B. Hecht)

geotechnical studies in Squaw Valley suggest that glacial till extends to more than 100 feet (30 m) below the surface and that overlying deposits are a mixture of fluvial and lacustrine deposits (Kleinfelder, 2000). At least six feet (2 m) of fluvial sediments are clearly exposed in the meadows section of Squaw Creek and represent aggradation of the valley floor during the Holocene. Large cut-and-fill stratigraphic sequences are not apparent in stream bank exposures suggesting few major fluctuations in base level conditions of Squaw Creek during the past few thousand years. The terminal glacial moraine at the east end of Squaw Meadows serves as the local base level for the meadows reach and is responsible for the relatively stable base level condition.

Hillslope deposits. Hillslope deposits include (1) thin mantles of weathered materials that may be in excess of several meters thick near the base of slopes and (2) thicker mass wasting and debris flow deposits near the toe of steep slopes. Several landslide scars are evident in aerial photographs along the northern portion of the valley. Because distal parts of the landslide and colluvial deposits appear to overlay the alluvial valley fill, they are probably the youngest of the mapped units. The presence of trees on portions of the slides in the 1939 aerial photographs indicate that the slides were not solely the result of anthropogenic disturbance in the watershed, as suggested by Jones (1981). Glacial deposits on hillslopes probably act a barriers to groundwater flow as indicated by groundwater seeps observed along the valley margins near the contact of the glacial till and bedrock where streams have incised deeply into the glacial deposits.

2.3.2 Geomorphology and geomorphic processes

The Squaw Creek watershed is a typical alpine drainage affected by glacial erosion and deposition. Subsequent post-glacial geomorphic processes also have exerted a profound influence on the relief and topographic character of the area. Elevation of the watershed ranges from 9,006 feet (2,745 m) at the top of Granite Chief to 6,120 feet (1,865 m) at the confluence of Squaw Creek and the Truckee River. The topography of the watershed reflects glacial erosion and deposition that occurred during multiple episodes of glaciation during the Pleistocene: steep U-shaped valleys in the lower parts of the watershed, steep headwall cirque basins, glacially plucked granite bedrock that form roche moutoneé topography (asymmetrical whaleback topography) in the valley floor higher in the drainage, and lateral and terminal moraine deposits. Roche moutoneé (landforms created during glacial abrasion on the gently sloping upstream side and intense quarrying or plucking of bedrock on the downstream side) has produced steep headwalls in both the north and south forks of Squaw Creek. Post-glacial modification of the landscape includes stream incision due in large part to base level changes in the Truckee River; erosion of steep slopes; and deposition of talus, alluvial fan and debris cones on the lower slopes, and alluvial valley fill in the lower meadow. Some incision likely occurred as a result of isostatic rebound following deglaciation and the removal of ice mass that caused local depression of the crust.

The great relief and elevation differences in the Squaw Creek watershed result in a crude stratification of geomorphic processes including production and transport of sediment. In this watershed, production of sediment includes weathering processes and transport includes mass wasting and fluvial processes.

Weathering processes: Weathering of rock and soil materials, driven in large part by chemical and physical processes, is the relatively slow process of breaking down rock masses into smaller particles that can be transported by various means. At higher elevations, mechanical weathering (physical breaking) plays a significant role in preparing rocks for chemical weathering. Transport of weathered rock is highly dependent upon slope, aspect, infiltration and runoff characteristics of hillslopes, and vegetation cover, which provides stability for slopes. Weathering processes are influenced by temperature and moisture regimes in the alpine environment. For example, high elevations are subject to the greatest accumulations of water and large diurnal fluctuations in temperature. Frequent temperature cycling at the higher elevations enhances mechanical weathering processes (e.g., freeze thaw, frost wedging).

Weathering characteristics and products of the basic rock units found in the Squaw Creek watershed differ considerably. For example, massive granitic outcrops at high elevations have relatively thin weathering rinds. In glacial moraines, however, relative ages are reflected in the thickness of the weathering rinds on granitic boulders (Burke and Birkeland, 1977). Weathering products, such as grus (i.e., pea-sized particles of decomposed granite), are transported by gravity down slope where they may be temporarily stored and weathered further. In contrast, the highly fractured granitic units near major fault zones and fracture systems that trend north-south through the area between High Camp and Broken Arrow are more intensely weathered to fine- and coarse-grained grus. Volcanic rock units characterized by pyroclastics breccias are more heterogeneous in texture and composition and tend to form deeper weathering profiles. Quaternary glacial deposits and other young surficial units have a variety of weathering characteristics depending on texture and age of the deposit. Some granitic and volcanic rocks were chemically altered during Tertiary volcanism. Rocks altered by these hot fluids are situated primarily along fracture and fault systems and have a tendency to weather rapidly, shedding fine-grained materials. Examples of this are observed along the fracture and fault zones that cross the Broken Arrow area of the watershed.

Mass wasting processes: Because of the relatively large proportion of hillslopes, the majority of geomorphic processes in the watershed are gravity-driven mass wasting processes. Rock falls on the upper slopes of the watershed are common, especially during the latter parts of winter when daily freeze-thaw cycles become more common. The larger particles travel relatively short distances and accumulate as talus. Some slope materials may be mobilized as debris flows or translational rock slides (see Varnes, 1978 for classification of landslides) and travel greater distances down the steep slopes. For example, debris slides composed of coarse-grained grus were observed to occur during winter months on steep hillslopes having southern exposures. The slide material most likely contained sufficient moisture that, upon freezing and subsequent partial thawing, overcame inertial forces and internal frictional resistance and rapidly flowed down slope as a cohesive mass. Most of the characteristics of debris flows (e.g., levees, depositional lobes) were observed even though the flow traveled on top of the hardened top crust of snow. 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 can serve as an effective sediment trap for fine-grained slope materials (e.g., Caine, 1986; Gardner, 1986).

Small-scale, shallow translational slides (e.g., Varnes, 1978) are found associated with steep slopes having thin mantles of colluvium. Some of these slides are influenced by moisture conditions on the hillslopes, which result in heaving and differential expansion of clay minerals. Some are directly related to disturbances such as road cuts. Other slides may be part of the natural hillslope erosion process that involves complex feedback mechanisms related to parent material, weathering, soil development, and climate (e.g., Tonkin and Basher, 1990; Simon et al., 1990; Renau et al., 1990).

Some mass wasting deposits have temporarily blocked small, steep tributary drainages in the upper parts of the north fork watershed. These serve as temporary dams that store sediment until the fluvial system recovers and adjusts to new gradient conditions. Mass wasting also is a factor along the banks of low-gradient streams. For example, localized slumping of banks has occurred primarily as a result of fluvial undercutting and groundwater sapping along the meadow section of Squaw Creek (slope is about 2°). Sapping, a term applied to erosion caused by the rapid discharge of groundwater through an unsupported rock or soil face, occurs when processes such as fluvial erosion remove confining pressures. As a stream headcuts into a meadow, for instance, it may intersect an elevated groundwater table. Once the stream incision occurs, the vertical face of the soil becomes weakened because of high pore pressures at the face and the loss of confining pressure. This phenomenon is well documented along streams in regions characterized by freezing and thawing of the soil along stream banks (Reid, 1985).

Except for a few large, ancient slides on the south-facing slopes bordering the meadows, large landslides are not common within the Squaw Creek watershed. One relatively large slide did occur several thousand years ago in the vicinity of Hidden Lake (William F. Jones, Inc., 1983), a small sag pond formed within a landslide mass in Tioga-age glacial till near the northeast end of the watershed. More recent, smaller landslides in the Hidden Lake area have been attributed in part to poor construction practices (William F. Jones, Inc., 1981, 1983). Small debris slides on the south side of the valley east of the Resort at Squaw Creek occurred during the wet winter of 1997.

A large area of irregular topography on the northern margin of the valley floor (partially covered by residential housing) represents an ancient slide mass. Processes occurring on the landslide scar (Fig. 4) include 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. The stream channel becomes distributary in nature on the alluvial fan that extends onto the valley floor. The distributary channels have very low gradients in their distal reaches before connecting with Squaw Creek. Although gravel was transported to the margin of the meadows in 1997, sediment reaching Squaw Creek from the landslide area is mostly very fine-grained and transported in suspension during runoff events.

Fluvial processes: Fluvial processes in the watershed include in-stream as well as overland flow on hillslopes. Overland flow occurs on many slopes, evidenced by the development of rills particularly on disturbed hillslopes, dirt road surfaces, and along the margins of dirt roads. Rills are typically a few centimeters deep and wide, although, some master rills have developed into larger gullies. Based on the estimated volume of sediment derived from the development of large gullies, the gullies are capable of producing significant amounts of sediment particularly in their initial expansion prior to equilibration (Seginer, 1966; Selby, 1982; Kavvas and Govindaraju, 1992). When overland flow occurs in the watershed, it most likely occurs as saturated flow in the spring when the soil profile is saturated from snow melt and Hortonian overland flow in the dry season during rain storms. Hortonian overland flow occurs when rainfall intensity exceeds the infiltration capacity of the surface soil, as opposed to saturation overland flow, which occurs from direct precipitation on saturated surfaces.

2.3.3 Soils

Soils found in the Squaw Creek watershed reflect the interaction of five soil-forming factors (Jenny, 1980): climate (precipitation, temperature, and wind), vegetation, topography and relief (including aspect), the parent material upon which the soils are formed, and time.

Figure 4. Landslide complex with prominent scar on south facing slope on the north side of Squaw Meadows. Current hillslope processes include shallow slumping at the head of the slide, shallow translational slides, and debris slides and flows in the lower parts of the slide complex. Homes in the foreground are situated on hummocky topography possibly associated with ancient landslide mass.

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Within the Squaw Creek watershed, the geology and recent geologic history (Pleistocene glaciation) exert a control over the types and locations of soils as well as their relative degree of development.

The relative degree of soil profile development provides a useful tool for interpreting and assessing spatial variability in hydrologic properties of surficial deposits throughout the landscape (Birkeland, 1990). The relative degree of soil development is related directly to the five soil forming factors and refers to the morphologic and geochemical characteristics of soils. Soil morphology refers to the physical properties including thickness of the soil profile, degree of development of horizonation, color, structure, texture, accumulation of clay in the profile, and horizon boundaries. As a soil is exposed at the surface for increasingly longer periods, the strength of individual soil morphologic properties tends to increase (Birkeland, 1999). This increase becomes diagnostic of age and can allow discrimination of soils, and hence land surfaces. From the diagnostic properties, relative ages of soils can be established. Increasing soil age also results in changes in hydrologic properties. Thus, in a landscape that has differing soil ages, there can be dramatic spatial variation in surface hydrologic properties, implying that there also may be spatial variation in the relative sensitivity of the landscape to erosion or disturbance.

Soils of Squaw Creek watershed: Soils found within the Squaw Creek watershed (Fig. 5; Table 3, 4) have been mapped and classified by the Soil Conservation Service (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. 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 (e.g., Shirley Lake area) and the meadows section of lower Squaw Valley. At elevations above about 6,500 feet (1,980 m), soils have formed from weathered volcanic, metasedimentary, and granitic rocks and include glacial and alluvial deposits. Soils at the lower elevations of the watershed are formed on alluvial and glacial deposits.

Table 3. Typical soil series found in the Squaw Creek watershed. Data and horizon nomenclature are from *Soil Survey of the Tahoe National Forest Area* (Soil Conservation Service, 1994)

Soil Series	**Taxonomic Class**	**Typical Profile**	**Profile Thickness in. (cm)**	**Thickness Bt horizon in. (cm)**	**Max Redness B-horizon or Profile (d/m*)**
Jorge	Frigid Ultic Haploxeralfs	O-A-Bt-C	>40 (101)	11 (28)	10YR/7.5YR
Meiss	Lithic Cryumbrepts	A-R	12-20 (30-51)	--	10YR
Tallac	Pachic Xerumbrepts	A-C	20-30 (51-76)	--	10YR
Tinker	Frigid, Andic Haplumbrepts	A-B-C	60 (152)	5 (12)	7.5YR/7.5YR
Waca	Typic Xerumbrepts	A-C	20-40 (51-101)	--	10YR/10YR

-- no Bt horizon
*d/m refers to dry and moist Munsell soil colors (Munsell Color Company, 1975); dry color if only one color shown.

Principal soil orders found in the watershed are Alfisols and Inceptisols (Soil Survey Staff, 1999; Soil Conservation Service, 1994). Common suborders are Umbrepts and Xeralfs. Many of the soils in the watershed belong to great groups associated with the udic to xeric moisture regime and frigid to mesic temperature regime. Some of the soil series and types reflect minimal soil development (entic soils). Most of the soils in the watershed are dry to moist and characterized by gray to brown surface horizons. The principal series shown on soil survey maps for the Squaw Creek watershed include Aquolls and Borolls on the valley floor and areas of very low slope (0-5%), and soils of the Jorge, Meiss, Tallac, and Waca series on the gradual and steeper slopes (Soil Conservation Service, 1994).

Stability and erosion considerations: Nearly all the slopes in the Squaw Creek watershed have soils comprised of complexes of the Jorge, Meiss, Tallac, and Waca series plus Cryumbrepts, rock rubble (e.g., talus), and bedrock outcrops (Table 4). Low to very low available water capacity and typically shallow rooting depths make these soils very difficult to manage and revegetate if disturbed (Soil Conservation Service, 1994).

The slope soil complexes generally are shallow, high in rock fragment content, and moderately to well drained. The matrix of these soils is typically very fine-grained silt and clay loam. The shallow soils associated with steep slopes make them highly susceptible to erosion if disturbed, and the fine-grained matrix in suspension is prone to being transported long distances down hillslopes and into tributary streams. The Cryumbrepts commonly have an impermeable substratum in the subsoil thereby reducing infiltration capacity and making them subject to ponding and susceptible to erosion during snowmelt.

On steep slopes, mass wasting processes tend to move loose material down slope faster than soils form. Therefore, vegetation cover capable of providing stability to slopes is limited. Disturbance of the vegetation cover on these slopes can result in the exposure of bare soil and impermeable underlying bedrock units that can lead to excessive sediment discharge.

Borolls and Aquolls (soil unit AQB, Fig. 5) are suborders of the Mollisol soil order (Soil Survey Staff, 1999) and represent soils that are wet for most of the year and typical of cool environments. These soils are found principally in the lower meadows of Squaw Valley and the Shirley Lake basin area (Soil Conservation Service, 1994). In general, these soils are less susceptible to erosion by virtue of their landscape position. If disturbed, however, they are capable of producing sediment particularly if situated near, or connected to, water bodies. These soils tend to form in low places where water collects and stands, but some form on broad flats or seepy hillslides. In the Squaw Creek watershed, these soils are shallow to moderately deep and have a thick, dark colored surface layer (Soil Conservation Service, 1994). Most have vegetation including grasses, sedges, and forbs.

Young fluvial deposits typically have dry mineral soils lacking significant development (e.g., layering). They are loamy to sandy soils formed on alluvial material and occur with intermixed gravel and boulders. These soils typically are associated with woody riparian vegetation and are susceptible to erosion, particularly during large discharge events. Young fluvial deposits are found primarily along the margins of the active channel of Squaw Creek and its tributaries as well as drainages developed on the slopes bordering Squaw Valley.

Bedrock, which may be exposed naturally or as a result of removal of thin overlying soil cover, and soils stripped of vegetation tend to inhibit infiltration and promote runoff. The result is that runoff from exposed bedrock and bare soil tends to be concentrated and may have adverse erosional effect on adjacent soils and surficial deposits.

Table 4. Selected properties of soil units found in Squaw Creek watershed.

Soil Unit	Map Unit	Depth (in)	Slope %	Erosion Hazard	Management Considerations
Aquolls and Borolls	AQB	<30	0 to 5	High	High water table; subject to flooding
Granitic rock outcrop	GRG	0	-	Na	Steep and very steep slopes; concentrated surface runoff and erosion of adjacent soils
Jorge Cryumbrepts	JSG	<47	30 to 75	High	Steep and very steep slopes; high water table; impermeable substratum at depth
Jorge-Waca-Tahoma	JWF	<47	30 to 50	High	Steep slopes; Waca soils have impermeable substratum at depth
Meiss gullied land – rock outcrop complex	MHG	<19	30 to 75	High	Steep and very steep slopes; shallow to bedrock; concentrated runoff
Meiss-rock outcrop complex	MIE	<19	2 to 30	High	Shallow soils; prone to runoff and erosion on adjacent soils
Meiss-rock outcrop complex	MIG	<19	30 to 75	High	Steep and very steep slopes; soils can generate concentrated runoff
Meiss-rock outcrop complex, severely eroded	MIG3	<11	30 to 75	Very High	Steep and very steep slopes; surface soil eroded; surface runoff
Meiss-Waca complex	MKE	<19-32	2 to 30	Mod-High	Meiss soils are shallow to hard bedrock and produce surface runoff; Waca soils are moderately deep; impermeable substratum at depth
Meiss-Waca complex	MKF	19-32	30 to 50	High	Steep slopes; Meiss soils are capable of producing surface runoff; Waca soils have impermeable substratum at depth
Meiss-Waca—Rock outcrop complex, severely eroded	MKF3	11-21	30 to 50	Very High	Steep slopes; weathered volcanic and tuff breccia mudflow rocks; surface runoff
Meiss-Waca-Cryumbrepts, wet complex	MLE	19-32	2 to 30	Mod to Very High	Meiss soils are shallow to hard bedrock, produce surface runoff; Waca moderately deep, impermeable substratum at depth; Cryumbrepts have high water table, puddling susceptibility, and impermeable layers at depth
Meiss-Waca-Cryumbrepts, wet complex	MLG	19-32	30 to 75	High to Very High	Same as MLE only steeper slopes
Rock outcrop, granitic Tinker complex	RRG	<33	30 to 75	High	Steep and very steep slopes; moderately deep soil, high amount of rock fragments; concentrated runoff from rock outcrop can increase erosion on adjacent soils
Rock outcrop, granitic-Tinker-Cryumbrepts, wet complex	RSG	<33	30 to 75	High to Very High	Steep and very steep slopes; Tinker soils are moderately deep; Cryumbrepts have high water table and puddling susceptibility; concentrated runoff from outcrop and increased erosion on adjacent soils
Rubble land-Jorge complex	STG	<47	30 to 75	High	Steep and very steep slopes; Jorge have coarse texture and high amount of rock fragments; rubble areas have potential for raveling

Soil Unit	Map Unit	Depth (in)	Slope %	Erosion Hazard	Management Considerations
Rubble land-Rock outcrop complex	SUG	0	30 to 75	-	Steep and very steep slopes; rock outcrop concentrates run off and can cause increased erosion on adjacent soils
Tallac very gravelly sandy loam	TAE	<41	2 to 30	High	Coarse textures; high amount of rock fragments
Tallac very gravelly sandy loam	TAF	<41	30 to 50	High	Steep slopes; coarse textures; high amount of rock fragments
Tallac-Cryumbrepts, wet complex	TBE	<41	2 to 30	High to Very High	Tallac soils have coarse texture, high amount of rock fragments; Cryumbrepts have high water table most of the year, susceptible to puddling, impermeable layers at depth
Tallac-Cryumbrepts, wet complex	TBF	<41	30 to 50	High to Very High	Same as TBE but on steep to very steep slopes
Tallac-Gullied land-Cryumbrepts, wet complex	THF	<41	30 to 60	High to Very High	Same as TBF and TBE. Gullied land areas produce concentrated runoff and can increase erosion of adjacent soils.
Tinker-Rock outcrop, granitic-Cryumbrepts, wet complex	TIE	<33	2 to 30	High to Very High	Tinker soils are moderately deep and have high amount of rock fragments; granitic outcrop can produce concentrated runoff that may increase erosion of adjacent soils; Cryumbrepts as TBE, TBF
Tinker-Rock outcrop, granitic-Cryumbrepts, wet complex	TIG	<33	30 to 75	High to Very High	Same as TIE but formed on steep to very steep slopes
Rock outcrop, volcanic	VRG	0	30 to 75	-	Concentrated runoff on exposed outcrop can increase erosion on adjacent soils
Waca-Windy complex	WAE	32-46	2 to 30	Moderate	High amounts of rock fragments; snowmelt accumulates over impermeable substratum
Waca-Windy complex	WAF	32-46	30 to 50	High	Same as WAE but formed on steep slopes
Waca-Cryumbrepts, wet-Windy complex	WBF	32-46	30 to 50	High to Very High	Same as WAE, WAF; Cryumbrepts have high water table and impermeable layers
Waca-Meiss complex	WDF	19-32	30 to 50	High	Steep slopes; Waca soils are moderately deep, have impermeable substratum; Meiss soils are shallow, capable of producing surface runoff
Waca-Meiss-Cryumbrepts, wet complex	WEE	19-32	2 to 30	Mod. to Very High	Characteristics of Waca, Meiss, and Cryumbrepts as described above
Waca-Meiss-Cryumbrepts, wet complex	WEF	19-32	30 to 50	High to Very High	Same as WEE but on steep slopes
Ledford Variant-Rock outcrop complex	WRG	<28	30 to 75	High	Steep and very steep slopes; deep, coarse texture; concentrated runoff from rock outcrop can increase erosion on adjacent soils

Note: Table and descriptions abstracted from *Soil Survey of the Tahoe National Forest* Area (Soil Conservation Service, 1994. Erosion hazard is based on little or no vegetative cover and the long-term average occurrence of two-year, six-hour storm events. Erosion hazard increases when storm frequency, intensity, and duration exceed long-term average occurrence. Very high and high erosion hazard – accelerated erosion will occur in most years. Moderate erosion hazard – accelerated erosion is likely to occur in most years. Low erosion hazard – accelerated erosion is not likely to occur, except in the upper part of the low erosion hazard range or during periods of above average storm occurrence

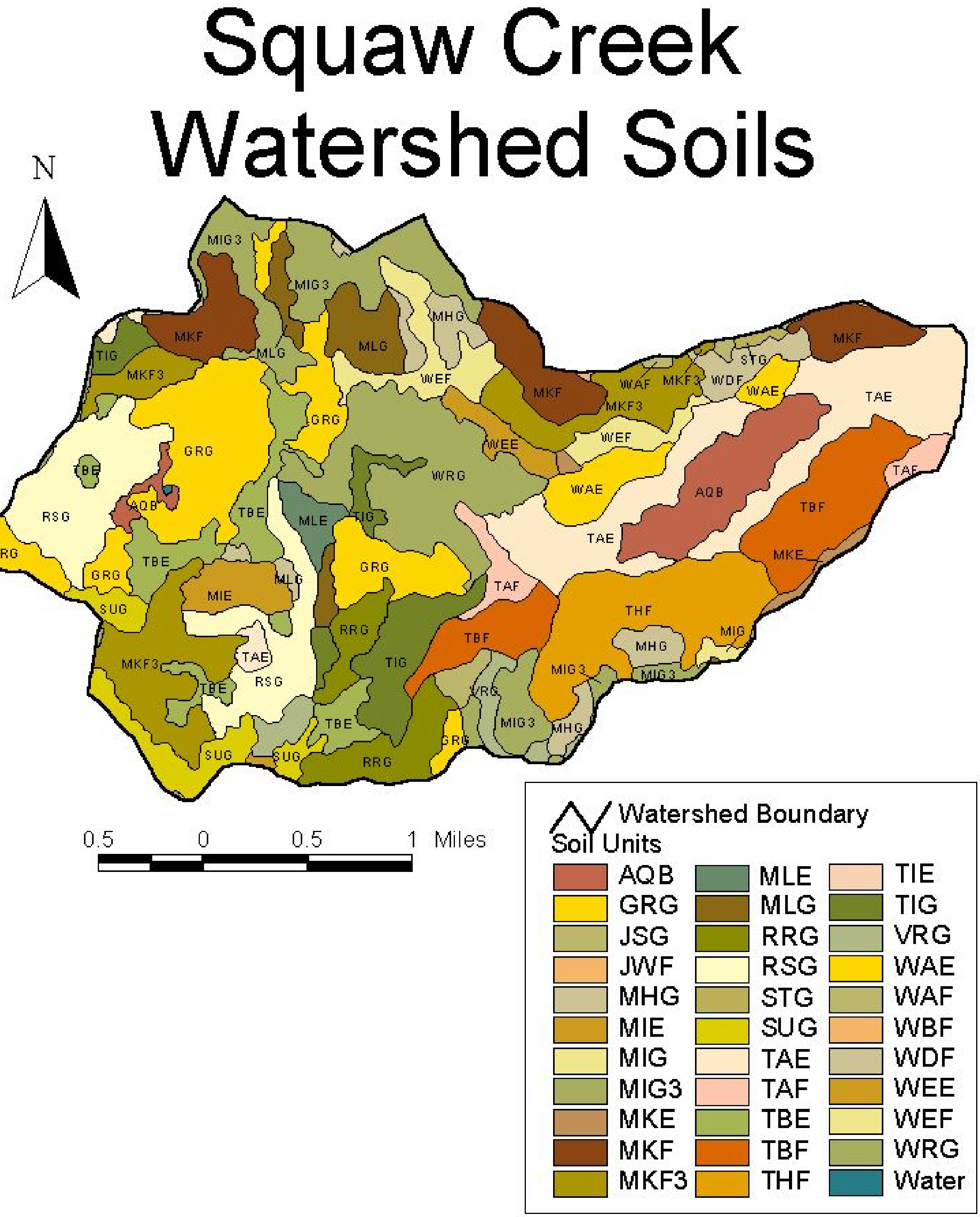

Figure 5. General soil map for the Squaw Creek watershed (from Soil Conservation Service, 1994).

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 (Fig. 6). A list of potential common and special interest plant and animal species for the Squaw Creek watershed is provided in Appendix C.

Lower montane zone: The lower montane zone ranges from the valley floor to approximately 7,000 feet (2,134 m). Three primary forest vegetation types are found in this zone. In order of decreasing abundance, they are as follows: mixed-conifer forest, Jeffrey pine forest, and white fir forest. Nonforest 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 contributes more than half of the total number of trees or canopy cover on average. Jeffrey pine forest is dominated by Jeffrey pine with minor associated conifer species such as white fir and incense cedar. White fir forest is dominated by white fir, 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 occurs 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 both an understory component of the three forest types described above and a dominant vegetation type on hillslopes. Montane chaparral is characterized by a diverse assemblage of shrubs including manzanita (*Arctostaphylos patula*), Sierra chinquapin (*Chrysolepis sempervirens*), huckleberry oak (*Quercus*

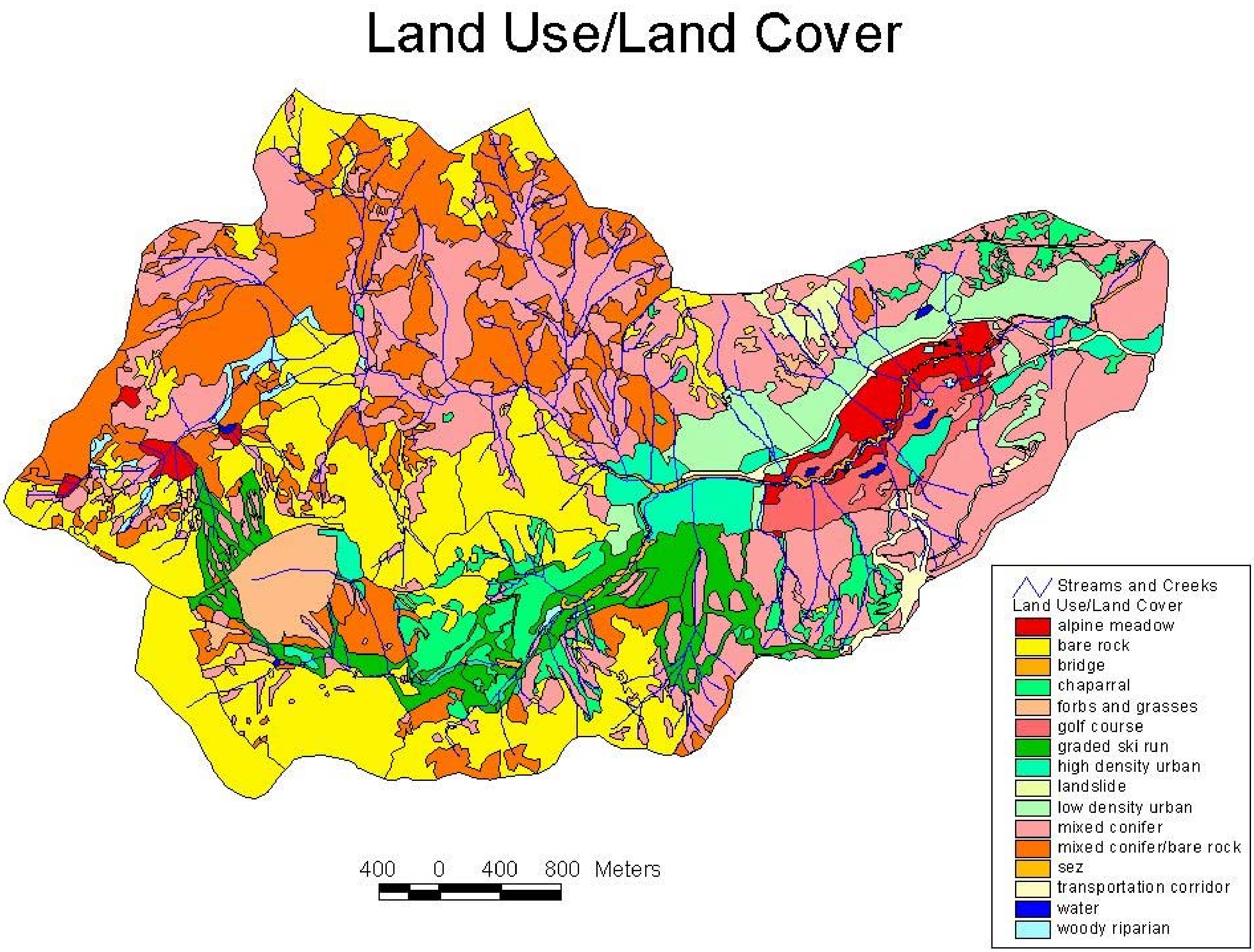

Figure 6. Land use and land cover map for the Squaw Creek watershed.

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*) also are associated with the montane chaparral vegetation type. Riparian vegetation is dominated by 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 primarily of willow species but also includes creek alder (*Alnus incana*) and dogwood (*Cornus sericea*). Meadow vegetation includes both wet and dry meadow associations and consists of numerous species of grasses, sedges (*Carex spp.*), rushes (*Juncus spp.*), and herbaceous plants.

Upper montane zone: The upper montane zone ranges from approximately 7,000 to 8,500 feet (2,134 to 2,591 m). Mixed conifer forest may occasionally occur in this zone; but the most common forest type is red fir. Additional species associated with this forest type include western white pine (*Pinus monticola*), lodgepole pine, and white fir. 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, creek alder, and dogwood. 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 occurs in locally wet areas at the edge of meadows and streams. Upper montane meadow vegetation 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, rushes, and herbaceous plants. Chaparral vegetation is limited in distribution in the upper montane zone, consists of the same species described in the lower montane chaparral, but tends to be dominated by manzanita.

Subalpine zone: The subalpine zone is above approximately 8,500 feet (2,591 m). 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 (e.g., white fir, lodgepole pine, and western white pine). Mountain summits and peaks are generally devoid of vegetation with occasional patches of herbaceous vegetation, such as mule's ear (*Wyethia mollis*).

2.5 Land and water use

The Squaw Creek watershed experienced numerous changes in land use during the past 150 years. In the late 1800s, cattle ranching, sheep herding, farming and logging supported a small community. Ranching and herding declined and were limited to sporadic summer grazing of sheep and cattle by 1950. It is likely that logging continued throughout this time period but has declined in recent decades. Little other business activity occurred until the development of the ski resort at Squaw Valley 1949.

Although numerous land use changes occurred in the watershed during the past 150 years, perhaps the most significant took place during the past 50 years, a period that has seen many residents and business move into the scenic valley. In anticipation of the 1960 Winter Olympics, the north slopes of Squaw Valley were subdivided into plots for single-family dwellings beginning in the late 1950s. Also in preparation for the Winter Olympics, the U.S. Army Corps of Engineers channelized Squaw Creek through the western end of the valley. Tributaries from the north-facing slopes at the west end of the meadows were diverted through a culvert where they passed through the former Olympic facilities area. These diversion treatments are still in place today and culverted tributaries discharge directly to Squaw Creek. The western end of the meadow was cleared of vegetation and graded for parking and access roads, and numerous ditches were constructed to drain the meadow for spectator parking areas.

Present uses in the valley include residential housing, hotels, and commercial development. An Olympic class ski resort, including ski runs and commercial businesses, occupies much of the south fork drainage and the western end of the valley. Recreational, commercial, and residential development has accelerated dramatically in recent years due to California's robust economy. Outdoor recreational activities include a championship golf course, commercial equestrian operations, sports fields, and an extensive network of hiking and bicycling trails.

Small-scale private timber operations continue on the forested slopes of the valley. Land ownership is largely private with public ownership limited to U.S. Forest Service land in the Shirley Canyon area of the north fork of Squaw Creek.

The impact of development in the watershed is readily apparent from the large areas of unforested slopes and road networks. Logging roads, residential development, trails, ski resort access roads, and ski runs have altered natural surface drainage patterns. These land uses have undoubtedly increased the amount of sediment available for transport into Squaw Creek.

Municipal water supplies are drawn primarily from wells within the valley-fill aquifer. The south fork of Squaw Creek is impounded in Gold Coast pond to supply water for snowmaking. All sewage is presently exported from the valley, potentially influencing the water budget. Squaw Creek water continues down the Truckee River to Nevada for municipal and agricultural use.

3. Methods and Techniques

Characterizing the types, locations, and magnitudes of sediment sources is an important step in source analysis and was accomplished through inventory of sediment sources affecting Squaw Creek. Existing environmental, geotechnical, hydrologic, and other technical reports related to sediment yield, land use, and disturbance were reviewed. Modern and archival topographic maps, repeat aerial photography, and satellite imagery enabled assessment of historic changes such as stream meandering and land use changes. Electronic databases from the U.S. Geological Survey (USGS), U.S. Forest Service (USFS), and other state and local agencies were incorporated into a GIS system (along with data collected during this study) and used to analyze spatial relationships among sources, land use, and land cover. In addition to reviewing existing data, field mapping the geomorphology and checking existing geologic maps at an appropriate scale provided details regarding spatial distribution of sources and geomorphic processes. Initial field reconnaissance trips were made to gain an overall impression of the watershed, begin assessing potential sediment sources, and develop an appropriate large-scale assessment strategy. The watershed was subdivided, potential sources were identified, and techniques for measuring sediment movement were chosen. Field techniques are described in the following sections.

3.1 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, subwatershed divides, and land use (Fig. 7). Within each sector, erosion pins and modified sediment traps were installed to assess the rates of sediment movement. The following paragraphs describe the extent, geomorphology and geomorphic processes, and geology of each sector.

3.1.1 Sector I - Squaw Creek Meadow

Sector I is comprised of the glacial valley of Squaw Creek from the confluence with the Truckee River to the upper parking lots at the lower tram terminal. Wetlands and dry meadows containing a mix of sedges and forbs, riparian vegetation, and a meandering reach of Squaw Creek characterize the valley. Relief on the valley floor is only a few feet. The valley geology consists of Quaternary alluvium overlying probable glacial outwash and lacustrine deposits. Fluvial processes that dominate in this sector include active channel migration, bank erosion, flooding, sediment storage, and transport. The stream has been modified in historic times by activities associated with grazing, recreational development, and restoration efforts (SCS; 1979; Woyshner and Hecht; 1987). Residential, recreational, and commercial development is the dominant land use in the valley.

3.1.2 Sector II – North-facing hillslope of Squaw Valley

Sector II is comprised of relatively steep north-facing slopes that border the meadow in Sector I. Vegetation consists of moderately dense mixed conifer forest that has been previously logged and some riparian vegetation along several tributaries to Squaw Creek. The geology is comprised of Tertiary volcanic and Quaternary glacial units. Glacial deposits associated with lateral moraines have been incised by existing tributaries in some areas, creating well-formed channels and alluvial/colluvial fans at the base of the hillslopes. Land use consists of

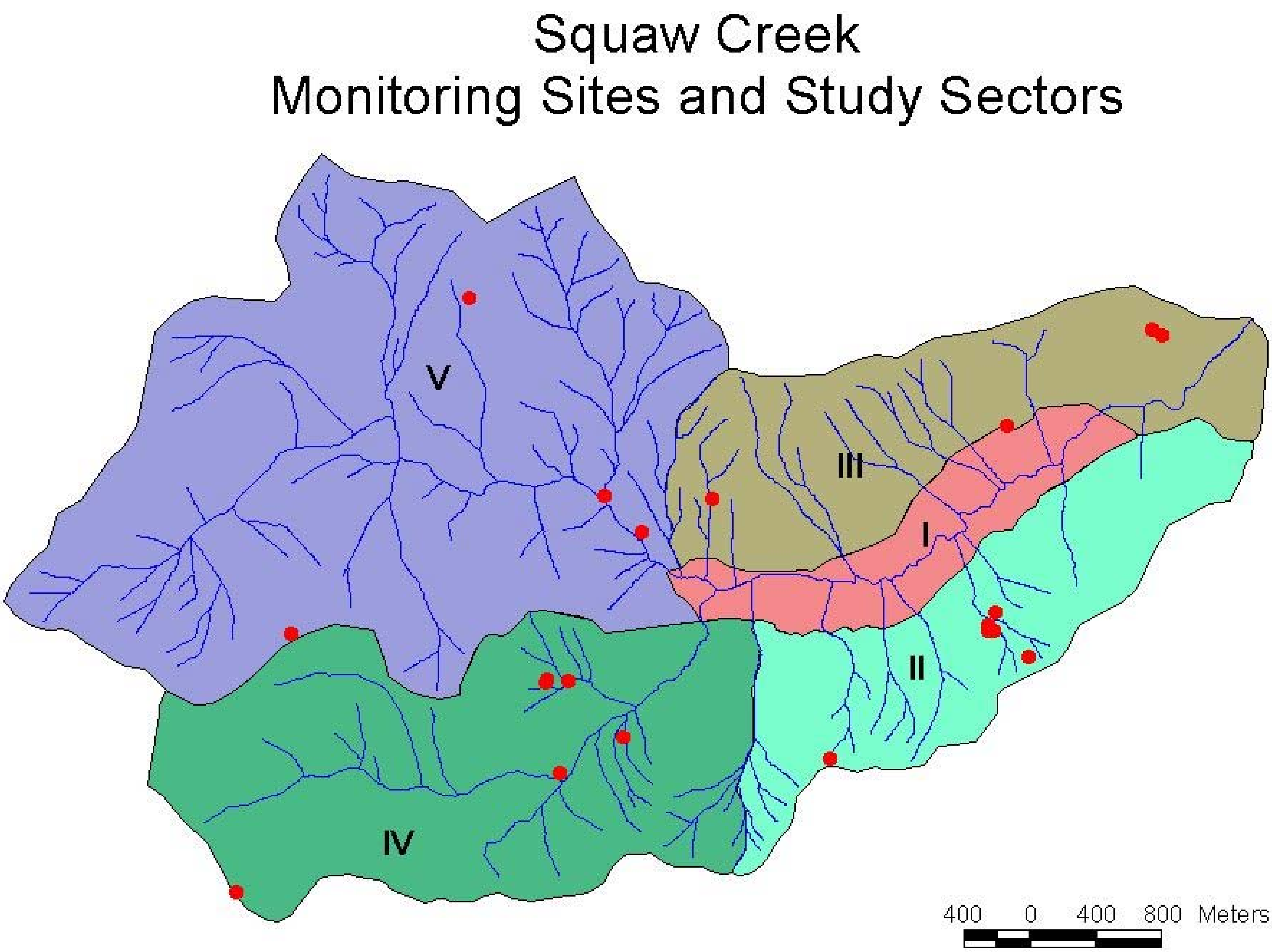

Figure 7. Map of the Squaw Creek watershed with sectors and locations of erosion monitoring sites (filled circles).

commercial, forestry, and recreational (golf and ski resort) activities. Numerous unpaved maintenance roads, ski lifts, and ski runs are found in Sector II.

3.1.3 Sector III – South facing hillslope of Squaw Valley

Sector III is comprised of relatively steep south-facing slopes that border the meadow in Sector I. Vegetation consists of moderately dense mixed conifer forest and montane chaparral that has been previously logged and minimal amounts of riparian vegetation along minor drainages. The geology is similar to Sector II. Evidence of several landslides is apparent, particularly in the western portion of the sector. A few access roads are present on the slope running from the subdivision to the ridge. Land use consists of residential development and natural preserve. A secondary paved-road network typical of roads associated with subdivisions is present on the lower slopes. A few unpaved roads ascend from the subdivision to the ridge top.

3.1.4 Sector IV – South Fork of Squaw Creek

Sector IV contains the south fork of Squaw Creek and associated tributaries and has the same approximate boundaries as the subwatershed. Topography is characterized by very steep slopes on both the north and south sides of the prominent, narrow valley formed along the south fork. The westernmost part of the sector has steep slopes in a bowl-shape reflecting the cirque basin formed during glacial erosion of the south fork. Vegetation is sparse, consisting of subalpine conifer species and shrubs. Glacial deposits, which represent a potentially significant supply of fine-grained sediment, cover the granitic bedrock in much of the lower valley of the south fork except where the stream has incised through the glacial cover to the underlying bedrock. In the upper elevations of the south fork, the dominant geologic unit is volcanic (andesite) rock. Granite is found as prominent outcrops in the Headwall area, along the divide between the north and south forks below High Camp and on the south side of the lower part of the south fork valley. Extensive modification of stream channels (rerouting, channelization) using a variety of engineered structures has occurred as a result of recreational development. Sector IV contains the most extensive network of unpaved single and double track maintenance roads of any of the sectors. Recreational alpine skiing is the primary land use in this sector, with additional activities available during the off-season (e.g., hiking and mountain biking).

3.1.5 Sector V – North Fork of Squaw Creek

Sector V is characterized by steep slopes and has boundaries that are approximately the same as the north fork of Squaw Creek and associated tributaries. Vegetation is moderately sparse, consisting of subalpine conifer species and shrubs, with a higher percentage of plant cover than Sector IV. Geology is dominantly granitic bedrock, and large areas of exposed bedrock are common. Roche moutoneé is present in the valley of the north fork and forms spectacular cliff faces, waterfalls, and glacially polished and striated granite. Ephemeral tributaries drain from volcanic rock (andesite) in the northern portions of the sector. Upper reaches of the north fork are structurally controlled by faulting. Land use in this less disturbed sector is limited to low impact recreation (hiking trails), with the exception of a few ski runs in the westernmost part of the sector.

3.2 GIS data and analysis

3.2.1 Spatial data

The GIS component of this study was utilized to construct a spatial database specific to the Squaw Creek watershed. The database was then used to analyze watershed geomorphology, land use, land cover, and geology.

Spatial database construction: A combination of data sets was used to build the Squaw Creek watershed GIS database including existing DRI, public domain, and newly created digital data. The data are described in Appendix D and include metadata descriptions for each data set. Data were projected into Universal Transverse Mercator (UTM) zone 10, datum NAD27 for this study.

Some data received by DRI were not rectified to an existing coordinate system. DRI received two compact discs containing scanned unrectified aerial photography of the Squaw Valley basin from Squaw Valley Ski Corporation. Many of these same aerial photographs were obtained in analog stereo format from the Tahoe National Forest (TNF) Truckee office.

Historic aerial photographs for Squaw Creek were obtained from TNF and are listed in Appendix E.

The Desert Research Institute's (DRI's) ArcView version 3.2a was used to construct the spatial database. Arc/Info version 8.0.2 (both Arc and the Grid module) was used to perform some of the spatial processing, but the database platform was developed in ArcView. All Arc/Info coverages obtained from public domain sources and DRI's archive were converted to ArcView shapefiles. The primary components of the database are ArcView shapefiles, grids, and image files (i.e., data formats representing vector data [points, lines, polygons], raster data [cell-based data structure], and image data [scanned topographic maps, orthorectified photographs], respectively). Each ArcView shapefile has a feature attribute table that contains fields of descriptive characteristics for the data set. Each grid has a value attribute table that contains descriptive fields for data set cells. Some tables in the database are stand-alone (i.e., they do not have a spatial feature component per se but contain descriptive information that can be linked to a related spatial data set using a field common to both tables, like a unit identifier or basin identification number). A good example of this kind of data linkage are the numerous tables containing Natural Resource Conservation Service (NRCS) State Soil Geographic (STATSGO) Data Base parameters such as map unit, layer, and composition data that can be linked to a spatial data layer that contains the actual polygons that represent the MuId and Muname for the soil type.

Spatial data used to parameterize the Squaw Creek watershed included:

- Ten meter digital elevation model (DEM) data from the USGS
- USGS digital orthophotographic quadrangles (DOQs; 1 m scale)
- Scanned digital raster graphic (DRG) images of the USGS quadrangle maps of the study area (Tahoe City and Granite Chief)
- Study sectors of the entire Squaw Creek watershed
- Geology digitized from Birkeland's 1961 geology map
- TNF Order (Level) 3 soil survey
- NRCS STATSGO soils data layer of the study area

- Streams and creeks originally derived from USGS digital line graph (DLG) data and subsequently modified using the scanned USGS topographic maps, DOQs, and field observations
- Modeled subbasins of Squaw Valley using 10 m DEM data and ArcView's hydrologic modeling tools
- Stream order calculated in ArcView using the Shreve classification method (Ritter et al., 1995)
- Stream order calculated in ArcView using the Strahler classification method (Ritter et al., 1995)
- Stream cross sections
- Stream geomorphic map
- Meadow portions of Squaw Creek (left, right, and thalweg)
- Erosion pin and fence sample points
- Hydrographic boundary for Squaw Creek derived from USGS DLG data and subsequently modified using the scanned USGS topographic maps
- Dirt roads modified from the original TNF data updated with air photo and DOQ interpretations
- Paved roads modified from the original TNF data updated with air photo and DOQ interpretations
- Road areas calculated for both paved and dirt roads using a buffering operator in ArcView and assigned road widths
- Land use database constructed from interpretation of aerial photographs and the mosaicked DOQs
- Land cover database derived from a combination of the TNF timber type data set, a University of Nevada, Reno (UNR)-Biological Resource Research Center (BRRC) vegetation database, the US Forest Service (USFS) Gap vegetation data set, and image interpretation of a Landsat Enhanced Thematic Mapper (ETM) scene of the study area acquired in August 1999
- Vegetative canopy cover percentage database derived from the same four sources as the land cover database

Most of the data listed above required processing, modification, or both in preparation for use in the study, regardless of whether the data was from public domain sources or developed at DRI. Data sources (e.g., geology, roads, stream parameters, land use, land cover, and canopy cover percentages) were updated or created by digitizing features on a digitizing tablet or computer screen. Erosion pin and fence data were derived directly from field sampling.

Geomorphic analysis: Hydrologic modeling tools in ArcView were used to delineate subbasins of the Squaw Creek watershed and calculate the stream order classifications. Using the DEM, a flow direction raster file (grid) was calculated for the entire basin, and sub-watersheds were derived based on a minimum cell size for each basin. Next, a flow accumulation grid was processed which calculated the number of upslope cells flowing to a location. From the flow accumulation grid, stream network grids were calculated. Stream orders were assigned to each stream segment, using both the Shreve and Strahler techniques.

Soils data layer: Original plans to use the high resolution (1:24,000 scale) NRCS (Soil Survey Geographic (SSURGO) database soils data for the study area were modified when it was discovered that the only SSURGO-level or SSURGO equivalent soils data set available for the study area was the TNF Level 3 soils resource inventory. Although the spatial scale of the data set was more than adequate for sediment analysis purposes (1:24,000 scale), the critical soil parameters necessary for use were not available in the limited-attribute table associated with Level 3 data. Other parameters were available from a document file (Adobe Acrobat PDF format) obtained from TNF but were limited to general soil profile descriptions, soil properties (effective root depth, water capacity class, available water capacity, permeability, erosion hazard), and soil management interpretations.

Road database: Road databases were developed using a set of criteria that divided paved roads and dirt roads into two categories each. Single-track roads are those wide enough to accommodate a single vehicle, and double-track dirt roads are those wide enough to allow two trucks to pass side by side. Single-track and double-track dirt roads were assigned widths determined from averages of road observations on the DOQs: 20 feet (6.6 m) and 40 feet (13 m), respectively. The widths assigned to the two classes of paved roads, primary and secondary, were 30 feet (9 m) and 26 feet (7.9 m), respectively and were derived using the same method as the dirt roads. Once the road widths were assigned to each road segment, a buffering operation was run in ArcView to determine the actual area (polygons) a road occupied in the study area. All of the road segment area measurements were then summarized by type for the study area.

Land use and land cover data layer: Developing the land use and land cover data layer was an iterative process involving interpretation of aerial photographs and DOQs as well as professional judgment regarding land use categories. The land use classification was based on a modified Anderson land classification system (Anderson et al., 1976) and focused on land cover types that have significant erosion and sediment source potential.

Initially, a land use and land cover map was generated automatically using spectral imagery. That map was rejected because land use categories and boundaries were frequently incorrect and inconsistent, necessitating manual production of the map. Land use and land cover were mapped from 1997 aerial photographs (scale 1:16,000) based upon texture, tone, color, and shape and from direct observations of the watershed. Following air photographic mapping, the interpretations were ground truthed. Sixteen land use and land cover categories were selected for the watershed because of their observed influence on sediment production (e.g., bare ground, roads, ski runs). These categories were then digitized into the GIS to assist in spatial evaluation of potential sediment sources (Table 5). The information was transferred into an ArcView shapefile layer for the project GIS database, to produce the land use and land cover map (Fig. 6).

Road surfaces, which had been categorized in different road databases, were combined into a transportation corridor class. Developed land areas were separated into two classes, high-density urban areas and low-density urban areas, based on the amount of impervious cover in each. Low-density urban areas include natural ground cover (rock, compacted soil, vegetation cover) as well as impervious structures and surfaces.

Table 5. Descriptions of land use and land cover categories, including percent of area covered by each land use or land cover type. These land cover categories were identified for the purpose of characterizing their sediment production potential.

Category	**Percent of Watershed Area**			
Land Use	**Squaw Creek**	**North Fork**	**South Fork**	**Description**
Bridge or culvert	0.02	0.0	0.1	Engineered structure crossing stream
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
Land Cover				
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
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 C for listing of species]

Development of the land cover and canopy cover databases involved integration of the TNF, BRRC, and USFS vegetation data sets, because no single data set covered the entire study area. The Landsat satellite data were used to update burned and regrown areas and to determine accurate land cover at the intersection of the input data sets. Some of the data sets, in particular the TNF timber data, were dated (the TNF timber type data were originally created in 1979-1980 by the Forest Service). The resulting integrated attribute tables of land cover and canopy cover percentage then were edited and checked for completeness and consistency with respect to land cover categories and canopy cover percentage classes.

3.2.2 Scale, accuracy and reliability

Development of the GIS database was driven and constrained by availability of existing spatial data sets for the Squaw Creek watershed and surrounding region. As such, certain scale and reliability limitations affecting accuracy had to be addressed and reported. Because most of the original data sets used in the project were from public domain sources and in digital form, almost all of the data used in this study conform to National Map Accuracy Standards (U.S. Bureau of the Budget, 1947). All photographic interpretation (e.g., roads, land use, hydrographic boundaries) was performed using the USGS DOQs which conform to National Map Accuracy Standards. Data in the database that do not comply with National Map Accuracy Standards include the digitized geology because the original base map was of poor quality. The polygon boundaries for geological units on the digitized version were updated, however, using the DOQs and field information for the Squaw Creek watershed area. The resultant digital product is a more accurate representation of geology in the study area.

3.3 Sediment

3.3.1 Sediment data from previous studies

Suspended and bedload sediment data were obtained from previous studies (Table 6) for comparison with reference watershed conditions. Two short records (2 years each) of suspended sediment data was obtained for a local study of sediment loading to Squaw Creek (Woyshner and Hecht, 1987) and during a regional study of sediment loading to the Truckee River (McGraw et al., 2001; Kuchnicki, 2001). The annual loads were converted to average

Table 6. Summary of suspended sediment and bedload data for Squaw Creek.

	SSC (tons day^{-1})	Bedload (tons day^{-1})
1985*	1.7	6.6
1986*	0.2	0.9
1996-1997†	<1–198	--
2000-2001†	<1–16	--
1996#	3.8 (0.8–19.8)	--
1997#	9.9 (1.9–53)	--
1996^	4.4	--
1997^	2.4	--

* Woyshner and Hecht, 1987; converted from annual load to average daily load for the year.
† Range of loads calculated from rating curves for Squaw Creek (McGraw et al., 2001)
# Predicted sediment loads modeled from rating curves developed from SSC and discharge data; range in parentheses (McGraw et al., 2001); converted from annual load to average daily load.
^ Average daily sediment loads for 1996 converted from annual loads of AnnAGNPS model calibration results; 1997 loads from validation of the AnnAGNPS watershed model to 1996 data (McGraw et al., 2001) also converted to average daily loads.

daily loads for comparison with daily load measurements for Squaw and Sagehen creeks. Although the SSC data provides useful information that can be converted into a sediment yield for the watershed, it reveals little about the sources of sediment or processes.

3.3.2 Identification of sediment sources

Several sediment sources were identified during initial field reconnaissance. These sources then were reduced to a smaller number for sampling based on professional judgment regarding location, extent, magnitude, and relative importance in the watershed. The principal sources investigated are listed below. Field methods employed to measure sediment contributions are described in section 3.3.3.

- *Bedrock sediment sources* were identified through analysis of aerial photographs and field mapping. Where feasible, measurements were made to estimate the direct sediment contribution from bedrock sources. Additional estimates were gained indirectly from observing bedrock-derived sediment adjacent to outcrops.
- *Hillslope sediment sources* from undisturbed and disturbed areas were selected in different geologic settings to make direct measurement of erosion rates (from which estimates of sediment yield were then made). Longer-term sediment movement on

hillslopes was assessed in natural settings such as sediment trapped behind fallen trees or sediment contained in small landslide deposits.

- *In-stream sediment sources* were assessed through change analysis observed during a 62 year period from 1939 to 2001 using repeat aerial photography, digital orthophoto quadrangles (DOQs), and GIS spatial analysis. Direct measurements of stream channel and bank erosion as well as sediment storage were made in the field.
- *Roads as sediment sources* were analyzed primarily as impermeable surfaces that contribute to increased sediment and water discharge. Analyses included aerial photographic mapping, GIS mapping, classification, and direct measurement of erosion (where practical).
- *Sediment contributed from land use practices* was estimated from field observations and direct measurements where it was practical to install measuring devices. The contribution of sand applied to roads during winter months was obtained from the road maintenance office for Placer County, California.
- *The relationship between sediment sources, land use practices, and sediment contributions to the impact on beneficial uses* was assessed by formulating a series of questions that could be answered using the GIS database. For example, we used GIS tools to analyze spatial relationships to determine if there is a relationship between the location of dirt roads, land use, and geology.

3.3.3 Field methods used to measure erosion in Squaw Creek watershed

Direct measurements of erosion rates were made on different hillslope and stream channel components. Repeat observations were used to estimate change through time and determine rates of erosion or deposition for different parts of the landscape. Hillslope soils and stream bank and bed materials were sampled to further characterize the nature of sediment sources.

Stream channel cross sections: Channel cross sections were installed to measure changes in the width-depth ratio (w/d) of channels and to estimate sediment contribution from channel banks and bed. Changes in w/d of stream channels can indicate a change in stream regime and sediment load (Knighton, 1998). For example, a change from a low to high w/d often indicates an increase in sediment load and probable aggradation or widening of the channel without increasing depth. A decrease in w/d typically indicates incision, which could be a response to change in sediment load conditions or channel bank stabilization. Stream banks are large contributors of sediment if eroded through undercutting, meander migration, or bank failure.

Channel cross section measurements were merited in the broad valley of Squaw Meadows because the greatest amount of sediment in the watershed is stored there. Although the stream gradient is low in the meadows reach, geomorphic processes occurring along the margins of the stream (e.g., various stages of bank collapse) were observed to introduce large volumes of sediment. Combined with bank erosion during high stream discharge events the meadows section has the potential to be a large contributor of sediment to Squaw Creek.

Repeat measuring of channel cross sections allows assessment of changes in streambed and channel banks and calculation of the amount of sediment contributed by those sources. This method uses a surveyed topographic profile from one bank of the stream to the other (Stott et al., 1986; Lawler, 1993). By conducting repeat measurements and superimposing the profiles, change is documented, estimates of sediment erosion or deposition recorded, and inferences about geomorphic processes affecting the channel can be made (Lawler, 1993). Longer-term rates of sediment contribution from bank erosion caused by meander migration were estimated by analyzing changes in channel location observed on repeat photography and DOQs for 1939, 1987, 1997, and 2001. Volumes were estimated by calculating the area of material eroded, the average bank height, and a value of 1.5 g cm^{-3} for sediment bulk density.

Two representative meadow section reaches containing four alternating pool and riffle sequences were identified and a total of eight cross sections established orthogonal to the flow direction (Fig. 8). An auto level and stadia rod was used to collect point elevation data along each profile. The left bank rebar monument was designated as the end point of each cross section.

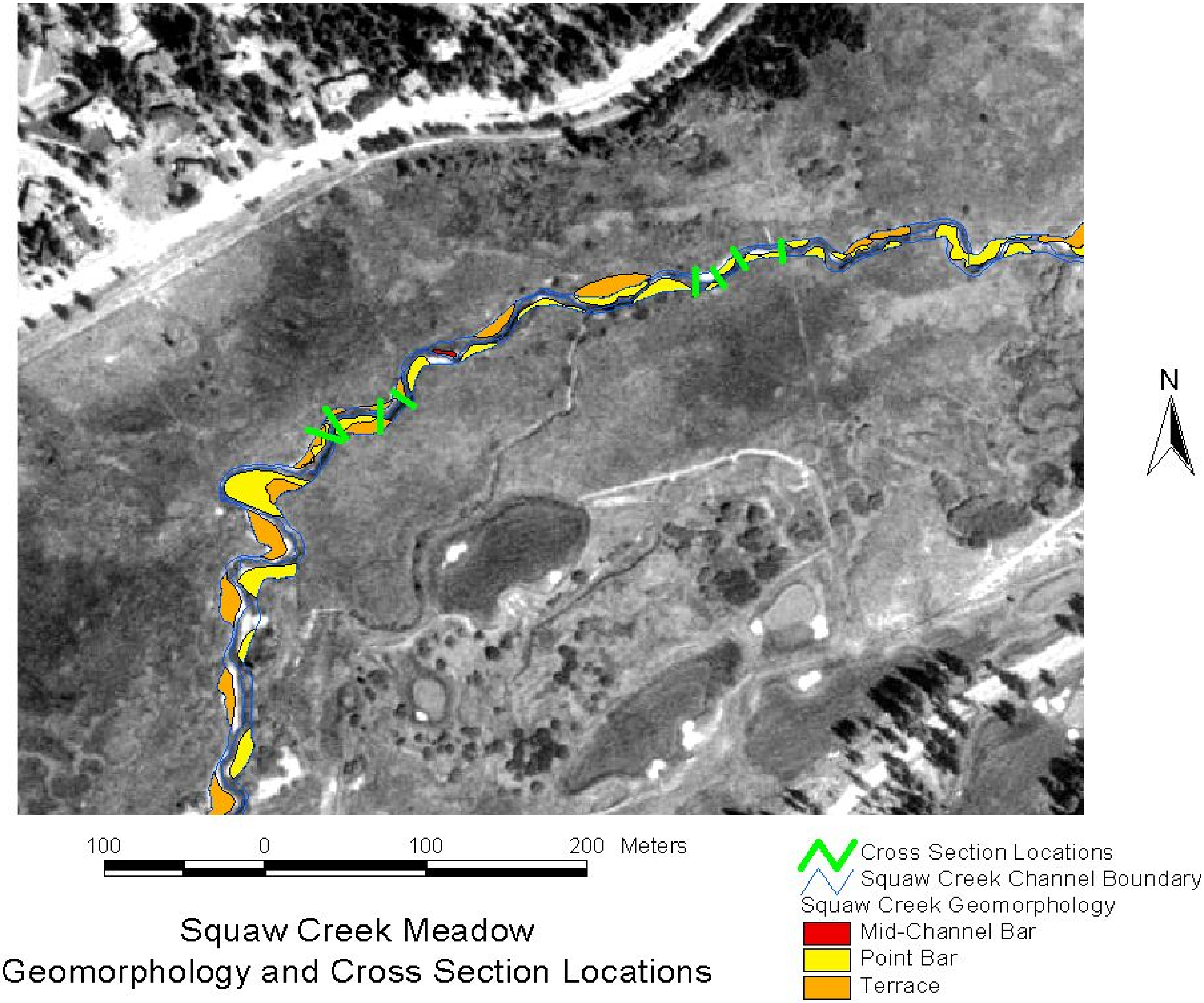

Figure 8. Geomorphology and cross section locations in the Squaw Meadows section of Squaw Creek.

Grab samples: Substrate grab samples were collected to assess in-stream sediment source materials and sediment in storage on gravel bars. Samples were collected at regular intervals along linear transects on the bars. Grab samples were collected from in-stream bars to help characterize the type and size of material transported during high flow events. Size distributions of the particles were determined using particle size analysis.

Soil pits: Surficial geologic materials were sampled from shallow pits to better understand the particle size of sediment contained in hillslope and stream deposits. Soil pits were excavated near hillslope erosion measuring sites to a depth of approximately two feet (0.6 meters). Hillslope stratigraphy was recorded in notes and digital photographs, and samples were collected for particle size analysis. Particle size analyses were performed in the Soil Characterization and Quaternary Pedology Laboratory at DRI.

Hillslope erosion: Erosion measurement devices were installed to determine erosion rates for disturbed (e.g., ski runs, road cuts, landslides) and undisturbed hillslopes (Fig. 9). The resulting erosion rates were used to approximate the rate and relative magnitudes at which sediment is entering the drainage network from roads and hillslopes. To approximate rates of sediment delivery, we assumed that measured rates obtained during monitoring represent reasonable estimates of delivery to streams. Relative magnitudes are derived from the erosion rates for different sources. Erosion rates obtained from monitoring sites were averaged and extrapolated to similar areas within the watershed to account for the fact that not all areas within the watershed could be monitored. The methodology for each measuring device follows.

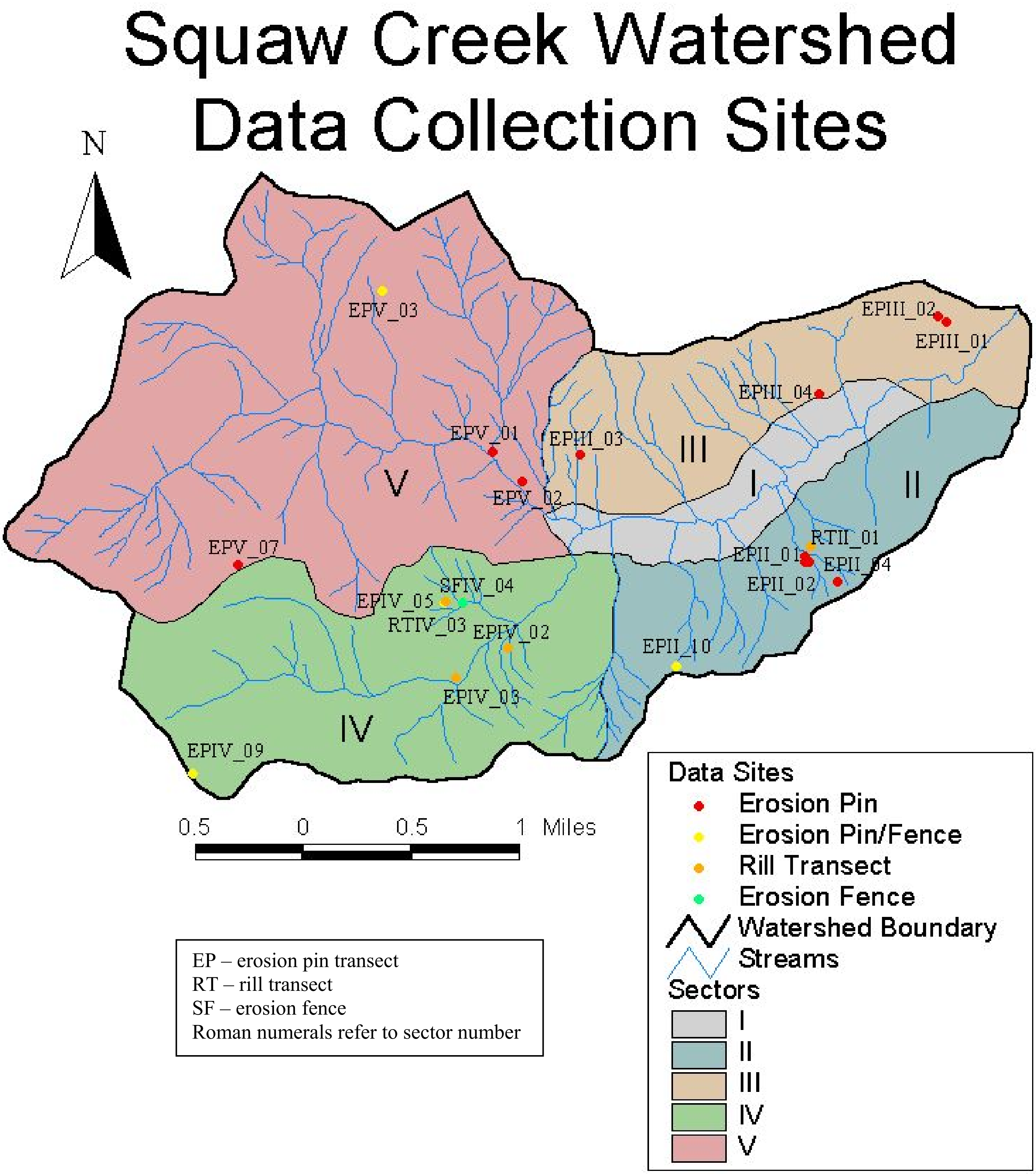

Figure 9. Map showing the locations of hillslope erosion measurement sites.

Erosion pin transects. Erosion pin transects are typically used for measuring soil losses or gains on hillslopes. Small diameter (5 mm) pins are inserted into the soil, and the top of each pin serves as the measurement datum (Goudie, 1981; Wells et al., 1983; FAO, 1993; Stott et al., 1986) (Fig. 10). To assist in assessing erosion associated with land use and land cover, erosion pin transects were established in areas exhibiting erosion potential (e.g., ski runs,downslope of roads) as well as undisturbed forest and chaparral areas. The location selection allowed rates to be extrapolated to similar areas of land use and land cover throughout the watershed, as suggested by Young and Saunders (1986).

At each site, transects were installed across and parallel to the slope. Pins were placed at 6.5 foot (2 m) intervals along the transect, unless an obstacle was encountered. Pins were installed to protrude above the soil surface approximately 3 to 6 inches (80 to 150 mm). A small, lightweight washer was placed over some pins to aid in determination and measurement of any erosion followed by deposition. Repeat measurements at each pin were made from June through November to record erosion or deposition activity. Erosion pin transects at higher elevations had few repeat measurements because of early snows. Erosion pin transects were photographed, and locations were determined using a global positioning system (GPS).

By averaging sediment transport (erosion and deposition) measurements for each site, relative rates of erosion were determined for the measured area and extrapolated across similar hillslope environments in the watershed. To determine the overall average movement occurring at a site for the sampling period, we calculated the change (+/-) in pin measurement height between visits. Positive values for change in pin height indicated deposition at the point, and negative values indicated erosion. The absolute values of the calculated change values were summed to indicate overall movement at the pin for the sampling period. The absolute value was used to (1) recognize that deposition at a pin resulted from erosion from some point above (summing the absolute values of the change provided an estimate of overall movement) and (2) ensure that the rate of movement at a site was depicted accurately (i.e., that instances of erosion and deposition occurring at the same pin did not negate each other). We then computed an average movement rate site by summing the overall movement obtained for each pin and dividing by the number of

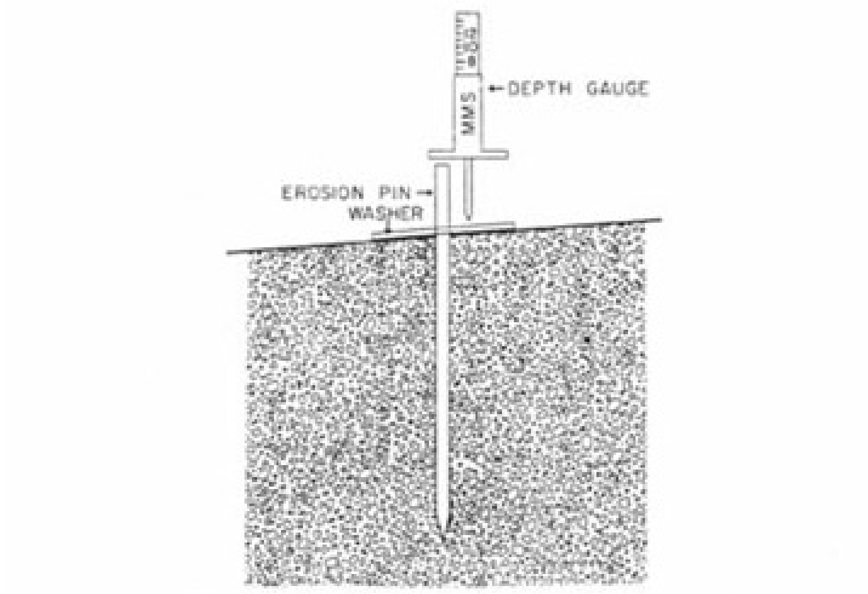

Figure 10. Schematic diagram of an erosion set up (top; from *Field Measurement of Soil Erosion and Runoff,* Food and Agriculture Organization of the United Nations, 1993) and part of actual erosion pin transect (bottom).

pins. Finally, precipitation data collected daily by the Squaw Valley Fire Department was utilized to extrapolate sampling period data and obtain an annual sediment movement rate at each site.

To accomplish this, we assumed that precipitation was the primary agent of sediment movement; thus, total movement at a site is the result of total precipitation occurring during the sampling period. Using this assumption, annual rates of movement were obtained by relating the precipitation that occurred during the sampling period to the average annual expected precipitation (annual average precipitation calculated from the average of annual precipitation values from 1964 to 1993). The equation below illustrates the computation used to derive annual movement rates:

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

where M_A is the annual movement rate (mm/year); M_{SP} is the sampling period movement rate (mm/sampling period); PPT_{SP} is total precipitation for the sampling period (inches); and PPT_A is average annual precipitation (inches).

It is important to note that erosion rates based on the identified assumptions and calculated using the above equation may be lower than actual rates because antecedent conditions; the timing, duration and magnitude of frontal systems moving through the region; or intensity of rain events can have a strong influence on erosion. For example, rain on snow events during the winter and spring can result in large magnitude erosion and runoff that are difficult to factor into time-averaged rates.

Sediment fences. These are simple, low cost measures designed for collecting samples of sediment moving on hillslopes. Sediment fences consist of fine mesh attached to two foot (0.6 m) lengths of five inch (13 cm) diameter posts modeled after instrumentation described by Stott et al. (1986). The fencing was installed below selected areas downslope of roads and in drainage ditches to collect sediment derived from the roads. This information assists in determining volumes of sediment derived from roads. A line was painted at the top of the installed fence to act as the baseline sediment level and serve as a general indicator of sediment movement.

Rill and gully transects. These transects are similar to channel cross sections in construction. Measurements of rill and gully dimensions were used to estimate active erosion. For this study, rills were considered to be about one inch (a few centimeters) wide and deep with width to depth ratios close to 1. Gullies were defined as steep-sided channels having a width or depth greater than 12 inches (0.3 m) and were identified by active headward erosion or associated with watershed disturbances, such as road runoff. Gully transects were established at two sites: a road cutslope and a graded ski slope. This data provided an estimate of the erosion rate on these types of slopes and the rate of development of rills, which have the potential to develop into larger gullies that can be significant producers and conveyors of sediment (Seginer, 1966; Kavvas and Govindaraju, 1992; Brunton and Bryan, 2000).

3.3.4 Other methods used to estimate erosion

In addition to installing instruments to measure sediment movement, sediment mass transport estimates can be made by measuring sediment trapped by a variety of natural and anthropogenic features. The following provide examples of traps that were investigated and used to supplement field measurements and observations:

- Natural sediment traps created by downed trees or other forest debris that blocks transport on hillslopes or through streams provides longer-term rates of sediment production and transport if residence time of the debris is known. In the Squaw Creek watershed, tree fall residence times ranging from one year to upwards of twenty years were observed. Although rates observed through this method are approximate, these observations provide solid evidence to support low rates of sediment transport on forested hillslopes.
- Stream blockage and deposition by small debris flows in many parts of the watershed. These temporary dams commonly result in upstream deposition recorded as small inset terraces. Indirect methods (e.g., debris flow morphology, degree of soil development, vegetation cover) of estimating the time of stream damming provide

supporting evidence of the magnitude of sediment production in the watershed under different land cover and land use.

- Man-made sediment traps (e.g., culverts and temporary sediment detention basins). These traps assist in deriving rates of sedimentation that can be related to hillslope erosion and sediment yield.

3.4 Bedrock sediment sources

Bedrock sources were assessed through a combination of field mapping, aerial photographic mapping and review of existing maps. Analysis of aerial photographs from 1939 (scale 1:24,000), 1987 (scale 1:30,000), and 1997 (scale 1:16,000) and field reconnaissance helped to confirm and update the geologic map first created for the area by Birkeland (1962) and allowed differentiation of natural and anthropogenic disturbances related to bedrock.

Geologic units were differentiated using air photo mapping 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 oldest (1939) and most recent (1997) air photos. Areas that show no apparent change through time 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 designated as natural sediment sources for the watershed. Sediment sources not present in both sets of photos that can be associated with non-natural features, 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. Sites were chosen for data collection this past field season based on the location of these natural and non-natural features in order to assess the relative degree of erosion and potential for sediment input to the fluvial system.

3.5 Geomorphic analyses

The effect of geomorphology on watershed processes cannot be overemphasized. Interrelationships between the geomorphology of a watershed and the geologic framework—

including bedrock, structure, and soil cover—play important roles in the movement of water and sediment. For example, bedrock, geologic structure, and soil cover exert control on surface permeability and resulting runoff characteristics, which in turn exert an influence on the development of drainage networks and the routing of sediment and water through the watershed. Bedrock texture and composition dictate the weathering products and geomorphic processes responsible for mobilization and transport of the sediments produced.

3.5.1 Morphometric analysis

Measurable geomorphic properties, or morphometry, of watersheds are related to surface hydrology and sediment yield (Parker, 1977; Ritter et al., 1995). For example, the physical characteristics of a watershed, such as geology, relief, basin shape, and slope exert control on the routing of runoff and storage of floodwaters on floodplains thereby influencing the shape of the flood hydrograph. Thus, the morphometric properties of watersheds can reveal relationships between watershed hydrology, geology, surficial processes, and the movement of water and sediment within a watershed. Similarly, the analysis of stream networks and derivative products, including drainage density and frequency, provides insight into the behavior of different parts of a watershed and the potential for erosion and production of sediment. For example, the drainage density, which is controlled in part by climate and geology factors, is an area morphometric relationship that provides a measure of the spacing of drainageways in a watershed and is related to sediment yield (Hadley and Schumm, 1961; Parker, 1977; Ritter et al., 1995).

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For this study, morphometric analyses were performed to gain an understanding of the physical nature of the Squaw Creek watershed. These analyses also allowed us to compare the geomorphology of the north and south forks of Squaw Creek, interpret the differences, and infer some of the underlying controls on sediment movement. The majority of drainage basin morphometric analyses were performed on the Squaw Creek DEM with ArcView Spatial Analyst and River Tools software.

Relief and sediment yield: Empirical relationships show that sediment yield tends to be higher in the contributing areas of the low order streams (i.e., first-order stream segments typically found in the steep headwater regions where sediment is transported easily) (Ritter et al., 1995). In contrast, sediment is more likely to be stored in the middle and distal parts of a watershed where floodplains have the space to develop (e.g., Hadley and Schumm, 1961). Stream power—which provides a measure of energy expenditure per unit length of channel and is proportional to the specific weight of water, discharge, and slope (Bull, 1991; Knighton, 1998)—should be lowest in the first order drainages where stream discharge is the least. Therefore, the first order streams are only capable of transporting a limited amount of sediment.

Relief ratio measures the overall steepness of a drainage basin (Ritter et al., 1995) and is calculated by dividing the maximum basin relief by the longest horizontal distance of the basin measured parallel to the major stream. Sediment yield tends to increase with increasing relief ratio (Hadley and Schumm, 1961; Parker, 1977).

Drainage network morphometry: Measurement of drainage network elements (i.e., stream segments and drainage area) provide morphometric relationships between linear and area watershed components that are used to assess surface water hydrology and general movement of sediment (Ritter et al., 1995). Many of these relationships have been derived from the study of network fabric, the systematic geometric arrangement and order of stream branches. Multiple methods of quantifying drainage morphometry typically are performed and results are analyzed together. The following analyses were used to aid in characterizing the Squaw Creek watershed:

- *Drainage density* of a watershed, defined as the total length of streams divided by the drainage area, represents a measure of stream channel per unit area and can be related to the hydrology of a drainage basin. The drainage density can also be used as a general measure of the length of overland flow on hillslopes to channels. Experimental studies have demonstrated that watersheds with higher drainage density intercept more surface flow and generate greater runoff and sediment yield than basins with lower drainage density (Parker, 1977).

- *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). Because first order streams are the principal collectors of rainfall in a watershed, the Shreve method is preferred in studies relating rainfall and runoff because at any point in the drainage the Shreve magnitude represents the number of first order (smallest) stream segments upstream from that point.

Hypsometry: Hypsometry of a watershed relates elevation to area and provides a quantitative measure of the spatial distribution of relief within a watershed. This relationship is typically represented graphically as a cumulative curve of the percent of land mass lying above a given elevation within the drainage (e.g., Strahler, 1952).

4. Results and Discussion

The following section describes the results of the geomorphic analysis, field observations, and measurements of erosion processes as well as sediment contributions of principal sources.

4.1 Geomorphic analysis

A summary of geomorphic analyses for the entire watershed as well as the north and south forks is given in Table 7. As noted previously, the north fork of Squaw Creek is nearly twice as large as the south fork. Overall relief within the north and south forks is similar, although the relief ratio for the south fork is slightly higher than for the north fork indicating that the south fork is slightly steeper. Given the similarity in relief ratios, sediment yields should be approximately equal for the two forks of the Squaw Creek watershed.

There is a notable difference in drainage density and frequency between the north and south forks and between the north and south facing slopes bordering Squaw Meadows. The larger north fork has both greater drainage density and drainage frequency suggesting that it should produce more runoff and transport more sediment than the south fork. As noted in the study by Woyshner and Hecht (1987), however, the south fork generates about twice as much runoff as the north fork and speculated it was related to land use. According to watershed modeling results by McGraw et al. (2001), the south fork produces about 15% of the sediment load of Squaw Creek and the north fork produces about 20%. When adjusted for sediment yield per unit area, the south fork produces nearly twice as much sediment per unit area than the north fork.

Apparent differences between the drainage density and frequency for the north and south facing slopes that border Squaw Meadows are consistent with local climate influences. This is due to the different aspect, vegetation cover, and bare surface area exposed by landslides. The drainage density and frequency for the south fork are most similar to the south facing slopes bordering Squaw Valley meadows, supporting the notion that vegetation cover and the area exposure of bare surfaces are contributing factors.

Measurable differences in the hypsometry of the north and south forks are apparent in the Squaw Creek watershed. A greater percentage of the south fork lies above 7,500 feet (2,300 m), which is likely a factor in the amount of winter snowfall, other precipitation, and runoff behavior from that portion of the watershed. Snow accumulations are also greatest on north-facing slopes.

Table 7. Summary of geomorphic analyses and morphometric relationships for Squaw Creek and the north and south fork subwatersheds[§].

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

Despite the fact that the north fork is nearly twice as large as the south fork, north-facing slopes comprise a greater relative area in the south fork. Therefore, the north-facing aspect of the south fork slopes predisposes them to receiving and maintaining greater amounts of snowfall that produce more runoff during the spring. Because of this characteristic, the steep upper watershed, and lack of stabilizing vegetation, the south fork appears is likely predisposed to higher runoff than the north fork. Runoff in the north fork is attenuated because of the relatively thick forest cover and broad, montane valley in the upper watershed.

Geomorphic characteristics of the watershed strongly suggest that the natural responses of the north and south forks should be slightly different. How much different cannot be determined because of the extreme level of disturbance in the south fork. The south fork is very sensitive to disturbance, although parts of the north fork underlain by Tertiary andesitic breccias are also very sensitive. The greater runoff from the south fork has implications for sediment transport in the upper watershed and erosion of stream banks in the lower watershed.

4.2 Surficial processes

4.2.1 Mass wasting

Sediment sources associated with mass wasting in the Squaw Creek watershed typically enter streams at a slow rate through sheet wash or creep processes. Where streams are separated from hillslopes by a valley floor, most hillslope sediment remains in storage despite the relatively constant movement of sediment. Landslides and debris flows are capable of rapidly delivering large amounts of sediment directly to streams, but most areas prone to mass wasting are stored on hillslopes or at the base of slopes and remain separated from stream channels by the valley floor. Roads, as discussed later, are capable of producing and delivering large amounts of sediment directly to streams.

Large-scale mass wasting is most apparent on the south facing exposure. Slide masses primarily involve glacial deposits associated with the lateral moraine on the north side of the valley. Some of these are historic landslides that formed on older, prehistoric slide masses.

Small-scale mass wasting is observed on road cuts. These small failures typically are on the order of a few inches thick but may be as much as 30 to 50 feet (9 to 15 m) wide and up to 200 feet (60 m) long. The larger road cut slopes may represent as much as 5,000 ft^3 (140 m^3) of material introduced into drainage ditches or directly onto roads, whereas most represent a few tens of meters of material. Small slope failures are especially prevalent where surface water and shallow throughflow drain onto the head of the road cuts. Creep and dry sliding are a mechanism for sediment transport during years of decreased precipitation. Most of the sediment transported by mass wasting processes accumulates on the slope, at the toe of slopes, and in roadside ditches.

Given the average sediment bulk density of 1.5 g/cm^3, a single large road cut represents approximately 230 tons of sediment. Depending on the location of the road cut relative to stream channels, ditch configuration, and detention structures, as much as 100% of the material derived from road cuts could enter streams.

Man-made examples of mass wasting are related to road building and side casting of rock debris related to ski lift construction. These activities are capable of quickly producing significant deposits of loose material that mantles hillslopes and is slowly transported down slope. For example, the blasting and side casting of debris at Funitel towers 4 and 6 produced many thousands of cubic feet of debris that was cast down the side of the mountain. A direct consequence of these types of activities is alteration of the surface hydrologic characteristics of the hillslope.

Other forms of mass wasting (e.g., rock falls and rock slides) typically do not transfer large volumes of sediment directly to streams. Most settings characteristic of rock falls are in the upper parts of the watershed where stream discharge is small and there is limited available stream power to move large particles associated with rock falls. The deposits created by rock falls, rock slides, and side casting, however, provide conditions favorable to entrapment and storage of fine-grained sediment on the hillslopes.

Rills and Gullies – Gullying and rilling are prominent on ski runs and roads. Compaction, slope, and vegetation cover influence the generation of overland flow necessary to initiate rills. Few rills and gullies are observed on undisturbed slopes that have forest and associated duff layer (e.g., pine needles, leaves) or shrub cover. This is especially true for undisturbed slopes formed on permeable surficial mantles derived from weathered granite outcrops. Gullies observed in natural environments typically are connected to large areas of bare rock or soil caused by slope failures (e.g., on the slopes east of the Resort at Squaw Creek). Although uniformity and general erosional resistance of substrate conditions is uncertain for engineered ski slopes, compaction of the soil and lack of vegetation lead to concentration of flows and generation of shear stresses capable of initiating rill and gully erosion.

Field observations indicate that once a rill is initiated, the potential for rapid gully formation and erosion is great. For example, we estimated that large gullies developed during the intense rains in January of 1997 yielded in excess of 15,000 ft^3 (>500 m^3), or about 800 tons of sediment. Longer-term rates are more difficult to assess because of the tendency of landowners to grade and fill gullies. On roads the rills are observed both on the roadbed and also on the outboard shoulders, fill slopes, and cut slopes. In the two seasons of field observations, rills were observed to form on roads; however, rills are removed during road maintenance. Based on direct observation, rill measurements, and conservative calculations we estimate that rills only half an inch deep and wide (10 x 10 mm) spaced approximately every foot (300 mm), that form on roads during a single precipitation event of less than an inch (25 mm) are capable of producing on the order of 300 tons of sediment from the 34.2 miles (55.1 km) of dirt roads in the watershed.

During field reconnaissance, evidence of overland flow on roads and sediment mobilization in the form of rill formation and plumes of sediment in drainage ditches was most notable in the south fork of Squaw Creek. Because of the impervious nature of roads and engineered fill on ski runs, a relatively small amount of precipitation is required to initiate rill formation. For example, rills formed on many of the roads in the south fork following a single precipitation event in late September 2001 (0.56 inches; 14 mm). Although frequent road grading limits the establishment of rill transects to estimate rates of erosion during the season, observed rill development on roads and graded ski runs between grading demonstrates increased surface runoff and erosion on disturbed surfaces. Visual estimates of the amount of sediment trapped by culverts indicates that, even in extremely dry years, roads generate many tons of sediment directly to upper tributaries of Squaw Creek.

4.2.2 Hillslope erosion rates

Data collected from erosion pin transects and sediment fences indicate that all areas of the watershed are actively eroding but at differing rates. Rates differ depending on land use and geology (Fig. 11). Measurable erosion or deposition occurred at all erosion pin transect sites, despite the short duration of monitoring and little to no precipitation, as well as measurements following precipitation events. The data collected from the monitoring sites were used to calculate erosion rates on different land use types and geologic conditions (Table 8).

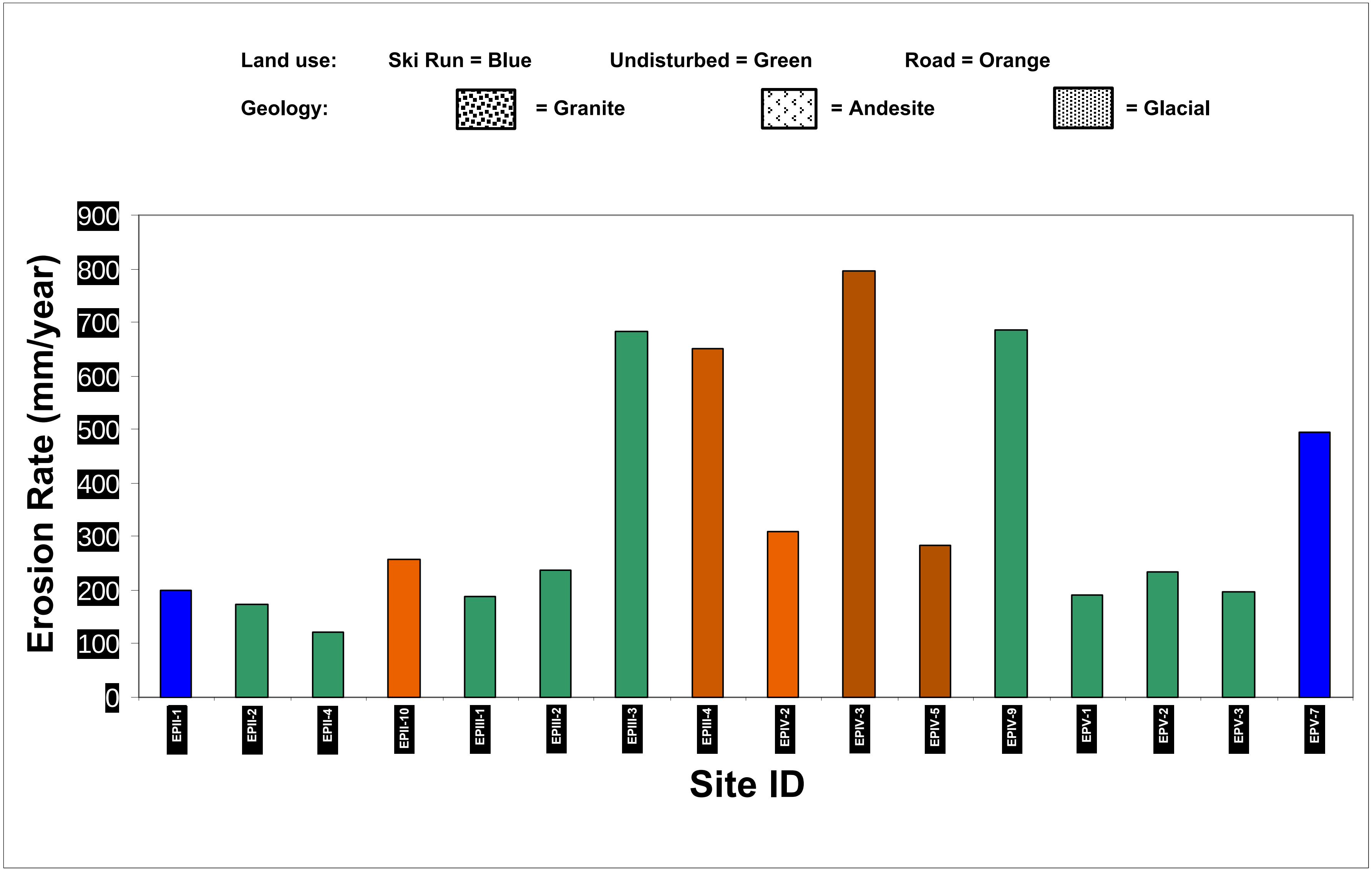

Figure 11. Graph showing estimated annual hillslope erosion rates according to land use and geology. See Figure 7 and Table 8 for location and description of measurement sites.

Table 8. Location and description of data measurement sites and associated erosion rates. (see Figure 7 for map locations)

Erosion Pin Site ID	Sector Location	Slope	Aspect	Vegetation	Bedrock or Surficial Geology	Description	Associated Land Use*	Sediment Movement Rate (mm/yr)
EPII-1	II	22°	N	Yarrow	Glacial	On ski slope behind golf course	Ski slope (d)	199
EPII-2	II	35°	N	Red fir Forest	Glacial	Above road cut	Mixed conifer (u)	173
EPII-4	II	25°	N	Red fir, white fir, pinemat manzanita, sugar pine, whitethorn	Andesitic	Under red fir forest canopy near top of ridge	Mixed conifer (u)	122
EPII-10	II	32°	N	Bare slope, red fir, white fir, pinemat manzanita, sugar pine, whitethorn below site	Andesitic	To the west of the top of Red Dog chair, downslope of road	Road (d)	258
EPIII-1	III	27°	S	Jeffery pine, White fir, manzanita, whitethorn, creeping snowberry, mtn mohagany, mule's ear	Glacial	Forest canopy upslope from subdivision	Mixed conifer (u)	187
EPIII-2	III	20°	S	Manzanita, whitethorn, bitterbrush, mtn mahogany, currant, mule's ear	Glacial	Above subdivision under shrub canopy	Chapparal (u)	238
EPIII-3	III	25°	S	Mule's ear, bitterbrush	Andesite bedrock and loose weathered andesite float	Above water tower just above west edge of subdivision	Chapparal (u)	238
EPIII-4	III	26°slope 30°cutbank	N	Some mule's ear on hillslope portion	Glacial	Squaw Vallley Road cutslope at bottom of subdivision	Road (d)	382

Table 8 continued

Erosion Pin Site ID	Sector Location	Slope	Aspect	Vegetation	Bedrock or Surficial Geology	Description	Associated Land Use*	Sediment Movement Rate (mm/yr)
EPIV-2	IV	38°	N		Andesitic	Cut slope below vegetated ski	Road (d)	651
EPIV-3	IV	17°	E	Sparse grass, immature shrub	Granitic	Ski slope	Ski slope (d)	795
EPIV-5	IV	33°;18° on graded	E		Granitic	Near road, old excavation site	Road (d)	285
EPIV-9	IV	36°	E	Bare	Andesitic	Below Squaw Peak	Bare rock (u)	685
EPV-1	V	25°	S	Bare	Granitic (gruss)	Near Squaw Creek	Bare rock (u)	190
EPV-2	V	27°	S	Bare	Granitic (gruss)	Near Squaw Creek	Bare rock (u)	233
EPV-3	V	34°	W	Sparse	Andesitic talus, sandy soils, outcrops of andesite	Steep slope	Bare rock (u)	195
EPV-7	V	32	N	Sparse	Andesite	Ski run between Silverado and Solitude chairlifts.	Ski slope (d)	494

* Land use: (d) disturbed; (u) undisturbed

Exposed rock slopes: Comparison of erosion rates obtained for undisturbed bare rock and soil monitoring sites indicate that the bare rock sites are moderate to very high producers of sediment, with the exception of bare granite in areas such as the north fork which exhibits few signs of active, measurable erosion. Erosion rates for bare andesite slopes indicate that those slopes erode more quickly than granite in the watershed.

Undisturbed – mixed conifer: The lowest erosion rates generally are associated with forested areas. These lower rates most likely reflect the presence of overstory canopy cover as well as litter and duff covering the soil, which have the effect of retarding rain drop impact, increasing infiltration, and limiting rill initiation. Unforested areas (e.g., chaparral, bare rock, soil) exhibit higher erosion rates, which are affected by the impacts of land use.

Erosion associated with graded ski runs: Erosion measurements from graded ski runs exhibit variability in erosion rates but generally are moderate to high sediment producers. Despite the brief measurement period, field observations support the high erosion rates on the graded or disturbed portions of ski runs.

The site measured to have the highest erosion rate [795 mm yr^{-1}] at 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 located upslope of a principal dirt road. In addition to having high rates of erosion and deposition, it was one of the few sites having well-developed rills. The calculated erosion rate and presence of rills on this relatively gently sloping site indicate that roads are capable of exerting a significant impact on the rate of sediment movement in the watershed.

Another graded ski run had an erosion rate of [199 mm yr^{-1}] (EPII-1), similar to values estimated for natural bedrock and bare soil sources. This value may be partly because (compaction retards soil movement during short duration, low intensity precipitation events). More intense or prolonged storms may be necessary to initiate rilling and gullying, however, as evidenced by the severe gullying east of the site. Additionally, compacted soils have lower infiltration capacities. Although the ski run itself may not erode during low intensity storms, increased runoff caused by the compacted conditions has an effect on the hydrograph and results in impacts further downslope and downstream.

Undisturbed slopes having chaparral cover: In general, undisturbed chaparral environments might be expected to have low rates of soil movement. One of the chaparral sites located adjacent to a mixed conifer forest transect, however, exhibited moderate levels of sediment movement despite the presence of mature shrubs and grasses. The reason for this apparent anomaly is not certain although it may be related to canopy cover, lack of vegetation litter at the surface, rain drop impact, and microclimate. For example, Morgan et al. (1986) reported that for canopy covers of less than 50%, the rates of soil detachment were equal to those obtained for bare soil and that most of the detachment occurred during the onset of precipitation events. In light of Morgan et al. (1986), the relatively sparse canopy afforded by the chaparral assemblage (generally open branches and small leaves) and the minimal litter and duff layers associated with the chaparral environments may tend to promote moderate rates of soil movement. This has implications for the sensitivity of different environments to disturbance. The noticeably high rate of erosion at one chaparral site [682 mm yr^{-1}]; site EPIII-3) is less a function of vegetative cover than site location. The site is situated in a natural gully at the contact between andesite bedrock and glacial deposits, two geologic units that are associated with potentially high erosion rates. The microclimate of the site (edge of the incised drainage on a drier, southern aspect hillslope) contributes to the elevated erosion rates.

Particle size analysis: The particle sizes of sediment available for transport from the hillslopes and stream channel were analyzed (Table 9; 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 sediment being transported on hillslopes. Particle size analysis showed that, in general, sediment available for transport was larger than (2 mm) (delineation between sand and gravel).

Table 9. Summary of particle size analysis of hillslope and stream sediment.

			Sand Fractions					Silt Fractions		Summary		
Sample	**Location**	**Gravel % wt**	**2.0-1.0 mm % wt.**	**1.0-0.5 mm % wt.**	**0.5-0.25 mm % wt.**	**0.2-0.125 mm % wt.**	**0.125-0.0625 mm % wt.**	**Fine Silt % wt.**	**Co Silt % wt.**	**Total Sand % wt.**	**Total Silt % wt.**	**Clay % wt.**
Bar sample 1	1	46.4	30.4	42.4	21.1	2.1	0.5	1.2	-0.1	96.6	0.6	2.8
Bar sample 2	1	67.3	30.4	26.4	30.4	5.8	1.4	2.1	0.8	94.5	3.0	2.6
1997 Slide Channel	2	65.2	20.6	23.1	22.5	10.0	4.7	6.0	5.1	80.9	11.1	8.0
EP-II-2	3	27.9	14.8	14.7	12.5	9.3	6.8	13.9	14.2	58.3	28.1	13.6
EP-II-2	3	55.7	13.0	14.7	12.5	9.3	8.0	13.8	14.3	57.7	28.0	14.2
EP-II-4	3	32.9	10.8	12.4	12.7	11.3	9.0	16.8	14.4	56.3	31.2	12.5
EP-III-1	3	52.7	15.1	16.9	13.8	9.7	7.8	10.2	11.7	63.7	21.9	14.4
EP-III-3	3	62.0	19.2	16.9	13.5	9.9	6.7	10.5	10.1	66.4	20.6	13.0
EP-V-1	3	52.7	28.3	20.1	14.4	9.8	6.6	6.0	6.6	79.3	12.6	8.1
EP-V-3	3	69.4	30.7	19.2	12.3	8.2	5.5	8.4	8.1	76.0	16.5	7.5

Notes: Location: 1 – Squaw Creek channel in meadows reach; 2 – landslide behind subdivision on north side of Squaw meadows; 3 – see Table 8 and Figure 9 for locations and descriptions of these erosion pin sites

At most sites in the Squaw Creek watershed, approximately 50 to 70% of the sediment available for transport is coarser than (2 mm). Of the remaining 30 to 50% of sediment, typically 75 to 80% is sand and only about 20% is silt and clay. In natural and artificial sediment traps and on certain types of hillslopes, however, there was less than 50% gravel and between 30 and 45% silt and clay, indicating that primarily fine sediment is transported.

Channel bar samples in Squaw Creek are dominantly sand and gravel with very small percentages of silt and clay, indicating that most silt and clay likely is transported through the system as suspended and wash load. Woyshner and Hecht (1987) also documented that suspended sediment discharge for Squaw Creek is dominated by silts, clays, and fine sand.

Relative erosion susceptibility of rock types: Physical and chemical weathering processes break down bedrock which eventually becomes sediment particles available for transport; thus, consideration of the relative erosion potential characteristics of rock types present in Squaw Valley provides a means by which to evaluate areas of potentially high erosion hazard.

Examination of the rock mineralogy provides a further means by which to evaluate erosion susceptibility. The 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 Valley basin and identified as being either bleached 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 (containing dark, ferromagnesian minerals) whereas the granite is compositionally more felsic (containing 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 (e.g., andesite) than felsic igneous rocks (e.g., granite) (Boggs, 1995; Hibbard, 1995). These relationships are reflected in the Goldich ease of weathering series (Allen, 1997).

Bedrock sources of sediment of greatest concern in this study are those prone to producing finer-grained sediment. Fine-grained particles derived through weathering processes (physical and chemical) are readily available for transport through hillslope erosional processes (e.g., seasonal soil creep, continuous creep, heave produced by swelling or freeze-thaw, and dry ravel) active in the Squaw Valley watershed (Ritter et al., 1995). In this watershed, rock units consisting of weathered andesite (which weather to silts and clays) and glacial deposits (generally heterogeneous mixes of coarse debris and fine silt) are the primary sources for fine sediment. Areas of granitic bedrock typically produce coarser material including gruss, talus, sands, gravels, and cobbles when weathered (Woyshner and Hecht, 1987; Boggs, 1995). Soil creep occurs primarily through the expansion and contraction of the soil caused by heating and cooling, wetting and drying, and freezing and thawing. This last mechanism is important in Squaw Valley since freezing and thawing processes dominate soil creep in mountains (Boggs, 1995; Ritter et al., 1995; Allen, 1997).

Relative rates of sediment production: Table 10 shows the distribution of major rock types within the watershed and their associated hillslope erosion rates derived from erosion pin data. Andesitic rock types tended to have higher erosion rates than granitic rocks. This is in part because the mineralogy of andesite weathers easily to produce finer, more readily transportable sediment than the mineralogy of granite. Thus, soils derived from weathered volcanic rock types and glacial deposits in the Squaw Creek watershed are more susceptible to erosion than soils formed from granitic types under little to no vegetative cover.

4.3 In-stream sediment sources

In stream processes include the erosion of bedrock channels, scouring of alluvial channels, bank erosion on outside bends of meanders, erosion of in-stream gravel bars, and deposition.

4.3.1 Bedrock channels

Both the north and south forks of the stream within the Squaw Creek watershed contain considerable portions of bedrock streams (Fig. 12). For this study, bedrock channels are defined as sections of stream consisting of at least 50% exposed bedrock within the channel

Table 10. Relative percentages of geologic units in (a) Squaw Creek watershed, (b) north fork of Squaw Creek, and (c) south fork of Squaw Creek and associated erosion rates.

	(a) Squaw Creek [A = 21.1 km ^{2}]				**(b) North Fork** [A = 9.3 km ^{2}]			**(c) South Fork** [A = 4.7 km ^{2}]		
Geology	**Area mi^2 (km^2)**	**Area (%)**	**Erosion Rate- (mm yr^{-1})**	**Part. Size d_{60}) mm**	**Area mi^2 (km^2)**	**Area (%)**	**Erosion Rate (mm yr^{-1})**	**Area mi^2 (km^2)**	**Area (%)**	**Erosion Rate- (mm yr^{-1})**
Granite (Kg)	3.0 (7.8)	37	190 - 233	0.7	2.3 (5.9)	63	190 – 233	0.7 (1.9)	40	--
Andesite (Ta)	2.8 (7.2)	34	122 - 685	0.2-0.7*	1.2 (3.1)	33	195	0.7 (1.9)	40	685
Metamorphic Rocks (Tr-Jm)	0.1 (0.3)	1	--	--	0.1 (0.3)	3	--	--	--	--
Glacial Deposits	1.6 (4.2)	20	173-238	0.2-0.3	--	< 1	--	0.3 (0.8)	17	173-238
Valley Fill Alluvium (Qal)	0.4 (1.1)	5	--	--	--	< 1	--	--	< 1	--
Alluvial Fans (Qf)	0.1 (0.2)	1	--			--	--	--	--	--

Notes:
*Sample from EPV-3, which is located near watershed divide at high elevation and little soil development
-- erosion rates not measured for these units

Figure 12. Bedrock channel in the north fork of Squaw Creek showing jointing and erosion.

Sediment produced by the erosion of bedrock channels is relatively low in the Squaw Creek watershed because of the resistance of the material. Exceptions are where intense fracturing, faulting, and hydrothermal alteration of the original rock make it more susceptible to weathering and erosion. Primary processes of erosion in stream channels are (1) corrosion or chemical weathering and solution, (2) corrasion or abrasion by sediment in transport along the channel, and (3) cavitation associated with turbulent flow (Wohl, 1998). Abrasion is probably the dominant bedrock channel erosion process in Squaw Creek, although cavitation is likely to contribute a minor amount to overall bedrock erosion. It is difficult to differentiate pure cavitation effects from cavitation and abrasion; therefore, sediment derived from both processes is not distinguished.

Abrasion is facilitated by impacts from entrained bedload and suspended sediment. Most bedrock channels in the upper Squaw Creek watershed transport sediment. The sediment in bedrock channels moderates the degree of incision. Insufficient sediment supply results in low incision rates because there is little abrasive material; an overabundance of sediment insulates the channel bedrock from abrasive forces and decreases the amount of erosion. Therefore, a sufficient supply of sediment must be present for abrasion to take place but not in quantities that 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 be at work in the north fork and portions of the south fork. The long-term erosion rate for streams flowing on granite, schist, and gneiss is in the range of 0.15 inches (3.9 mm) per year (Wohl, 1998), a reasonable value for bedrock channels in Squaw Creek. Assuming an average channel stream width of about 6.5 feet (2 m), total stream lengths of about 35 miles (56 km), and a standard rock density (2.65 g/cm^3), the yield for the north and south forks of Squaw Creek is about 120 tons per year. A concrete arch dam (approximately 20 feet [6 m] high) on the south fork, however, traps up to about 30 tons and restricts the transport of coarse sediment to the downstream reach (identified as a bedrock channel). Thus, the net load from bedrock channel erosion may be as much as 30 tons per year less. Because of less bedload immediately downstream of the dam, there is reduced bedrock channel erosion but there is a tendency for streams to erode alluvial channels downstream of dams.

4.3.2 Alluvial channels

In Squaw Creek, a significant amount of sediment appears to be derived from the accelerated erosion of the stream banks, which occurs principally in the meadow section (Fig. 13), but also is observed near the confluence of the north and south forks. Evidence of bank erosion is from field observation and analysis of sequential aerial photographs from 1939 to 2001. Although stream bank erosion was measured to be very minor during this study, measurements of stream cross sections in 2001 document the undercut nature of the meadow reach of Squaw Creek and indicate the potential significance involving streambank erosion for introducing sediment directly to the fluvial system.

Figure 13. Examples of stream bank failure along Squaw Creek in Squaw Meadows. Stratigraphy exposed in alluvial stream bank shows fine-grained fluvial and lacustrine sediments overlying less resistant sand and gravel layers.

Significant amounts of sediment storage were not observed in the tributary stream valleys of the upper watershed. This suggests that sediment accumulated in the upper watersheds is either transported to lower parts of the watershed during the year or is flushed out of the upper tributaries with the peak snowmelt. A bioassessment study in Squaw Creek watershed (Herbst, 2002) showed relatively low imbeddedness for cobbles in the channel (measure of how much of a clast is buried) and a healthy macroinvertebrate population that supports the relatively low accumulation of sediment in the streams of the upper watershed. Channel storage in the meadow reach, which we calculated to be approximately 20,000 tons (18,140 metric tons), attests to the large amount of bedload transported by Squaw Creek. The high bedload tends to distribute gravel and reshape the channel bottom such that spatial distribution of low flow pools and riffles changes significantly from year to year. The result is that the gravel load disrupts benthic habitat, discharge through the channel is decreased, and fine-grained sediments accumulate in pools and riffles. This also was documented by the Herbst (2002) study that showed greater cobble imbeddedness and an increase in macroinvertebrate species indicative of degraded water quality.

Slumping of stream banks: Slumping of stream bank material is apparent throughout the meadow portion of the watershed and is a significant supply of sediment to Squaw Creek. Slumping occurs through at least two mechanisms. In dry seasons, accelerated rates of stream bank erosion result from formation of tension cracks in the valley fill sediments as drying occurs and failures initiate along the fracture plane. In addition, undercutting of the valley fill sediments can result in slab failure of undercut banks due to loss of vertical support. During the dry season, the problem may not be as apparent because of low flow conditions. During spring months, however, 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 stream flows are capable of easily eroding and undercutting the weakened bank sediments resulting in bank failures. The frequency of slumping is high based on evidence that includes the freshness of slump features, erosional modification, position relative to the active channel, and vegetation condition (dead, dying, or different composition).

Stream bank erosion: Stream bank erosion is a natural process of most low-gradient, meandering alluvial streams. The meandering observed in Squaw Meadows is in large part controlled by bed and bank materials, which provide some channel stability, but also by the local base level influences that restrict the stream gradient. The late Pleistocene terminal moraine at the east end of the meadows is the local base level for Squaw Creek. This means that Squaw Creek likely will not increase the depth of incision in the meadows unless deep incision occurs through the moraine. Analysis of aerial photographs shows that Squaw Creek has been a meandering stream since at least 1939. Significant changes in the pattern of the meadows reach have occurred, however, since the onset of development of the ski resort at Squaw Valley. Overall sinuosity has steadily decreased since 1939, meaning that overall the channel has straightened (Table 11). From analysis of the aerial photographs, it is clear that the locations of straight and tightly meandering reaches have migrated through time (Fig. 14). The average meander migration from 1939 to 2001 is 40 feet (12 m), and the average annual migration is 0.65 feet (0.2 m) (ranges from 0.95 to 2.3 feet [0.3 to 0.7 m]).

Table 11. Change in sinuosity of Squaw Creek in the meadows reach since 1939

Year	**Sinuosity**
1939	1.57
1987	1.44
1997	1.43
2001	1.41

The character of the channel has changed below the confluence of the north and south forks. From 1939 to 1955, the channel in the upper part of the meadows (west end) below the confluence of the north and south forks to at least downstream of the large customer parking lot for the Squaw Valley Ski Corporation was wide, shallow, and transported a coarse load. Between the parking lot and the terminal moraine, there was more than one channel of Squaw Creek in 1939 (now abandoned). The major change in channel character coincides with the

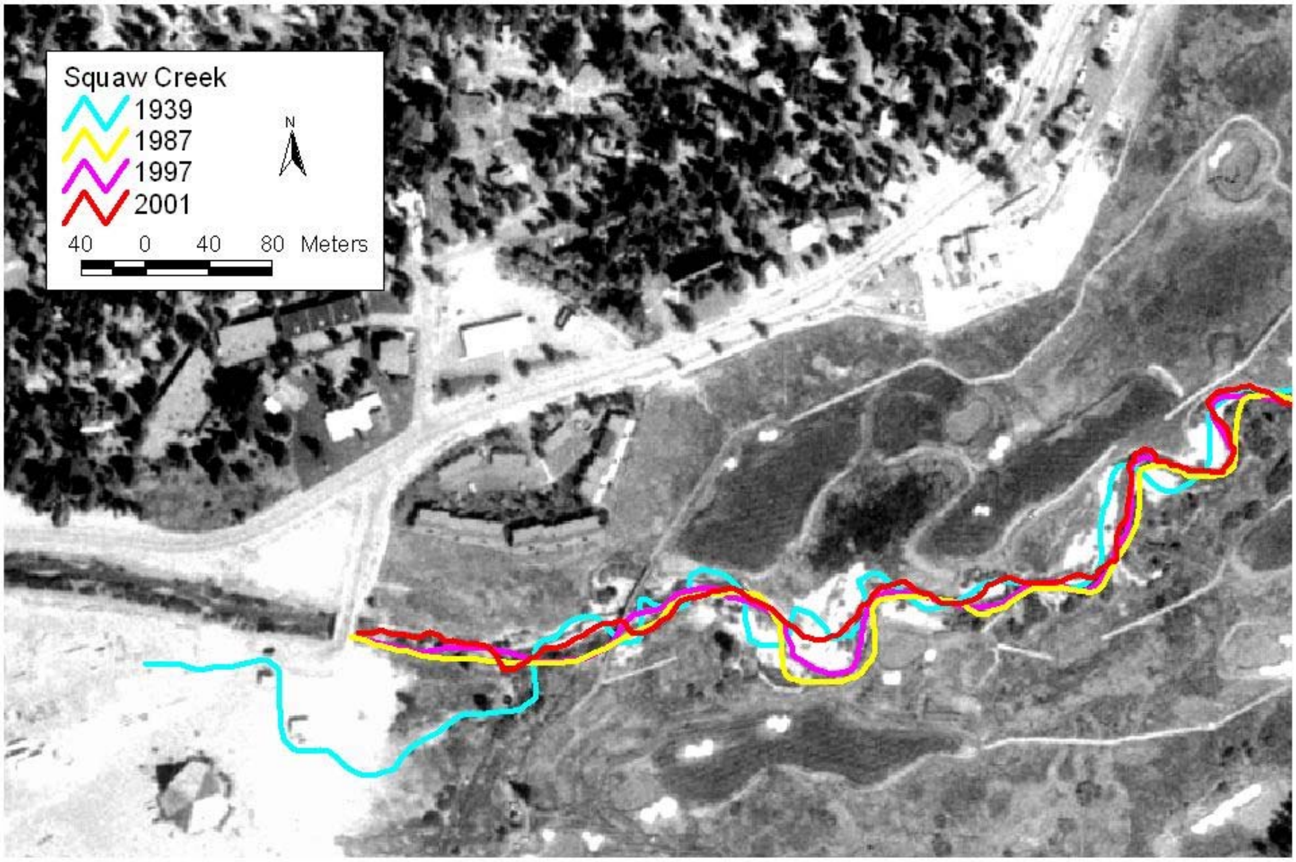

Figure 14a. Changes in stream channel migration in the meadows reach of Squaw Valley. This image comprises the western third of the meadows reach and shows the location of the stream thalweg (deepest part of the stream channel) for years 1939, 1987, 1997, 2001). A portion of the lower end of the main ski area parking lot is shown in the lower left. Note the engineered channel upstream (left) and downstream of the bridge leaving from the parking lot to Squaw Valley Road. The straightened reach extends downstream of the foot bridge used by golfers. Most meander bends between the golf course fairways have been protected with boulder rip rap. Figure 14b begins at the right edge of Figure 14a. Overlap of the images is intended to help visually match the photos.

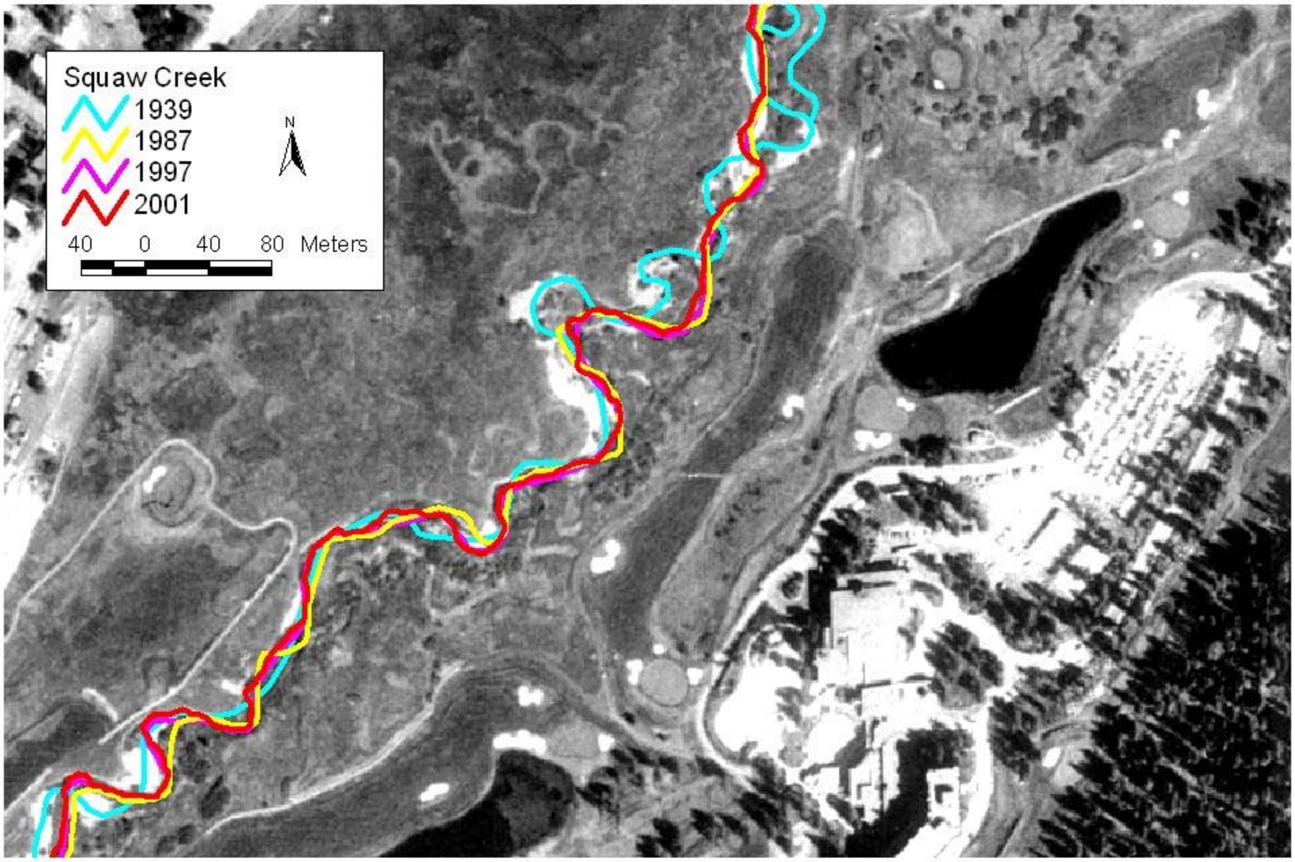

Figure 14b. Continuation of Figure 14a showing the middle third of the meadows reach of Squaw Creek. Stream flow is from bottom to top of the image. Prominent buildings and parking lot in lower right corner (high reflectivity) are the Resort at Squaw Creek. Many of the meander bends, particularly near the golf course fairways have been protected with boulder rip rap. Note the bifurcation of the 1939 channel. Figure 14c joins with the upper part of the image.

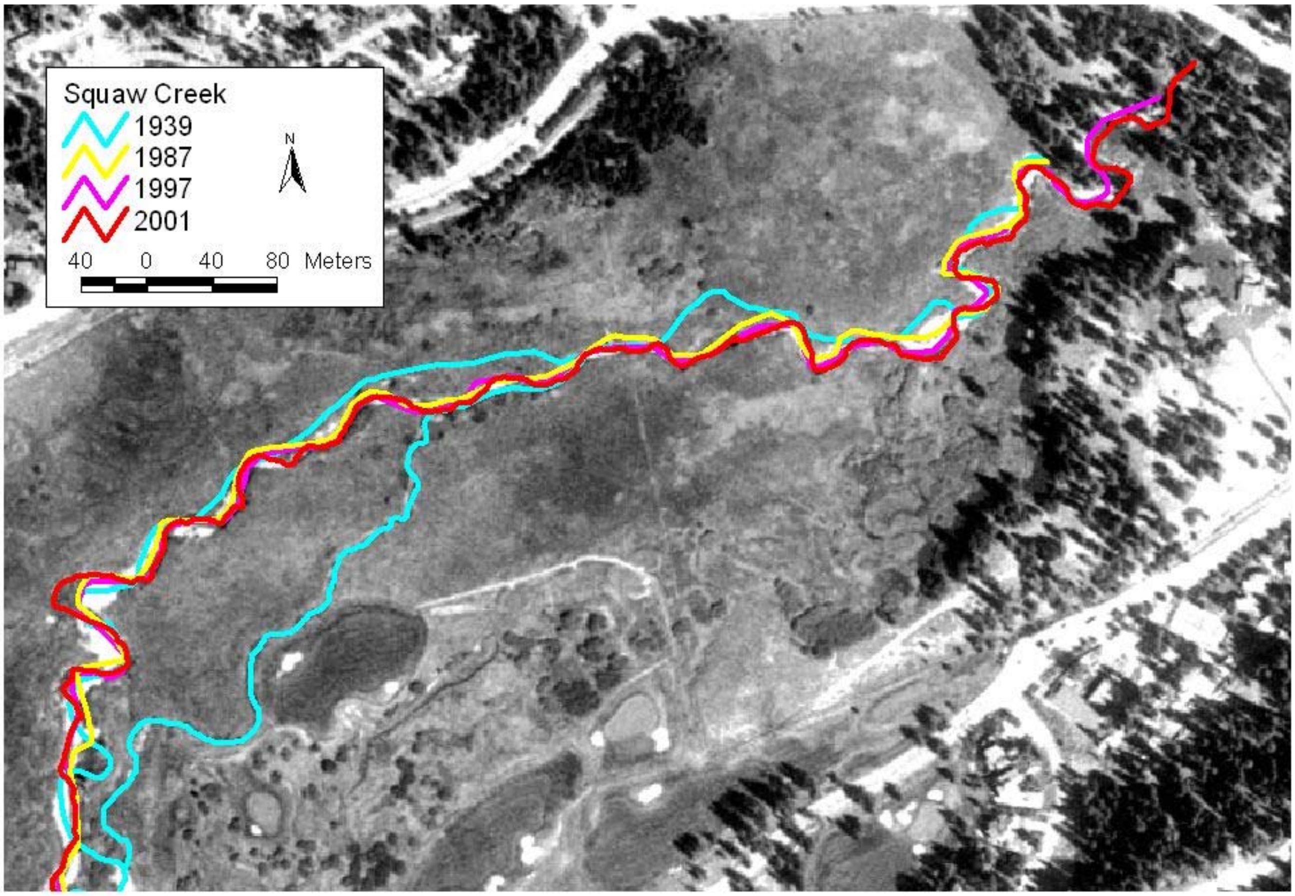

Figure 14c. Eastern third of the meadows reach of Squaw Creek. Stream flow is from lower left to upper right. The end of the colored thalweg locations of Squaw Creek is at the terminal moraine just upstream of the highway bridge. Figure 14b joins this figure in the lower left corner. Note the bifurcation of the 1939 channel at the lower left of the image.

increase in ski area development. Development of the base region of the ski area resulted in channelized reaches of the south fork above the confluence with the north fork and from the confluence to about 200 yards (180 m) downstream from the bridge at the lower end of the parking lot to below the golf course footbridge. In these reaches, a trapezoidal-shape channel was constructed and reinforced with rip rap in several places. Bridge abutments effectively lock the channel in position. The effect of the engineered channel is to transport large volumes of water at high velocity through those reaches and into the meadows reach. The channel was further modified by the addition of boulder rip rap protection on many of the stream meander bends where the channel is close to the Resort at Squaw Creek golf course. The combined effect of the channelized reaches and rip rap protection is to accelerate stream flow through the reaches. The result is that high velocity flows begin to erode the unprotected downstream bends.

Sediment mass associated with bank erosion: The mass of sediment eroded from stream banks and bars was calculated by measuring the area of channel removed during stream migration and multiplying by the average thickness of the deposits determined from field measurements. An average bulk density of (1.5 g cm^{-3}) for sediments was used to calculate the mass per unit area, which was then multiplied by the volume to arrive at total mass. The total mass was divided by the 62-year interval to provide an average mass per year. The total volume removed during the 62 years is estimated to be 500,000 $feet^3$ (142,000 m^3). This represents a total mass of about 235,000 tons (213,145 metric tons) during 62 years, a long-term average of about 3,800 tons (3,447 metric tons) yr^{-1}.

These long-term bank erosion rates and load calculations are within the same order of magnitude as the 1986 annual bedload of 2,200 tons (1995 metric tons) reported by Woyshner and Hecht (1987). Woyshner and Hecht (1987) reported that bedload sediment (primarily coarse sand) constituted 80% of the total sediment discharge for Squaw Creek, an exceptionally high fraction. Transport of coarse sediment also was found to be much greater for Squaw Creek than other similar streams in the region, such as Sagehen Creek. The elevated loads are attributed primarily to disturbances in the streambed and bank failures (Woyshner and Hecht, 1987). Our calculated long-term rate estimates are consistent with

Woyshner and Hecht's measurements and analysis of repeat photography and field observations confirm that the stream banks are one of the major sources of sediment.

4.4 Roads as sediment sources

4.4.1 Background

Dirt roads are noted in the literature to represent a primary mechanism for significant increases in sediment delivery to streams (Grace et al., 1996; Sun and McNulty, 1997) and are considered to be more important than such factors as deforestation (Swanson and Dryness, 1975). Roads and their associated attributes in the road corridor (e.g., 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 (Forman and Alexander, 1998).

Roads and road corridors function both as sediment sources and delivery mechanisms for runoff and sediment by concentrating flows and increasing overall watershed drainage density. This leads 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 engineered structures (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 Dryness, 1975; Forman and Alexander 1998; Jones et al., 2000).

Brown (1994) notes that the extent and degree of impact from roads are related to vegetation and cover, soil types, topography, and the level and type of use associated with road corridors. 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; Forman and Alexander, 1998; Jones et al., 2000).

4.4.2 Roads in the Squaw Creek watershed

Roads are a visible presence in the Squaw Creek watershed. At least 57.4 miles (92.4 km) of roads were mapped and measured in the watershed using the GIS database. These roads consist of primary and secondary paved roads as well as single and double track dirt roads. All play important roles in the movement of water and sediment. A GIS data layer was constructed of the road types to help assess relationships between roads, geology, streams, and land use (Table 12; Figs. 15, 16).

Paved roads: The 13.2 miles (21.2 km) of paved roads comprise about 28% of the roads in the Squaw Creek watershed and almost 1% of the total surface area of the watershed. Paved roads were classified as either primary (e.g., Squaw Valley Road) and secondary (e.g., the paved roads in the subdivisions on either side of Squaw Valley). Road widths were determined from DOQ measurements. Primary paved roads were 30 feet (9.1 m) wide, and secondary paved roads had an average width of 26 feet (7.9 m).

Table 12. Total road length and road surface area in the Squaw Creek watershed by road type.

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

Paved roads generally produce little sediment from erosion of the road surface itself, but the impervious cover formed by the roads contributes to excessive direct runoff, transport of any sediment on the road surface, and the erosion of ditches and adjacent land surface. Most places in the watershed do not have curbs or gutters next to the paved roads, thus making the dirt shoulders vulnerable to erosion. Along the primary paved road, the shoulder is several

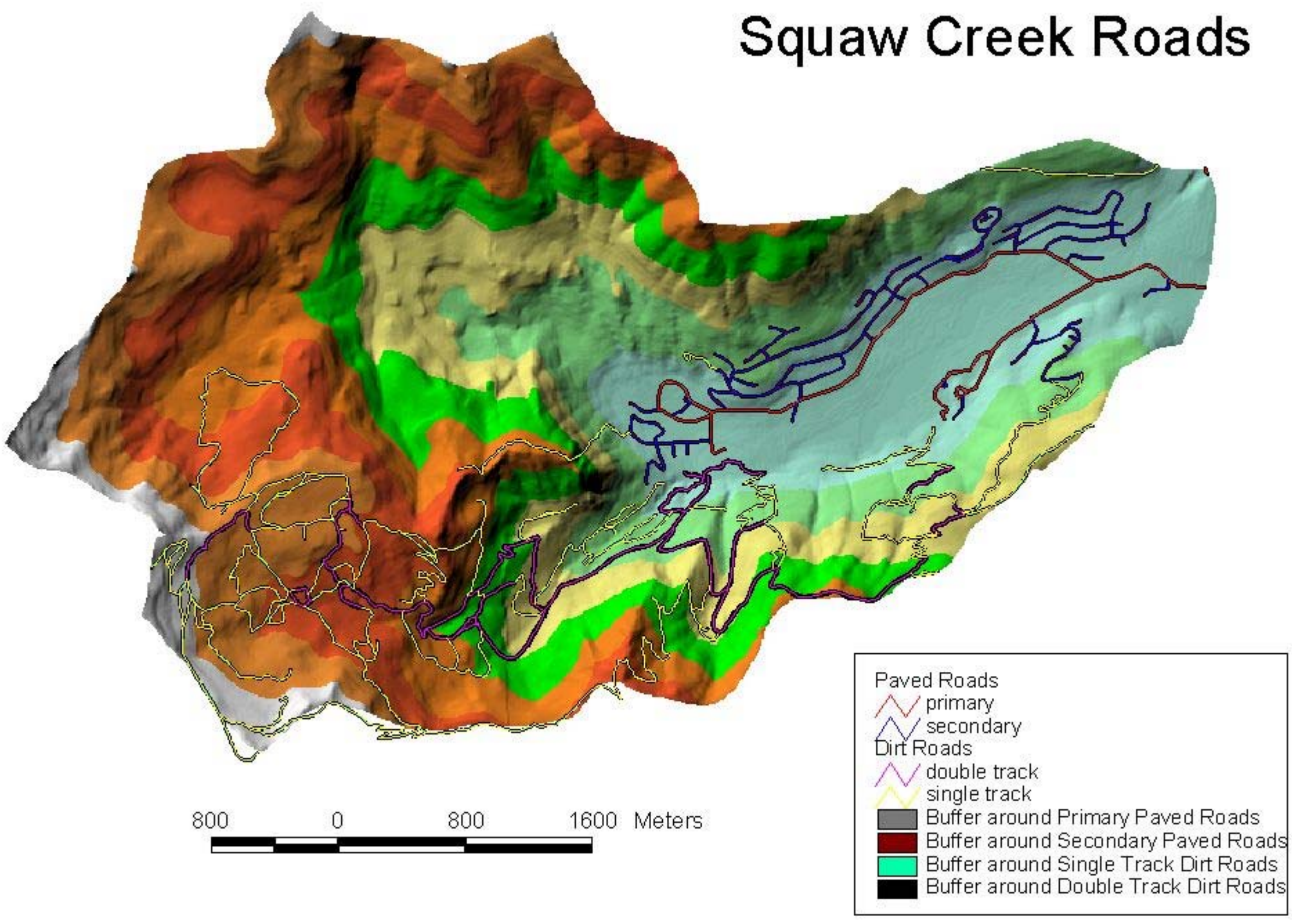

Figure 15. Map of the road distribution in the Squaw Creek watershed. Types of roads are described in greater detail in the text. Double and single track dirt roads refer to the number of vehicles that can safely pass on the road without stopping. Single-track dirt roads are designed for one vehicle, double-track roads can handle two large vehicles side by side. Buffers were created in ArcView to determine the road surface area, which were based on widths measured from digital orthophoto quadrangles.

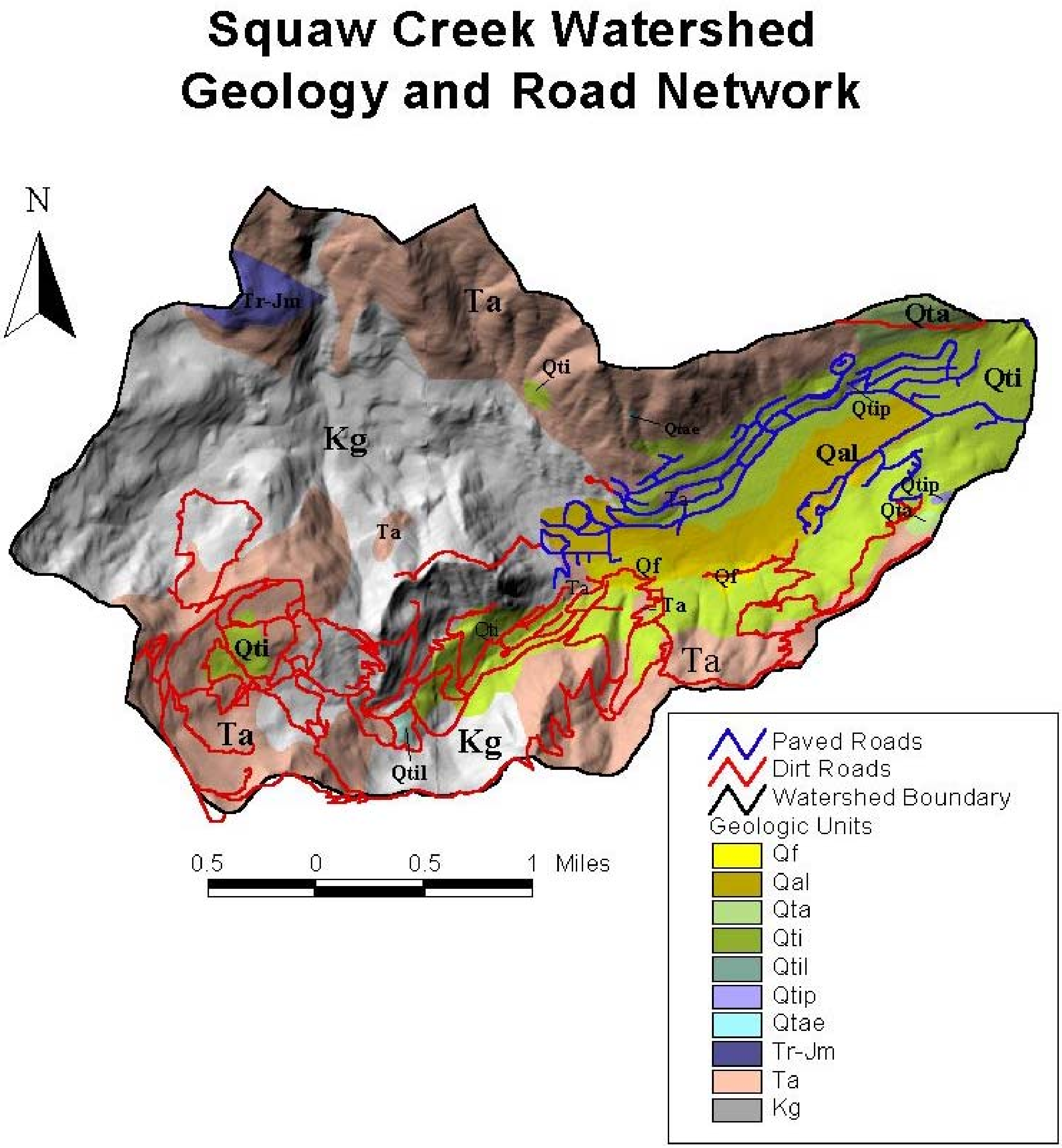

Figure 16. Map showing the spatial relation between geology and roads in the Squaw Creek watershed.

feet wide in most places. Secondary roads have little to no shoulder adjacent to the pavement, but some unlined ditches are adjacent to the road surface. Poor maintenance and inadequate drainage result in the potential for significant erosion. Coarse material is typically trapped behind culverts or deposited on the margin of the meadows. Fine-grained material transported in suspension finds its way into Squaw Creek with relative ease, especially during times of snowmelt activity close to the valley floor.

During winter months, sand is applied to the paved roads in Squaw Valley. Placer County, California road maintenance (responsible for sanding the paved road network in Squaw Valley, Bear Valley, and Cabin Creek) reported in 2002 that approximately 720 tons of sand was applied to the 17 miles (27.4 km) of paved roads in those three watersheds. Application records for the individual watersheds were not available. Assuming equal application density, approximately 50% of the sand is applied to Squaw Valley roads. This represents a yearly average of approximately 1 ton (0.9 metric ton) of sand per day, although most is applied during a five-month period. Some of the sand applied in winter is mechanically swept up, however (Placer County reported that records are not maintained). Much of the sand and finer particles derived from crushing by vehicles makes its way into these drainages directly or via culverts and tributaries.

Dirt roads: There are more than 34 miles (55 km) of dirt roads in the Squaw Creek watershed. This represents about 72% of the total length of roads in the watershed. The total surface area of dirt roads is approximately 2% of the entire watershed surface area. Most of the dirt roads are concentrated in the south fork and make up 5.8% of the watershed surface area. This large surface area of relatively impervious surface has a profound impact on hydrology and sediment transport in the watershed.

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 ridges are generally not directly connected to streams by virtue of their position in the watershed; however, runoff generated on roads can increase the flow and erosion on the hillslopes below.

Jones et al. (2000) and others found that road networks in steep, forested landscapes are associated with an increase in the frequency of debris slides, debris flows, and landslides compared to similar forested watersheds that didn't have roads (Wemple et al., 1996). These mass movements are considered to be the major source of sediment in some mountain streams (Fredricksen, 1970; Madej 2000). Rills and gullies formed on nonvegetated cut and fill slopes associated with roads tend to provoke slope failures and provide direct sediment input to streams.

Mid-slope road crossings of first through third order streams (Strahler method) were found to have significant occurrences of debris flows, indicating the major impacts of road crossings (Jones et al., 2000). Jones et al. (2000) therefore propose that cumulative effects resulting from road stream crossings increase at downstream locations in areas with high densities of these crossings. In the Squaw Creek watershed, a query of the GIS road database for Squaw Creek found a total of 66 drainage crossings that are likely to affect hydrologic routing within subdrainages of the south fork of Squaw Creek.

Roads located in middle and lower portions of a watershed typically cross stream reaches more frequently and therefore are directly connected to the stream network (Jones et al., 2000). Roads located in these areas commonly are oriented parallel to the main stream, which is favorable for rills, gullies, and culverts to transport sediment directly to the stream. Mid- to lower-slope road cuts have been shown to be more likely to intercept subsurface water flow, causing the flow to become surface runoff in addition to runoff from the road itself (Wemple et al., 1996). 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 to stream networks.

4.4.3 Road density effect on erosion and sediment transport

Road density is frequently used as an overall index of the impacts of roads in a watershed because detrimental effects increase with increased road density (Forman and Alexander, 1998). The Squaw Creek watershed exhibits a particularly high density of roads in certain portions of the basin. The road density for the overall watershed is 5.78 mi/mi^2 (3.62 km/km^2), with the highest density occurring in the south fork subbasin (11.76 mi/mi^2 [7.31 km/km^2]) (Table 13). Using the logging road density (5–7 km/km^2) from Madej (2000) for a North coast watershed, the latter value for the south fork of Squaw Creek is approximately three times greater than a typical managed (logged) watershed. Forman and Alexander (1998) noted that increased peak flows in streams may be evident at road densities of 2–3 km/km^2. These figures indicate that roads in the south fork of Squaw Creek and on the north-facing valley hillslopes are sufficiently dense to create a negative impact on the stream network.

Table 13. Density of dirt roads in the Squaw Creek watershed and principal subwatersheds.

	Road Density (mi/mi^2[km/km^2])-
Area	**Above basin outlets**
South Fork sub-watershed	11.76 (7.31)
North Fork sub-watershed	0.77 (0.48)
North-facing valley of Squaw Meadows	5.78 (3.60)
Squaw Creek watershed	5.78 (3.62)

Road density and movement of water and sediment: Dirt roads can be considered stream links because most are connected directly or indirectly to streams. Road density, therefore, has the effect of increasing connectivity of stream networks and the contribution of sediment and water to streams. In the Squaw Creek watershed, this becomes an important factor. Since elsewhere in the Lake Tahoe basin it has been shown that stream channels are the dominant source of stream sediment, it follows that drainage density is an important variable controlling sediment yield (Nolan and Hill, 1991).

The drainage density (D_d) of a watershed is defined as the summation of the stream lengths (ΣL_S) divided by the basin area (A):

$$D_d = \Sigma L_S/A \text{ (Wemple et al., 1996)}$$

Drainage density is commonly used as an indicator of the efficiency of a stream network (i.e., larger values of drainage density indicate greater discharges, erosive power, and sediment transport within a watershed). A suspended sediment budget study for four drainages in the Lake Tahoe basin (Nolan and Hill, 1991) reported that the most dominant source of sediment is stream channels, indicating that drainage density is a strong indicator of sediment yield.

Wemple et al. (1996) and Jones et al. (2000) showed 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. Both of these studies observed minimum drainage density increases ranging from 21 to 50% for several areas with roads and indicate the increase would have been greater if gullies (a byproduct of the road corridor) connected to the stream network had been included in the analysis. An increase in drainage density results in higher peak flows, increased delivery of runoff and sediment to streams, and more in-stream erosion.

Dirt roads in the Squaw Creek watershed provide a direct connection to streams, particularly in the highly disturbed south fork compared to the relatively undisturbed north fork subwatersheds (Table 14). We used the length of dirt roads located in each subwatershed to determine the increase in drainage density. In the entire drainage basin, the development of dirt roads increased the effective drainage density by about 90%. Dirt roads in the south fork of Squaw Creek increase the drainage density by 3.5 times (about 250%). In contrast, roads in the north fork increase the drainage density by a factor of 1.1 (about 10%). Drainage density increases by about 70% on the north-facing hillslopes of Squaw Meadows due to roads. Hiking trails in all areas were not included in the effective drainage density calculations because they did not show clear evidence of increased stream connectivity or signs of active erosion (e.g., rill or gully formation, splays of sediment coming off of the trail).

Table 14. Stream network drainage density and effective drainage density adjusted for dirt road connectivity to streams.

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

Influence of road density on flow characteristics: Peak flow, or peak discharge, is defined as the maximum volume flow rate passing by a given location in a stream during a precipitation event or specified timeframe. Increases in peak flow can bring about alterations in stream channels (e.g., increased channel width, channel incision, rapid soil movement, bank erosion, and bank failure) (Madej, 2000). Studies have shown that road networks connected to streams cause peak flow increases through hydrologic rerouting of hillslope water that normally infiltrates through soil (Forman and Alexander, 1998; Jones et al. 2000). Paired watershed studies in the Idaho Batholith by Wemple et al. (1996) showed statistically significant changes in peak flows as a direct result of dirt roads.

Increases in peak flow caused by road network connectivity commonly result in increases in the magnitude and frequency of peak discharge (Wemple et al., 1996; Jones et al., 2000; Madej, 2000). Roadside drainage ditches reroute precipitation runoff generated from compacted road surfaces and intercepted through flow (shallow subsurface water) from road cuts.

Culverts: Culverts present unique problems in determining watershed erosion. Runoff from road surfaces, ditches, and cut slopes is concentrated by rerouting through culverts, thus increasing erosive power. This can lead to increases in delivery of sediment to the stream network where culverts are directly discharging into streams as well as gully formation and incision below culvert outlets which then deliver additional sediment and flow. Megahan et al. (1986) report deposition up to 15 times greater from gullies resulting from culvert discharge compared to 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).

In the Squaw Creek watershed, many culverts were damaged, plugged, or lost during the large flood in January 1997. During the course of this study, evidence of culvert damage or loss was not found because an aggressive program of culvert replacement had taken place prior to the study. Photographic documentation by LRWQCB staff, however, clearly showed the effects of ineffective and damaged or lost culverts, especially notable in the south fork of Squaw Creek. These effects included intensified gully formation, rilling, upstream deposits of thick wedges of sediment, and sediment deposition beyond the banks of streams.

Roads and their effect on sediment yield: 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. Past studies in the northwestern U.S. provide useful comparisons of sediment load in disturbed (with roads) and undisturbed (no roads) 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 following road construction the initial sediment output was 250 times that of the undisturbed condition and that within a few years, sediment output decreased to two or three times that of the undisturbed condition. 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.

4.5 Erosion susceptibility in the Squaw Creek watershed

The land use and land cover map including roads was used in conjunction with geology, geomorphology, erosion rates from field measurement, and professional experience to produce a ranking of sediment sources relative to their dominance and susceptibility to erosion (Table 15; Fig. 17). Because geology influences the source of sediment and geomorphic processes to a certain degree, variability of the susceptibility to erosion was assessed for the different geologic settings. Areas of relatively high and low erosion susceptibility within the watershed were identified using the GIS, field data and observations, aerial photographic analysis, and knowledge of geomorphic processes affecting sediment movement.

Table 15. Relative ranking of dominant sediment sources in the Squaw Creek Watershed in order of most dominant and most susceptible to least and within each ranked source the variability of susceptibility dependent upon geologic setting.

Ranked Sources	Glacial Deposits	Weathered Andesite	Weathered Granite	Fresh Granite	Valley Fill
Double track dirt roads	high	high	moderate	Low	low
Single track dirt roads	high	high	moderate	Low	low
Graded Ski runs	high	high	moderate	Low	--
Paved roads & parking lots	moderate	--	moderate	--	moderate
Road cuts	high	high	low	Low	--
In stream	high	Moderate	low	Low	mod-high
Chaparral	mod-high	Moderate	moderate	Low	--
Forested	low	Low	low	Low	low

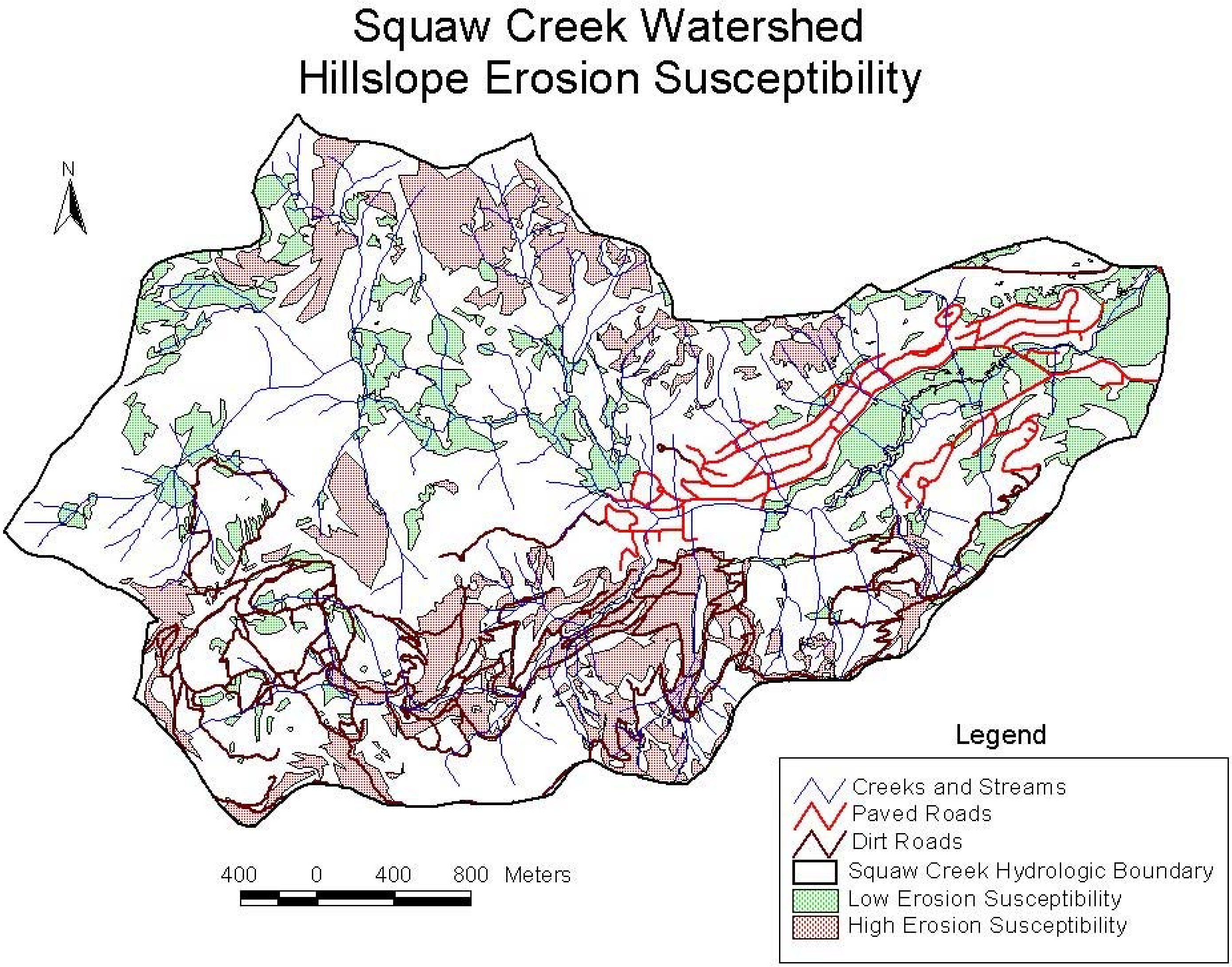

Figure 17. Map showing areas of high and low susceptibility to erosion in the Squaw Creek watershed. Dirt roads depicted on the figure actually comprise polygons designated as high erosion susceptibility. The stream reach through Squaw Meadows is also an area of high erosion susceptibility, however the width of the zone is too narrow to show on the figure.

To determine areas of high erosion susceptibility, all slopes greater than 30º were identified and categorized as "steep" from the Squaw Creek 10 m digital elevation model (DEM). Areas of chaparral and bare or marginally vegetated rock and soil that intersected steep slopes were designated with high susceptibility. Granite outcrops were excluded due to the higher degree of resistance to erosion for this rock type in relation to the other dominant rock types occurring within the Squaw Creek watershed. Moderately steep slopes (15–30º) were next identified and categorized. Areas of chaparral, graded ski runs, and bare or marginally vegetated "very high erosion hazard" soils (as classified in the SCS/Tahoe National Forest Soil Survey, 1994) that intersected steep or moderately steep slopes and were intersected by significant road networks were categorized as having high erosion susceptibility. Single and double track roads and major landslide scars were also categorized as high erosion susceptibility, regardless of slope. These areas align in greatest part with sensitive geologic units (weathered andesite and glacial deposits), disturbed vegetation cover (logging and trail cutting for ski runs), high road density, and the grading and compaction of ski slopes.

To determine areas of low erosion susceptibility, all slopes less than 20º were identified and categorized as "moderate". Areas of mixed conifer and forbs and grasses land cover classifications that occurred on moderate slopes were determined to be of low erosion susceptibility. Additionally, alpine meadow and nonflowing water body land cover classifications were identified as low erosion susceptibility, since these features act as storage sites for sediment transported to them.

4.6 Sediment budget

Lehre (1981) defines the sediment budget of 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 (stream bank 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 are considered estimates that can range from a half to a full order of magnitude or larger. 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:

$$QS = MS - SS, \text{ where}$$

QS = sediment discharge
MS = mobilized sediment
SS = stored sediment

Because of the disparity in sediment loads measured and modeled for Squaw Creek, determining an accurate numeric sediment budget is challenging. Assuming that the major source of sediment originates on hillslopes, we have estimated the total amount of sediment available on hillslopes in the watershed be on the order of 1 to 2 million tons of sediment. This is based on field erosion measurements, land use and land cover, and modeling with GIS. The amount of sediment mobilized on hillslopes is estimated to be 10 to 30% of the total sediment available on hillslopes. This estimate is based on the sediment delivery ratio equation

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

where, slope = % slope of the main stem channel (Reid and Dunne, 1995), and estimates that the majority of sediment entering streams during the year travels less than 10 m to the streams.

Of the 10 to 30% sediment mobilized, it is estimated that as much as 75 to 80% remains stored on hillslopes, leaving approximately 25 x 10^3 T in transit throughout the watershed via rills, gullies, and sheetwash on hillslopes. Direct measurements indicate that as much as 20 x 10^3 T are potentially in storage in stream channels and point bars at any time. We also estimate, based on erosion rates and volume calculations of material stored in ditches and behind culverts, that an additional 1 to 2 x 10^3 T of sediment are transported directly from hillslopes, rills, gullies, and sheetwash into the stream. Measurements of the long-term rate of erosion from stream banks and bedload measurements by Woyshner and Hecht (1987) suggest that an additional 2–3,000 T of sediment are eroded from stream banks and channels. The sum of the output reaching Squaw Creek is estimated to be on the order of 8 to 10,000 T per year. If roads are taken into consideration, the direct linkage effect of the roads increases the sediment yield by an order of magnitude.

While not a precise figure, the estimates for the yield based on the sediment budget are within the same order of magnitude as results from modeling by McGraw et al. (2001) and sediment loading determined from rating curves developed from SSC and discharge (Kuchnicki, 2001). The budget is a reasonable representation of the relative contributions of the different principal sediment sources in the watershed, however. The budget also shows that roads are large sediment contributors and are effective at circumventing hillslope processes. The net result is that sediment delivery rates are increased significantly by roads that crisscross the landscape.

5. Source Linkage

According to the EPA TMDL protocol (EPA, 1999a), the linkage between the target and the source must be established. The linkage between sediment sources and the targets can be approached in two ways. For point source pollutants, this can be a relatively straightforward procedure. For nonpoint source pollutants, in particular sediment, the direct linkage between target and sediment source is more difficult. The other approach, which is used in this study, is the physical connection between the sediment source and the target. For purposes of this discussion, this approach can be defined as the physical linkage or geomorphic linkage. For example, in Squaw Creek, the measuring point is the creek itself, either at the outlet, in the meadows, or elsewhere in the system. If excessive sediment is observed or measured in the creek, then there must be a physical connection between the sediment source and the creek. The sediment sources identified in the Squaw Creek watershed are largely connected to Squaw Creek by smaller tributary streams. Hillslope processes are the link between hillslope sources and the small tributaries. In-stream sediment sources are linked to sediment discharge by channel and bank erosion.

The linkage systems in the south fork of Squaw Creek and the western and southern half of the north fork are severely disturbed by graded ski runs, roads and road drainage systems, past construction of ski lift towers, loading stations, and detention ponds. Disturbances—which have included removal of stabilizing vegetation, grading and compaction of hillslopes, and development of extensive networks of dirt roads—tend to disrupt the geomorphic equilibrium of the natural system and deliver greater volumes of water and sediment to Squaw Creek. Therefore, physical linkage for the majority of the watershed has been disrupted such that the ability of the natural system to absorb disturbances has been altered. This alteration has forced the natural stream system to attempt to adjust to changed stream flow and sediment conditions in downstream reaches. Part of the adjustment has included changes in channel geometry and increased channel and bank erosion.

In the Squaw Creek watershed, the dirt road network appears to have the greatest impact on the linkage of sediment from otherwise low-magnitude sources directly to tributaries. Roads were observed to generate direct runoff during precipitation events and intercept overland flow from adjacent hillslopes. Roadside ditches also intercept overland flow as well as the shallow, unsaturated interflow or throughflow in the surficial mantle. The result is increased erosion of sediment from roads and ditches as well as an increase in the delivery rate of water and sediment to tributaries and the main stem of the north and south forks of Squaw Creek.

In the northern half of the north fork of Squaw Creek, the poorly maintained foot trails are sediment sources as well as a link between sources and the stream. This in itself can be problematic if hillslope surficial deposits become destabilized from trail erosion and produce greater amounts of sediment. But for the most part in the northern half of the north fork, there is little disturbance and material tends to move slowly down the hillslopes and through the small tributaries at rates commensurate with the discharge that the streams are capable of handling. In the northern half of the north fork of Squaw Creek, there is in essence equilibrium between the capture area of small tributaries, the sediment delivered, and the discharge required to transport the material to the main stem of the north fork.

6. Load Allocation

6.1 Reference watershed conditions

EPA (1999a) states that a method for establishing target values is by comparison to a reference site or sites:

> Reference sites are representative of the characteristics of the region and subject to minimal human disturbance. This comparison is typically done by comparing data collected from impaired sites to similar data from the same sites collected before impairment and/or from one or more appropriate reference sites where designated uses are in good condition. Conditions at the reference site (e.g., suspended sediment concentrations) can then be interpreted as approximate targets for the indicators at the impaired site. The reference sites may be within the study watershed or in nearby or even distant watersheds, and they should be selected based on careful comparison of key watershed characteristics and processes (e.g., geology, soils, topography, land use). (EPA, 1999b, p. 4-15, 4-21).

It is difficult if not impossible to find a watershed in the Sierra Nevada that resembles Squaw Creek watershed in all physical respects. A watershed similar to Squaw Creek that has remained undisturbed by human activities is even more challenging to locate. The north fork of Squaw Creek was considered as a possible reference site because some parts are relatively undisturbed, but it was rejected because of surface disturbances in much of the southern half and lack of hydrologic and sediment data. Blackwood Creek, located a few miles south of Squaw Creek has similar dimensions, geology, and hydrology to Squaw Creek and a good record of stream discharge. Blackwood Creek has been severely disturbed by grazing and mining activities in the valley, however, and the hydrology has been severely altered. Thus, Blackwood Creek could not be considered as a reference site.

6.2 Sagehen Creek reference watershed

Sagehen Creek, located about 15 miles (24 km) north of Squaw Creek is selected as the reference watershed for Squaw Creek. Sagehen Creek has geologic characteristics, glacial history, geomorphology, soils, and vegetation similar to Squaw Creek, and it has experienced little historical disturbance other than forest fire and road building. Table 16 summarizes the physical attributes of the Sagehen Creek watershed. Sagehen Creek also has a long record of stream discharge and sediment data and serves as the reference site for this study.

Table 16. Comparison of physical characteristics for Sagehen Creek and Squaw Creek.

Attribute	Sagehen Creek	Squaw Creek Watershed	South Fork Squaw Creek	North Fork Squaw Creek
Area	18.42 mi^2 (47.7 km^2)	8.2 mi^2 (21.1 km^2)	1.8 mi^2 (4.7 km^2)	3.6 mi^2 (9.3 km^2)
Relief	2,976 ft (907 m)	2,904 ft (885 m)	2,665 ft (812 m)	2,786 ft (849 m)
Maximum Elevation	8,714 ft (2,656 m)	9,006 ft (2,745 m)	8,885 ft (2,708 m)	9,006 ft (2,745 m)
Total Dirt Roads	59.7 miles (96 km)	34.2 miles (55.1 km)	21.2 (34.3 km)	2.8 (4.5 km)
Road Density: mi/mi^2(km/km^2	3.24 (2.01)	5.78 (3.62)	11.76 (7.31)	0.77 (0.48)
Drainage Density: mi/mi^2(km/km^2)	1.26 (0.78)	6.50 (4.02)	4.72 (2.93)	7.37 (4.58)
Effective Drainage Density: mi/mi^2(km/km^2)	9.83 (2.79)	12.3 (7.6)	16.48 (10.24)	8.14 (5.06)

Sagehen Creek is particularly useful as a reference watershed for several reasons:

1. It is slightly larger than the Squaw Creek watershed.
2. Geologic units that are most susceptible to erosion in the Squaw Creek watershed are the predominant rock units of the Sagehen Creek watershed.
3. The long-term suspended sediment load of Sagehen Creek is lower than Squaw Creek
4. Both watersheds have a network of dirt roads (Fig. 18)
5. Bioassessment studies by Herbst (2002) indicate that the suite of aquatic macroinvertebrates are indicative of a healthy watershed.

Although the geology is not identical to Squaw Creek, the majority of Sagehen Creek is underlain by andesite, andesitic tuffs, breccias, and mudflows and is covered by glacial deposits. This makes Sagehen most similar to the south fork of Squaw Creek that has suffered the most disturbance by humans. Thus, Sagehen serves as an excellent template for estimating targets and reductions.

6.3 Target, load reductions, and allocations

As shown in this report, road density increases the effective drainage density of a watershed, which contributes to excessive sediment discharge. Therefore, road density is an appropriate target for reductions and allocations.

The road density in Sagehen Creek of 3.24 mi/mi^2 (2.01 km/km^2) is the target for the Squaw Creek watershed (Fig. 18). In the entire Squaw Creek watershed, road density needs to be reduced by a factor of about 1.8. Because of the large difference in road density in the south fork relative to the north fork and the entire watershed, reductions in effective density will be greatest in the south fork. Road density in the south fork of Squaw Creek watershed needs to be reduced by a factor of at least 3.5 to achieve a density equivalent to that in Sagehen Creek. This is equivalent to decommissioning approximately 20 km of dirt roads and rehabilitating these sites in the south fork of Squaw Creek. Road density in the north fork of Squaw Creek does not appear to be problematic.

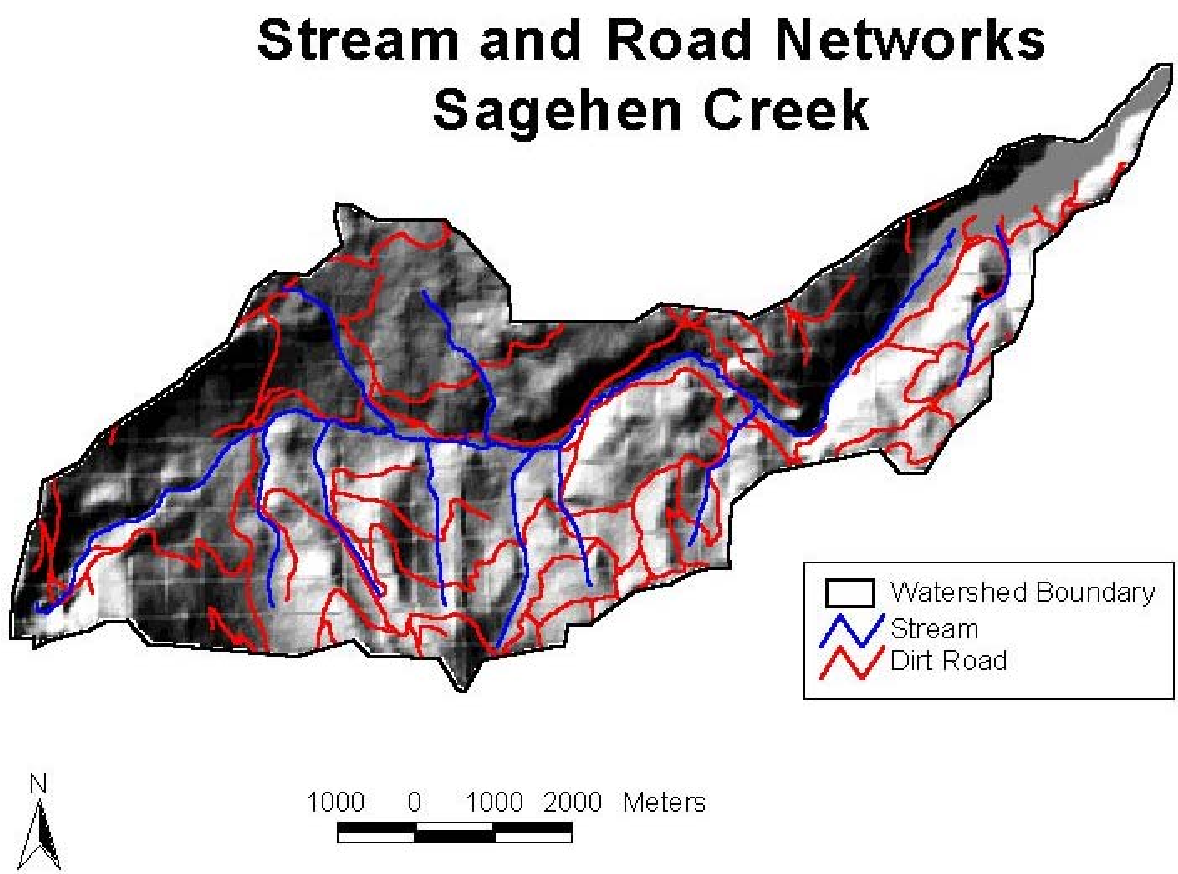

Fig. 18. Distribution of roads in the Sagehen Creek watershed.

6. Summary and Conclusions

The Squaw Creek watershed is characterized by excessive sediment discharge primarily related to land use activities. The geology and geologic history of the watershed have resulted in the south fork being a highly sensitive subwatershed by nature, requiring diligence when considering alterations in land use activities. Two principal factors are observed to have the greatest impact on sediment discharge from the watershed:

1) Removal of natural vegetation and grading of ski runs
2) The vast network of dirt roads and poorly maintained drainage systems

Additionally, engineered structures have significant impact on the erosion and discharge of sediment from the watershed. These include:

1) Straightening of Squaw Creek on the north side of the main parking lot
2) Rip rap protection of banks along Squaw Creek through the principal residential area at the base of the mountain
3) Rip rap protection of banks through the meadows reach
4) Culverts that deliver sediment directly to Squaw Creek

These structures are installed primarily to convey water rapidly through the area during spring runoff and high intensity rain events. The result is that the discharge velocity increases and is capable of causing excessive erosion of unprotected stream banks in the meadow.

Finally, paved roads are a source of sediment from road sand applied during winter months, most of which finds its way into Squaw Creek. Paved roads also contribute to runoff. Inadequate drainage and sediment control associated with paved roads contribute to the increase in magnitude of discharge of water and sediment into the creek.

The dirt road network in the Squaw Creek watershed should be reduced to a density that is similar to the road density in Sagehen Creek. Sagehen Creek watershed is a highly sensitive watershed with respect to the geologic and soils setting. Because Sagehen Creek has a relatively low sediment discharge, the road density in that watershed appears to be in equilibrium with the sediment discharge. Therefore, a reasonable and appropriate target for sediment load reductions is the road density in Squaw Creek. In particular, the high road density in the south fork needs to be reduced by a factor about 3.5 to achieve a similar road density as Sagehen Creek.

Finally, an effort must be made to improve drainage along all roadways, protect road crossings from direct sediment discharge, implement aggressive revegetation of disturbed hillslopes to enhance infiltration and reduce runoff, and consider improved engineering designs to reduce the velocity of flows and bank erosion through the meadows section.

8. References Cited

Anderson, J.F., Hardy, E.E., Roach, J.T. and Witmer, R.E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 28 p.

Birkeland, P.W., 1961, Pleistocene history of the Truckee Area, North of Lake Tahoe, California [Ph.D. Dissertation]: Palo Alto, CA, Stanford University, 126 p. (includes Plate 1, Geologic map of the Truckee area, California, scale 1:62,500)

Birkeland, P.W., 1962, Multiple glaciation of the Truckee area, California, *in* P.A. Lydon, (Ed.), U.S. Highway 40, Sacramento to Reno, Dixie Valley and Sand Springs Range, Nevada: Geological Society of Sacramento Annual Field Trip Guidebook, p. 64-69.

Birkeland, P.W., 1963, Pleistocene volcanism and deformation of the Truckee area, North of Lake Tahoe, California: Geological Society of America Bulletin, v. 74, p. 1453-1464.

Birkeland, P.W., 1990, Soil-geomorphic research - a selective overview, *in* P.L.K. Knuepfer and L.D. McFadden, (Eds.), Soils and Landscape Evolution: Geomorphology, v. 3, p. 207-224.

Birkeland, P.W., 1999, Soils and geomorphology (Third Edition): New York, Oxford University Press, 430 p.

Bish, N. and Kundert, T., 1993, A guide to threatened and endangered species/management indicator species plants and animals of the Lake Tahoe Basin Management Unit: U.S. Forest Service, U.S. Department of Agriculture, 40 p.

Brown, K. J., 1994, River-bed sedimentation caused by off-road vehicles in the Victorian Highlands, Australia: Water Resources Bulletin, v. 3, p. 239-250.

Brunton, D.A. and Bryan, R.B., 2000, Rill network development and sediment budgets: Earth Surface Processes and Landforms, v. 25, p. 783-800.

Bull, W.B., 1991, Geomorphic responses to climate change: New York, Oxford University Press, 326 p.

Burnett, J.L., 1971, Geology of the Lake Tahoe Basin: California Geology, v. 24, p. 119-130.

Caine, T.N., 1986, Sediment movement and storage on alpine slopes in the Colorado Rocky Mountains, *in* Abrahams, A.D., (Ed.), Hillslope Processes: Boston, Allen & Unwin, p. 115-137.

CalFlora, 2000, Information on California plants for education, research and conservation: [web application] Berkeley, California, The CalFlora Database [a non-profit organization]. Available: http://www.calflora.org/

California Department of Fish and Game, 2001, California Natural Diversity Database.

Donaldson, S. and Johnson, W., 1999, The war against tall whitetop: University of Nevada Cooperative Extension Fact Sheet 99-95, 3p.

EPA, 1999a, Protocol for Developing Sediment TMDLs: Washington, D.C., U.S. Environmental Protection Agency Office of Water, EPA 841-B-99-004.

EPA, 1999b, South Fork Eel River Total Maximum Daily Loads for sediment and nutrients: Downloadable online: http://www.epa.gov/region09/water/tmdl/final.html.

FAO, U.N., 1993, Field Measurement of Soil Erosion and Runoff: Food and Agriculture Organization of the United Nations.

Forman, R.T. and Alexander, L.E., 1998, Roads and their major ecological effects: Annual Review, Ecological Systems v. 29, p. 207-232.

Fredriksen, R.L., 1970, Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds: Portland, Oregon, U.S. Department of Agriculture, USDA Forest Service Research Paper PNW-104, 15 p.

Gardner, J.S., 1986, Sediment movement in ephemeral streams on mountain slopes, Canadian Rocky Mountains, *in*, Abrahams, A.D., (Ed.), Hillslope Processes: Boston, Allen & Unwin, p. 97-113.

Goudie, A., 1981, Geomorphological techniques: Boston, George Allen & Unwinn, 395 p.

Grace, J.M., Wilboit, J., Rummer, R. and Stokes, B., 1996, Surface erosion control techniques on newly constructed forest roads: 1996 ASAE Annual Internation Meeting, ASAE, Phoenix Civic Plaza, Phoenix, AZ.

Grayson, R.B., Haydon, S.R., Jayasuriya, M.D.A. and Finlayson, B.L., 1993, Water quality in mountain ash forests-separating the impacts of roads from those of logging operations: Journal of Hydrology, v. 150, p. 459-480.

Hadley, R.F. and Schumm, S.A., 1961, Sediment sources and drainage basin characteristics in upper Cheyenne River basin: U.S. Geological Survey Water Supply Paper 1531-B, p. 137-196.

Hancock, G.S., Anderson, R.S. and Whipple, K.X., 1998, Beyond power: bedrock river incision process and form, *in* Tinkler, K.J. and Wohl, E.E., (Eds.), Rivers Over Rock: Fluvial Processes in Bedrock Channels: Washington, D.C., American Geophysical Union.

Harr, R. D., Harper, W.C., Krygier, J.T., and Hsieh, F.S., 1975, Changes in storm hydrographs after road building and clear cutting in the Oregon Coast Range: Water Resources Research, v. 11, p. 436-444.

Hunt, C.B., 1988, Geology of the Henry Mountains, Utah, as recorded in the notebooks of G.K. Gilbert, 1875-1876: Geological Society of America Memoir 167, 230 p.

JARA, 1975, Squaw Valley Master ski lift Draft Environmental Impact Report: James A. Roberts Associates, Inc., Sausalito, CA.

Jones, J.A., Swanson, F.J., Wemple, B.C. and Snyder, K.U., 2000, Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks: Conservation Biology, v. 14, p. 76-85.

Kavvas, M.L. and Govindaraju, R.S., 1992, Hydrodynamic averaging of overland flow and soil erosion over rilled hillslopes: Erosion, Debris Flows, and Envrionment in Mountain Regions, Proceedings of the Chengdu Symposium, IAHS Publication 209, p. 101-111.

Kelson, K.I. and Wells, S.G., 1989, Geologic influences on fluvial hydrology and bedload transport in small mountainous watersheds, northern New Mexico, U.S.A.: Earth Surface Processes and Landforms, v. 14, p. 671-690.

Kleinfelder, 2000a, Technical memorandum of Squaw Valley groundwater background data: Reno, NV, 14 p. +2 plates and 16 appendices.

Kleinfelder, 2000b, Report of field activities, Squaw Valley Public Service District, water resources assessment project, Olympic Valley, California: Reno, NV, 14 p. +3 tables, 11 plates, and 3 appendices.

Knighton, D., 1998, Fluvial forms and processes: New York, John Wiley and Sons, 383 p.

Kuchnicki, J.D., 2001, Truckee River watershed assessment: sediment indicators and associated target values [MS thesis]: Reno, University of Nevada, 134 p.

Mackin, J.H., 1948, Concept of the graded river: Geological Society of America Bulletin, v. 59, p. 463-512.

Madej, M.A., 2000, Erosion and sediment delivery following removal of forest roads: U.S. Geological Survey Western Ecological Research Center, Arcata, CA.

Mayer, K.E. and Laudenslayer, W.F., (Eds.), 1988, A guide to wildlife habitats of California: Sacramento, California, State of California, Resources Agency, Department of Fish and Game,166 p.

McGraw, D., McKay, A., Guan, G., Bullard, T., Minor, T., and Kuchnicki, J., 2001, Water quality assessment and modeling of the California portion of the Truckee River basin: Reno, Nevada, Desert Research Institute, Division of Hydrological Sciences Publication No. 41170, 167 p.

Megahan, W.F., Seyedbagheri, K.A. and Mosko, T.L., 1986, Construction phase sediment budget for forest roads on granitic slopes in Idaho, *in* Hadley, R.F., (Ed.), Drainage Basin Sediment Delivery: Oxfordshire, UK, IAHS Press, p. 31-39.

Miller, A.J., 1995, Valley morphology and boundary conditions influencing spatial patterns of flood flow, *in* Costa, J.E., Miller, A.J., Potter, K.W., and Wilcock, P.R., (Eds.), Natural and Anthropogenic Influences in Fluvial Geomorphology: American Geophysical Union, Geophysical Monograph 89, p. 57-81.

Morgan, R.P.C., Finney, H.J., Lavee, H., Merritt, E., and Noble, C.A., 1986, Plant cover effect on hillslope reunoof and erosion: evidence from two laboratory experiments, *in* Abrahams, A.D., (Ed.), Hillslope Processes: Boston, George Allen & Unwin, p. 77-96.

Munsell Color Company, Inc., 1975, Munsell soil color chart: Baltimore, Maryland, Munsell Color Co., Inc.

Murphy, D.D., and Knopp, C.M., Eds.), 2000, Lake Tahoe watershed assessment: Volume I. Gen. Tech. Rep. PSW-GTR-175, Albany, California: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, 736 p.

Nolan, K.M. and Hill, B.R., 1991, Suspended-sediment budgets for four drainage basins tributary to Lake Tahoe, California and Nevada, 1984-1987: U.S. Geological Survey Water-Resources Investigations Report 91-4054, 40 p.

Parker, R.S., 1977, Experimental study of drainage basin evolution and its hydrologic implications: Fort Collins, Colorado, Colorado State University Hydrology Papers No. 90, 58 p.

Patton, P.C. and Baker, V.R., 1976, Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls: Water Resources Research, v. 12, p. 941-952.

Pazzaglia, F.J., Gardner, T.W. and Merritts, D.J., 1998, Bedrock fluvial incision and longitudinal profile development over geologic time scales determined by fluvial terraces, *in* Tinkler, K.J. and Wohl, E.E., (Eds.), Rivers Over Rock: Fluvial Processes in Bedrock Channels: Washington, D.C., American Geophysical Union.

Ray, R.G., 1960, Aerial Photographs in Geologic Interpretation and Mapping: U.S. Geological Survey Professional Paper 373, 230 p.

Reid, J.R., Jr., 1985, Bank erosion processes in a cool-temperate environment, Orwell Lake, Minnesota: Geological Society of America Bulletin, v. 96, p. 781-792.

Reid, L.M. and T. Dunne, 1984, Sediment production from road surfaces: Water Resources Research 20, p. 1753-1761.

Reid, L.M. and T. Dunne, 1996, Rapid evaluation of sediment budgets: Resikirchen, Germany, Catena Verlag, 164 p.

Richards, K., 1982, Rivers: New York, Methuen, 358 p.

Ritter, D.F., Kochel, C.R., and Miller, J.R., 1995, Process geomorphology, 3rd edition: WBC/McGraw-Hill,

Saucedo, G.J. and Wagner, D.L., 1992, Geologic map of the Chico quadrangle: California Department of Conservation, Division of Mines and Geology, scale 1:250,000.

Schumm, S.A., 1973, Geomorphic thresholds and complex response of drainage systems, *in* M. Morisawa, (Ed.), Fluvial geomorphology: Boston, George Allen & Unwin, p. 299-310.

Schumm, S.A., 1977, The fluvial system: New York, John Wiley & Sons, 338 p.

Seginer, I., 1966, Gully development and sediment yield: Journal of Hydrology, v. 4, p. 236-253.

Selby, M.J., 1982, Hillslope materials and processes: Oxford, Oxford University Press, 264 p.

Siegel, B.S. and Gillespie, A.R., 1980, Remote Sensing in Geology: New York, John Wiley & Sons, 702 p.

Simon, A., Larsen, M.C., and Hupp, C.R., 1990, The role of soil processes in determining mechanisms of slope failure and hillslope development in a humid-tropical forest, eastern Puerto Rico: Geomorphology, v. 3, p. 263-286.

Sklar, L. and Dietrich, W.E., 1998, River longitudinal profiles and bedrock incision models: stream power and the influence of sediment supply, *in* Tinkler, K.J. and E.E. Wohl, E.E., (Eds.), Rivers Over Rock: Fluvial Processes in Bedrock Channels: Washington, D.C., American Geophysical Union.

Soil Conservation Service (SCS), 1979, Soil Survey of Placer County, California, Western Part: Washington, DC, US Department of Agriculture.

Soil Conservation Service, 1994, Soil survey, Tahoe National Forest area, California: U.S. Department of Agriculture, 377 p.

Soil Survey Staff, 1999, Soil Taxonomy: U.S. Department of Agriculture, Natural Resources Conservation Service.

Strahler, A.N., 1952, Hysometric (area-altitude) analysis of erosional topography: Geological Society of America Bulletin, v. 63, p. 1117-1142.

Sun, G. and McNulty, S.G., 1997, Modeling soil erosion and transport in forest landscape: Southern Global Change Program, USDA Forest Service, Raleigh, NC.

Swanson, F.J. and Dryness, C.T., 1975, Impact of clearcutting and road construction on soil erosion by landslides in the Western Cascade Range, Oregon: Geology, v. 3, p. 392-396.

Tonkin, P.J. and Basher, L.R., 1990, Soil-stratigraphic techniques in the study of soil and landform evolution across the Southern Alps, New Zealand: Geomorphology, v. 3, p. 547-575.

Varnes, D.J., 1978, Slope movement and types and processes, *in* Transportation Research Board, National Academy of Sciences Special Report 176: Chapter 2, Landslides: Analysis and Control: Washington, D.C.

Wells, S.G., Jercinovic, D.E., Smith, L.N., Gutierrez, A.A., and Pickle, J., 1983, Instrumented watersheds in the coal fields of northwestern New Mexico, *in* Wells, S.G., Love, D.W., and Gardner, T.W. (Eds.), Chaco Canyon Country: American Geomorphological Field Group, 1983 Field Trip Guidebook, p. 99-112.

Wemple, B.C., Jones, J.A. and Grant, G.E., 1996, Channel network extension by logging roads in two basins, Western Cascades, Oregon: Water Resources Bulletin, v. 32, p. 1195-1207.

Western Regional Climate Center (WRCC), 2001, Northern California climate summaries, http://www.wrcc.dri.edu/summary/climsmnca.html: Reno, Nevada, Desert Research Institute.

William F. Jones, Inc., 1981, A geotechnical investigation for Hidden Lake Subdivision, Squaw Valley, California (includes Squaw Valley Seismic Survey): San Mateo, CA, 58 p.

William F. Jones, Inc., 1983, A geotechnical study of the landslide at Lot 2, Tiger Tail Road, Squaw Valley, California: San Mateo, CA, 25 p.

Wohl, E.E., 1998, Bedrock channel morphology in relation to erosional processes, *in* Tinkler, K.J. and Wohl, E.E., (Eds.), Rivers Over Rock: Fluvial Processes in Bedrock Channels: Washington, D.C., American Geophysical Union

Woyshner, M. and Hecht, B., 1987, Sediment, solute and nutrient transport from Squaw Creek, Truckee River basin, California: Walnut Creek, CA, Kleinfelder and Associates, p. 190-219.

Young, A. and Saunders, I., 1986, Surface Processes and Denudation, *in* Abrahams, A.D., (Ed.), Hillslope Processes: Boston, George Allen & Unwin, 414 p.

Zeiner, D.C., W.F. Laudenslayer, Jr., K.E. Mayer and M. White (Eds.). 1990a. California's wildlife, Volume I Amphibians and Reptiles: Sacramento, CA, The Resources Agency, California Department of Fish and Game, 732 p.

Zeiner, D.C., W.F. Laudenslayer, Jr., K.E. Mayer and M. White (Eds.). 1990b. California's Wildlife, Volume II Birds. Sacramento, CA, The Resources Agency, California Department of Fish and Game, 732 p.

Zeiner, D.C., W.F. Laudenslayer, Jr., K.E. Mayer and M. White (Eds.). 1990c. California's Wildlife, Volume III Mammals: Sacramento, CA, The Resources Agency, California Department of Fish and Game, 732 p.

9. Appendices

APPENDIX A

TMDL Problem Statement for Squaw Creek Watershed

A.1 Introduction

The California Regional Water Quality Control Board, Lahontan Region (Regional Board) and the Desert Research Institute (DRI) are preparing this Draft Report to present the technical and scientific background for the forthcoming Total Maximum Daily Load (TMDL) for sediment in Squaw Creek, Placer County, California. This Draft Report contains the draft TMDL technical support elements as recommended by United States Environmental Protection Agency (EPA, 1999a) to restore the water in Squaw Creek to meet State water quality standards and objectives, and to protect designated beneficial uses.

A.2 Legal Authority

The Water Quality Control Plan for the Lahontan Region, also known as the Basin Plan, sets standards for surface waters and ground waters in the region. These standards are comprised of designated beneficial uses for surface and ground water, numeric and narrative objectives necessary to support beneficial uses, and the State's antidegradation policy. Such standards are mandated for all waterbodies within the state under the Porter-Cologne Water Quality Act. In addition, the Basin Plan describes implementation programs to protect all waters in the region. The Basin Plan implements the Porter-Cologne Water Quality Act and serves as the State Water Quality Control Plan applicable to Squaw Creek, as required pursuant to the federal Clean Water Act (CWA).

Section 305(b) of the CWA mandates biennial assessment of the nation's water resources, and these water quality assessments are used to identify and list impaired waters. CWA Section 303(d)(1)(A) requires each state to identify a list of waters that, based on the biennial assessment, do not meet standards. This list is referred to as the 303(d) list. The CWA also requires states to establish a priority ranking for impaired waters and to develop and implement TMDLs. A TMDL specifies the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards, and the TMDL allocates pollutant loadings to point and non-point sources such that those standards will be met, and designated beneficial uses protected.

The EPA has oversight authority for the 303(d) program and must approve or disapprove the State's 303(d) lists and each specific TMDL. The EPA is ultimately responsible for issuing a TMDL if the state fails to do so in a timely manner.

Regional Board Resolution No. 6-91-937 (November 14, 1991) identified Squaw Creek as impaired by excessive sedimentation and recommended it be placed on the 303 (d) list. Squaw Creek was placed on EPA's 303(d) list in 1992. The listing was based on a description of elevated sediment levels in Squaw Creek (Woyshner and Hecht 1988). It was also based on numerous, ongoing complaints and violations of permit conditions. It has continued to be listed based upon reports, unpublished data collected by Regional Board staff, complaint driven sampling, and violations detected through Self-Monitoring Programs.

A.3 Regulatory Context

The CWA is administered by the Regional Board under federally designated authority. This Regional Board is one of nine other regional boards in California, each generally separated by hydrologic boundaries. The State Water Resources Control Board (State Board) establishes statewide policies and serves as the review and appeal body for the decisions of the regional boards. The State Board is made up of five members appointed by the governor. Each Regional Board consists of nine governor-appointed members who serve four year terms. Scientific information is gathered and policy is developed for the Regional Board by its civil service employees (staff).

The Regional Board has adopted a Basin Plan that specifies water quality standards for the Lahontan Region and implementation measures to enforce those standards. Some measures that go beyond the scope of the current Basin Plan, such as TMDLs, must first be adopted by the Regional Board in a Basin Plan amendment process before they are implemented. The process involves a public review and comment period on the proposed TMDL, followed by a Regional Board hearing to respond to comments and relevant revisions to the proposed amendment. The Regional Board then votes on its adoption, and if the amendment is adopted, it is sent to the State Board to undergo a parallel process. Next, it is sent to the Office of Administrative Law (OAL) to determine whether the amendment is consistent with the California Administrative Procedures Act (APA). State TMDL adoption is complete after OAL approval and state transmittal to the EPA for final approval. The USPEA does not currently require states to include implementation plans as a part of the TMDL submittal. However, the State's position is that State law requires the Regional Boards to adopt implementation provisions concurrent with TMDLs.

The entire Basin Plan amendment process can take one to three years to proceed through all steps. The EPA has authority to promulgate its own regulatory actions if they believe that the State process is not meeting the requirements of the Clean Water Act in a reasonable amount of time.

A.4 Surface Water Quality Objectives Violated and Standards Not Attained

The Water Quality Control Plan for the Lahontan Basin (Basin Plan) reads:

> The suspended sediment load and suspended sediment discharge rate of surface waters shall not be altered in such a manner as to cause nuisance or adversely affect the water for beneficial uses.

The current level of sedimentation in Squaw Creek was judged to exceed the existing narrative Non Degradation Objective, and the narrative Water Quality Objectives for sediment, settleable and suspended materials, and turbidity.

Narrative water quality objectives for Squaw Creek include the following:

- nondegradation objective (Basin Plan page 3-2)
- nondegradation of aquatic communities and populations (Basin Plan page 3-5)
- sediment (Basin Plan page 3-6)
- settleable materials (Basin Plan page 3-6)

- suspended materials (Basin Plan page 3-6)
- turbidity (Basin Plan page 3-7)

These water quality objectives are narrative primarily because of the absence of numeric standards for sediment and related objectives.

Degradation, sediment, settleable and suspended materials, and turbidity have increased with watershed disturbance and have caused an increased sediment load to Squaw Creek. The apparent lack of consistent and comprehensive Best Management Practices (BMPs) and revegetation within disturbed areas contribute to the sediment loss from uplands and within Stream Environment Zones (SEZs).

The purpose of the Squaw Creek TMDL is to identify reductions of sediment delivery to the creek system that, when implemented, are expected to result in the attainment of applicable water quality standards and protection of water for all designated beneficial uses.

A.5 Beneficial Uses

The Squaw Creek watershed supports the following beneficial uses: MUN, AGR, GWR, REC-1, REC-2, COMM, WILD, COLD, RARE, MIGR, SPAWN, WQE, AND FLD. Summary definitions of these uses are provided below within the context of the study area. Complete definitions for these uses can be found in the Basin Plan. Excessive sediment introduced into Squaw Creek can be linked to the impairment of all of these beneficial uses. However, for reasons of clarity, the Squaw Creek TMDL will address the impairment of the most sensitive beneficial uses: COLD, RARE, and WILD—implying that protection of the most sensitive uses will protect the others.

A.6 Impairment of Beneficial Uses by Increased Suspended Sediment and Bedload

By definition, fluvial systems are conveyance systems for water and sediment produced in a watershed. As such, sediment is an important, naturally occurring component of healthy streams and rivers that serves beneficial purposes to many components of the biologic community. Nonetheless, an excessive amount of sediment in a stream can have adverse effects upon not only the biologic communities associated with a stream, but also on recreational uses. A description of beneficial uses appears in Chapter 2 of the Basin Plan. Squaw Creek's beneficial uses are specified in Table 2-1 of the Basin Plan on Page 2-15. Impairment to each designated beneficial uses for Squaw Creek are as follows:

MUN: Downstream municipal and domestic users who draw their water from the Truckee River, Squaw Creek’s receiving water, have had to shut the intake on Truckee Meadows Water Authority Chalk Bluff treatment plant and ration water due to excessive sediment loading during storm events.

AGR: The agricultural use of water in Squaw Valley later than 1972 has been livestock grazing. Geomorphic responses to increased sediment load can include channel down cutting, which in turn lowers the water table in meadow areas, damaging range vegetation.

GWR: Land use practices within the Squaw Valley watershed have increased impervious surfaces and reduced vegetative cover, resulting in lower infiltration rates and impacted quality and quantity of groundwater recharge.

REC-1: Swimming and wading, the primary Rec-1 activities in Squaw Creek, are not greatly impacted by sediment because of timing. High in-stream sediment loads occur with high precipitation and run-off events. Few people tend to swim or wade during storm events.

REC-2: Numerous complaints regarding the aesthetic concerns of turbid water have been received and investigated by Regional Board staff.

COMM: Recreational fishing is impaired when COLD, MIGR, SPWN are impaired.

WILD: See RARE. Healthy native vegetation to support wildlife requires a natural range of variability in physical and biological process and function. Excessive sediment and disturbed upland areas can exceed thresholds required by wildlife.

COLD: Cold freshwater habitat is impaired by an increase in the sediment budget in a variety of ways that involve the physical and biological process linkage and response. The investigation of these relationships will form the basis of the Squaw Creek TMDL.

RARE: The willow flycatcher depends upon healthy willow vegetation that is reduced by geomorphic responses induced by excessive sediment loading. Lahontan Cutthroat Trout depend upon physical and biological system components adapted to a sediment regime in balance with its hydrologic regime. Changes in sediment discharge, frequency, magnitude, and timing outside the expected range of variability can induce threshold geomorphic events, resulting in unsuitable habitat.

MIGR: Changes to channel form and velocity distribution (e.g., pools and riffles) resulting from increased sediment can limit the migration and movement of aquatic organisms. It needs to be determined weather or not sedimentation is linked to the channelized section of Squaw Creek being a “loosing reach” and limiting migration during low flow, or if that feature is natural to the Squaw Creek system.

SPAWN: Reproduction and rearing are limited by high bedload, poor pool quality, and inadequate substrate size. This is a result of increased sediment availability.

WQE: Increased sediment loading can compromise the natural ability of the meadow reach to settle, treat, and store sediment through channel aggradation and increased rate of braiding, or meander cut-off activity.

FLD: An increase in sediment loading can result in channel aggradation, reducing the capacity for flood peak attenuation. Infiltration rates can be altered as discussed above in GWR

In addition to alterations in sediment discharge, hydrologic alterations affecting flow and ultimately the system's ability to transport sediment must be considered. Changes to the hydrologic cycle include: Snowmaking, ground water pumping, sewage exported from basin, infiltration rates reduced by impervious surface and vegetation removal, soil compaction and re-routing of natural drainage patterns by dirt and paved roads.

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APPENDIX B

Public Participation

The purpose of this appendix is to document the public participation portion of this study. Valuable insights and contributions regarding the direction of this study came from input received at public meetings. Two public presentations were made during the course of the study and a third is scheduled following acceptance of the draft report. The dates and topics are listed below:

August 8, 2000: Presentation overview at the Nevada Water Resources Association annual conference. This was very early in the inception of the project and the presentation introduced the general goals of the study and initial thoughts regarding the sediment source assessment for Squaw Creek and methodology.

October 2000: Public forum at the Squaw Valley Municipal Advisory Committee meeting at Squaw Valley. The presentation to the MAC included the study plan as required by the contract and TMDL protocols.

Spring 2002: A final presentation is anticipated for the Regional Water Board.

APPENDIX C

Plant and Wildlife Species at Squaw Creek

The lower montane, upper montane, and subalpine vegetation zones of the Squaw Creek watershed include the following dominant habitat types: mixed conifer, Jeffrey pine, white fir, red fir, and subalpine forest habitats; montane chaparral; meadow; and riparian (Mayer and Laudenslayer, 1988). The watershed provides habitat suitable for common species such as red-tailed hawk (*Buteo jamaicensis*), Stellar's jay (*Cyanocitta stelleri*), coyote (*Canis latrans*), black bear (*Ursus americanus*), raccoon (*Procyon lotor)*, mule deer (*Odocoileus hemionus*), and species of terrestrial and arboreal rodents (Murphy and Knopp, 2000). To a lesser degree, habitat exists that may support select species of amphibians and reptiles, such as pacific tree frogs (*Pseudacris regilla*) and western aquatic garter snakes (*Thamnophis couchii*). A list of the more common wildlife species that may occur in the Squaw Creek watershed is provided below (Zeiner et.al., 1990a, b, c).

Birds	Western Tanager (*Piranga ludoviciana*)	**Amphibians**	Pacific Tree Frog (*Pseudacris regilla*)
	Dark-Eyed Junco (*Junco hyemalis*)		American Bullfrog (*Rana catesbeiana*)
	Mallard (*Anas platyrhynchos*)		Western Toad (*Bufo boreas*)
	Canada Goose (*Branta canadensis*)		Long-Toed Salamander (Ambystoma macrodactylum)
	Mountain Chickadee (*Poecile gambeli*)	**Reptiles**	Western Fence Lizard (*Sceloporus occidentalis*)
	Steller's Jay (*Cyanocitta stelleri*)		Western Aquatic Garter Snake (*Thamnophis couchii*)
	Hairy Woodpecker (*Picoides villosus*)		Terrestrial Garter Snake (*Thamnophis sirtalis*)
	Downy Woodpecker (*Picoides pubescens*)		Rubber Boa (*Charina bottae*)
	American Robin (*Turdus migratorius*)		
	Red-Tailed Hawk (*Buteo jamaicensis*)		
Mammals	Yellow-Bellied Marmot (*Marmota flaviventris*)		
	Douglas' Squirrel (*Tamiasciurus douglasii*)		
	Golden-Mantled Ground Squirrel (*Spermophilus lateralis*)		
	Coyote (*Canis latrans*)		
	Raccoon (*Procyon lotor*)		
	Beaver (*Castor canadensis*)		
	Porcupine (*Erethizon dorsatum*)		

Plant species found within the watershed are similar to those found elsewhere in the Sierra Nevadas. These include conifers, chaparral shrub species, meadow grasses and grasslike species (sedges, rushes), and riparian vegetation. Common occurring species in the watershed are listed below (CalFlora, 2000).

Herbaceous	Buttercup	**Shrubs**	Greenleaf Manzanita (*Arctostaphylos patula*)
	Mountain Mule Ears and Arrow-Leaved Balsamroot		Pinemat Manzanita (*Arctostaphylos nevadensis*)
	Sulphur Flower		Huckleberry Oak (*Quercus vaccinifolia*)
	Dwarf Alpine Aster		Sierra chinquapin (*Chrysolepis sempervirens*)
	Meadow Penstemon		Bitterbrush (*Purshia tridentata*)
	Lupine		Creeping Snowberry (*Symphoricarpos mollis*)
	Thistle		Whitethorn (*Ceanothus cordulatus*)
	Columbine		Tobacco Brush (*C. velutinus*)
	Indian Paintbrush		Squawcarpet (*C. prostratus*)
	Snow Plant		Sagebrush (*Artemisia tridentata*)
	Shooting Star		Rabbitbrush (*Chrysothamnus naseosus*)
	California Corn Lily		Dogwood (*Cornus sericea*)
	Cow Parsnip	**Trees**	White Fir (*Abies concolor*)
	Mariposa Lily		Red Fir (*Abies* concolo)r
	Ranger Buttons		Jeffrey Pine (*Pinus jeffreyi*)
	Common Yarrow		Ponderosa Pine (*Pinus ponderosa*)
Grasses/ Grasslike	**Poa spp.**		Sugar Pine (*Pinus lambertiana*),
	Carex spp.		Incense Cedar (*Calocedrus decurrens*).
	Juncus spp.		Creek Alder (*Alnus incana*)
			Willow (*Salix spp.*)

It is important to note that a non-native plant species was observed during field data collection activities near the top of the Papoose chairlift. Tall whitetop (*Lepidium latifolium*) is an exotic plant originally from southeastern Europe and southwestern Asia and is a recognized noxious weed by the State of Nevada. Tall whitetop can crowd out native riparian vegetation in stream corridors, resulting in degraded wildlife habitat and accelerated streambank erosion (Donaldson and Johnson, 1999). Because the species was not observed in any of the drainages or primary stream channels, it is recommended that a botanist accurately identify the plant as tall whitetop and management activities be undertaken to control it quickly.

A recent (December 2001) California Natural Diversity Database (CNDDB) search in a nearby project area within the Truckee River watershed was referenced to determine the potential for the presence of special status species, including listed federal and state threatened, endangered, and candidate species. The database search resulted in previous occurrences of twelve species within the Tahoe City 7.5' quadrangle, which includes the eastern half of the Squaw Creek watershed. Special interest species identified in or adjacent to the Squaw Creek watershed include:

- Mountain yellow-legged frog (*Rana muscosa*) in and near Squaw Valley;
- Lahontan cutthroat trout (*Oncorhynchus clarki henshawi*) in Pole Creek;
- Mountain Beaver (*Aplodontia rufa californica*) in Pole, Silver, and Deer Creeks;
- California Wolverine(*Gulo gulo luteus*) in Squaw Valley;
- Munroe's Desert Mallow (*Sphaeralcea munroana*) in Squaw Valley;
- Donner Pass Buckwheat (*Eriogonum umbellatum var torreyanum*) in Squaw Valley and Silver Creek, and;
- American Manna Grass (*Glyceria grandis*) near Squaw Valley.

A number of special interest plant and wildlife species (such as those recognized by the California Department of Fish and Game and the USDA Forest Service) have the potential to occur in portions of the Squaw Creek watershed. A list of these species and their general habitat requirements, based upon several recognized references, is presented below (Zeiner et.al., 1990a, b, c; Bish and Kundert, 1993; CalFlora, 2000; DFG, 2001):

Northern goshawk *(Accipiter gentilis)*: Uses a wide variety of forest ages, structural conditions, and successional stages. Foraging habitat is the transitional zone from wetland to forest and forest to shrubland, as well as riparian zones and mosaics of forested and open areas. Uses old-growth forest stands and large, dense deciduous stands as nesting sites. Home range size is 6,000 acres, consisting of nest area, fledging area, and foraging area.

Nest area is about 30 acres in size, usually in a mature forest stand that has a multi-layered canopy with dense to open understory on north aspects in drainages with streams. Within a home range there are typically two to four alternative nest areas. Nest trees exhibit characteristics such as a crotch, fork, or several limbs on one side to support the platform nest. Post-fledgling family area is about 420 acres of a mosaic of forest types that provide hiding cover for the fledglings and habitat for abundant prey. Foraging area is about 5,400 acres of shrublands, forests, and openings with perching trees to observe prey.

California spotted owl *(Strix occidentalis occidentalis)*: Generally nest in cool, shaded areas with well-developed understory. Prefer natural cavities in large-diameter trees with broken tops and mistletoe infestations. Will use mid-successional forests to some degree for foraging.

Require stands with high canopy closure for thermal regulation and hiding cover. Intolerant of high temperatures and are stressed at temperatures above 80° to 87°F. Tend to roost in small trees in the forest understory during warm weather and high up in the large trees during cold or wet weather. Layered canopy structure in old forests provides both types of roosts.

Mule deer *(Odocoileus hemionus)*: Prefer rocky or broken terrain at elevations near or at the subalpine zone and are most likely to be found in open forested regions. Require areas of shrub or similar cover for predator escape, foraging, and rearing.

Pileated woodpecker *(Dryocopus pileatus)*: Uses late successional stages of coniferous or deciduous forest, but also younger forests that have scattered, large, dead trees. Roost cavities are in live and dead trees within a mature or old stand of coniferous or deciduous trees. Roost and nest holes are nearly all created by decay rather than excavation. Roost and nest trees are typically in old-growth stands of fir and pine that have experienced little or no logging and have >60% canopy closures.

Mallard *(Anas platyrhynchos)*: Emergent wetlands with dense cover. May remain year-round wherever food and open water are available. Uses dry sites with dense, tall vegetation, including willow, shrubs, and herbaceous vegetation.

Black bear *(Ursus americanus)*: Prefer forested and shrubby areas but use wet meadows, ridgetops, burned areas, riparian areas, and avalanche chutes. Prefer mesic over dry sites and timbered over open areas. Use dense cover for hiding and thermal protection, as well as for bedding. Build dens in tree cavities, under logs, rocks, in banks, caves, or culverts, and in shallow depressions.

Blue grouse *(Dendragapus obscurus)*: Occurs in open stands of conifer, particularly fir, near water. Prefers conifers greater than 14 inches in diameter and greater than 40% canopy cover, and dense tree foliage for roosting, but nests on ground using shrubs and logs as cover.

Willow flycatcher *(Empidonax trailii)*: Large expanses of mature, continuous willow near water source.

Lahontan cutthroat trout *(Oncorhynchus clarki henshawi)*: Cool alpine streams with a diversity of instream habitat, including riffles, pools, and at least 25% stream bank cover. Lahontan cutthroat appear to be intolerant of competition or predation by non-native salmonids, and rarely coexist with them.

Rainbow trout *(Salmo gairderi)*: Medium to large alpine streams and large lakes. Spawns in the spring.

Brook trout *(Salvelinus fontinalis)*: Small to large alpine streams and lakes, spawns in the stream in the fall.

Great Gray owl *(Strix nebulosa)*: Occurs between 4,500-7,500 feet elevations in dense, old growth red fir, mixed conifer, and lodgepole pine forests near wet meadows.

California Wolverine *(Gulo gulo luteus)*: Habitats used in the southern Sierra Nevada include medium to high elevation (6,400-10,800 feet) forest habitats of red fir, mixed conifer, and lodgepole pine near wet meadows and chaparral. Prefers low human disturbance.

Townsend's big-eared bat *(Corynorhinus townsendii)*: May use buildings, bridges, rock crevices and hollow trees or snags as roost sites. This bat forages in edge habitats along streams and areas adjacent to and within a variety of forested habitats.

Sierra Nevada red fox *(Vulpes vulpes necator)*: Red fir and lodgepole forests near meadows and similar forest openings above 7,000 feet. Rock outcrops, talus slopes, and down logs are used for den sites.

American marten *(Martes americana)*: Dense (40 to 60 percent canopy closure), uneven-aged, old growth conifer stands with understory habitat for prey (mice, voles). Martens usually den in large rotten logs and sometimes slash piles and use dense understory and log piles for denning and hiding. Martens typically avoid open areas adjacent to these forests.

Mountain yellow-legged frog *(Rana muscosa)*: Associated with streams, lakes and ponds in montane riparian, lodgepole pine, subalpine conifer, and wet meadows, mostly above 6,000 feet.

Northern leopard frog *(Rana pipiens)*: Occurs in or near quiet, permanent and semi-permanent water in with high vegetation cover and submerged and emergent aquatic vegetation cover.

Galena Creek Rock Cress *(Arabis rigidissima var. demota)*: Rocky area at the edge of aspen groves and brushy slopes.

Tahoe Draba *(Draba asterophora var. asterophora)*: Loose hillsides and slopes of decomposed granite at or above the timberline.

Cup Lake Draba *(Draba asterophora var. macrocarpa)*: North facing slopes above 9,000 feet above the timberline in coarse, decomposed granite (gruss).

Subalpine fireweed *(Epilobium howellii)*: Moist meadows and seeps in subalpine forests.

Donner Pass buckwheat (*Eriogonum umbellatum var. torreyanum*): Occurs in meadows and seeps in conifer and red fir forests in volcanic substrate.

Long-petaled Lewisia *(Lewisia longipetala)*: Grows in cracks in granitic slabs and moist gravelly volcanic soil directly below persistent snow on high elevation leeward slopes.

Sierra sedge *(Carex paucifructus*): Occurs under moist and wet conditions in streambank and meadow habitats between 4,000 and 10,000 feet in conifer and red fir forests.

American manna grass (*Glyceria grandis*): Occurs in freshwater wetlands, bogs, fens, meadows and seeps, and riparian and lake-margin habitats.

Donner Pass buckwheat (*Eriogonum umbellatum var. torreyanum*): Occurs in meadows and seeps in conifer and red fir forests in volcanic substrate.

Boggs Lake hedge-hyssop (*Gratiola heterosepala*): Occurs almost always in wetland habitats and vernal pools.

Plumas ivesia (*Ivesia sericoleuca*): Occurs in volcanic substrate in moist conditions in meadows and vernal pools in sagebrush scrub and pine forest habitats.

Stebbins phacelia (*Phacelia stebbinsii*): Occurs in meadow and seeps in foothill woodland and pine forest habitats.

Oregon fireweed (*Epilobium oreganum*): Occurs in moist and wet meadows, bogs, and fens between 4,000 and 10,000 feet in pine and red fir forests.

Marsh skullcap (*Scutellaria galericulata*): Occurs in moist meadows, seeps, and freshwater marshes between 4,000 and 7,000 feet in pine forest habitats.

Water bulrush (*Scirpus subterminalis*): Occurs in lake margin and freshwater wetland edge habitats.

Holly fern (*Polystichum lonchitis*): Occurs on granitic substrate between 6,500 and 8,500 feet in pine and red fir forests.

Shore sedge (*Carex limosa*): Occurs in wet meadows and bogs between 4,000 and 8,700 feet in pine and red fir forests.

Dissected-leaved toothwort (*Cardamine pachystigma var dissectifolia*): Occurs in rocky soil on serpentine substrate in chaparral habitat.

APPENDIX D

Database Dictionary Describing the MetaData for
the Squaw Creek Watershed Sediment Source Assessment GIS database

ArcView Grid: svdemf

Coverage description: The svdemf grid is a continuous raster grid of elevation values for the entire Squaw Creek watershed.

Coverage type: Arc/Spatial Analyst grid

Coverage extent: Greater Squaw Creek watershed region

Coverage creator: DRI

Creation date: 2/3/02

Feature type: cell

Data source: U.S. Geological Survey 7.5 minute 10 meter Digital Elevation Models

Source map units: meters

Source map scale: 1:24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: mosaicked original 7.5 minute quadangles (Tahoe City and Granite Chief) into single grid representing entire watershed; ran averaging filter over quadrangle edges to smooth tile intersections. Individual DEM quads were acquired from the USGS Tahoe Data Clearinghouse and the USGS EROS Data Center.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svdemf.vat (Grid value attribute table)

VALUE	elevation in meters
COUNT	number of cells in database with same elevation value

ArcView Image File: svdoqmosaicf.bil, svdoqmosaicf.hdr, and svdoqmosaicf.stx

Coverage description: The svdoqmosaicf.bil image file is a high resolution black and white (panchromatic) image of the entire Squaw Creek watershed area. The svdoqmosaicf.hdr file is an ascii header file required to display the rectified image in ArcView or Arc/Info.

Coverage type: Arc image file

Coverage extent: Greater Squaw Creek watershed region

Coverage creator: DRI

Creation date: 12/19/01

Feature type: image cell

Data source: U.S. Geological Survey 7.5 minute quarter quadrangle Digital Orthophotoquadrangles (DOQs).

Source map units: meters

Source map scale: 1:24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: mosaicked original 7.5 minute quarter quadangles (Tahoe City and Granite Chief) into a single image representing entire watershed using ER Mapper image processing software. Converted the resultant image back into an Arc image file format (band interleaved by line (BIL) image format, with an ascii header file (HDR)). The DOQs were obtained from the USGS Tahoe Data Clearinghouse and the Lahontan Water Quality Control Board.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

TIF Image Files: svtahoecitydrgf.tif, svtahoecitydrgf.tfw, and svgranitechiefdrgf.tif, and svgranitechiefdrgf.tfw

Coverage description: The svtahoecitydrgf.tif and svgranitechiefdrgf.tif image files are the scanned, rectified USGS topographic maps for the entire Squaw Creek study area. The svtahoecitydrgf.twf and svgranitechiefdrgf.twf header files contain the coordinate information for the image files and allow them to be displayed in ArcView and/or Arc/Info.

Coverage type: TIF image file

Coverage extent: Greater Squaw Creek watershed region

Coverage creator: USGS

Creation date: 1/15/02

Feature type: image cell

Data source: U.S. Geological Survey 7.5 minute quadrangle maps

Source map units: meters

Source map scale: 1:24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: acquired the scanned topographic maps in USGS Digital RasterGraph (DRG) format from Lahontan Water Quality Control Board.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

ArcView Shapefile Names: svsectorsf.shp, svsectorsf.dbf, svsectorsf.shx, svsectorsf.sbx, svsectorsf.sbn

Coverage description: The svsectorsf shapefile is a polygon feature shapefile of Becky Maholland's study sectors in the Squaw Creek watershed

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/18/02

Feature type: polygon

Data source: Digitized study sector boundaries developed by Becky Maholland using ArcView

Source map units: meters

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Sector boundaries selected based on topography and digitized in ArcView using scanned topographic maps and DOQs.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svsectorsf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
ID	ArcView identifier
SECTOR	Sector number
AREA_SQM	Area in square meters
AREA_SQMI	Area in square miles

Shapefile Names: ***svgeologyf.shp, svgeologyf.dbf, svgeologyf.shx, svgeologyf.sbn, svgeologyf.sbx***

Coverage description: The svgeologyf shapefile is a polygon feature shapefile of Birkland's 1961 geology map of the study area.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/30/02

Feature type: polygon

Data source: Copy of original Birkland geology map.

Source map units: meters

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Original geology map was digitized by Peregrine Environmental and UC Davis using ArcView and Arc/Info. Delivered to DRI as a shapefile suite.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svgeologyf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
AREA	Area of polygons in square meters
PERIMETER	Perimeter of polygons in meters
POLY_	Internal polygon number
ID	ArcView identifier
FORK	Squaw Creek fork associated with geological unit
AREA_KM	Area in square kilometers
GEOLOGY	Geology type Kg – Granitic rocks Qal – Alluvium

Qf – Alluvial fans
Qta – Tahoe Till
Qtae – Tahoe erratics
Qti – Tioga Till
Qtil – Late stade Tioga Till
Qtip – Ponded areas behind Tioga lateral moraines
Ta – Andesitic sequence
Tr-Jm – Metamorphic rocks

ArcView Shapefile Names: svtnfsoilsf.shp, svtnfsoilsf.dbf, svtnfsoilsf.shx

Coverage description: The svtnfsoilsf shapefile is a polygon feature shapefile of the Tahoe National Forest Level (Order) 3 soils survey data.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 2/8/02

Feature type: polygon

Data source: Digitized TNF Level 3 soils data obtained from the Tahoe National Forest regional office in Nevada City, originally in Arc/Info coverage format. Original data capture done with LT4X software, in June, 1991. The majority of USGS quads were scanned in at PSW Berkeley on an Eiconix Scanner and processed through DWRIS. Those quads were exported into LT4X in June, 1993 and edited/edgematched. The data dictionary descriptions for the TNF level 3 soils database and the TNF 1994 soils survey document (Adobe Acrobat PDF format) can be found in the following documents on the Data Product CD; **tnfsoils.doc** and **tnfsoils.pdf**.

Source map units: meters

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Original Arc/Info coverage, in export format (.e00) imported into Arc/Info, then coverted into ArcView shapefile format. Level 3 data were clipped with Squaw Creek watershed boundary.

<u>Coordinate System Description:</u>

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svtnfsoilsf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
AREA	Area of polygons in square meters
PERIMETER	Perimeter of polygons in meters
TNFSOILS_	Series number associated with soil type
TNFSOILS_I	Identification number associated with soil type
SOIL_TYPE	Map Unit Soil Name for soil type

AQB
GRG
JSG
JWF
MHG
MIE
MIG
MIG3
MKE
MKF
MKF3
MLE
MLG
RRG
RSG
STG
SUG
TAE
TAF
TBE
TBF
THF
TIE
TIG
VRG
W
WAE
WAF
WBF
WDF
WEE
WEF
WRG

ArcView Shapefile Names: statsgosoilsf.shp, statsgosoilsf.dbf, statsgosoilsf.shx, statsgosoilsf.prj

Coverage description: An Arcview polygon feature shapefile of the NRCS STATSGO level soils for the entire Truckee River watershed

Coverage type: Arcview shapefile

Coverage extent: Truckee River watershed

Coverage creator: DRI

Creation date: 2/12/01

Feature type: polygon

Data source: USDA Natural Resource Conservation Service (NRCS) State Soil Geographic (STATSGO) Data Base for California and Nevada

Source map projection: Albers Equal Area

Source map datum: NAD 27

Input/Transfer method and History: Original plans to use the high resolution (1:24,000 scale) NRCS SSURGO soils data for the study area had to be modified when it was discovered that the only SSURGO-level or SSURGO equivalent soils data set available for study area was the TNF Level 3 soils resource inventory. Although the spatial scale of the data set was more than adequate for the study (1:24,000 scale), the critical soil parameters necessary were not available in the limited attribute table associated with the Level 3 data. The only attribute parameters available from the TNF data set were map unit name, slope class, and a soil phase related to erodibility. Other parameters were available from a soil survey document file (Adobe Acrobat PDF format, 1994) obtained from the TNF, but were limited to soil profile descriptions, some soil properties (effective root depth, water capacity class, available water capacity, permeability, erosion hazard) and some soil management interpretations. DRI used the STATSGO level soils databases for California and Nevada. The two data sets were joined together, then reprojected. A soilcode unique to each soil unit was assigned to the resultant feature attribute table. Separate map unit, layer, and composition tables were extracted from the STATSGO database and linked to the feature attribute table.

The data dictionary for the STATSGO soils database can be found on the Data Product CD. It is an Adobe Acrobat PDF file called statsgo_db.pdf.

<u>Coordinate System Description:</u>

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: statsgosoilsf.dbf (ArcView Feature Attribute Table)

SHAPE Polygon
AREA Area of each soil unit polygon
PERIMETER Perimeter of each soil unit polygon
MUID A symbol that consists of the state alpha Symbol FIPS code and a three digit Arabic number. It uniquely identifies a mapunit within a state. It is the common field used to link to other STATSGO parameter tables.
IDS The three digit Arabic number representation of the mapunit
MUNAME Correlated name of the mapunit (recommended name or field name for surveys in progress).
SOILCODE Internal soil code attached to each mapunit

File: castat_comp.dbf (California STATSGO soil composition data)

See STATSGO data dictionary PDF file - statsgo_db.pdf, Appendix D.

File: castat_layer.dbf (California STATSGO soil layer data)

See STATSGO data dictionary PDF file – statsgo_db.pdf, Appendix D.

File: castat_mapunits.dbf (California STATSGO soil mapunit data)

See STATSGO data dictionary PDF file – statsgo_db.pdf, Appendix A.

File: nvstat_comp.dbf (Nevada STATSGO soil composition data)

See STATSGO data dictionary PDF file – statsgo_db.pdf, Appendix A.

File: nvstat_layer.dbf (Nevada STATSGO soil layer data)

See STATSGO data dictionary PDF file – statsgo_db.pdf, Appendix A.

File: nvstat_mapunit.dbf (Nevada STATSGO mapunit data)

See STATSGO data dictionary PDF file – statsgo_db.pdf, Appendix A.

ArcView Shapefile Names: svstreamsf.shp, svstreamsf.dbf, svstreamsf.shx, svstreamsf.sbn, svstreamsf.sbx

Coverage description: The svstreamsf shapefile is a line feature shapefile of the streams and creeks in the Squaw Creek watershed.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/30/02

Feature type: polyline

Data source: USGS Digital Linegraph (DLG) data, modified with DOQs, scanned topographic maps, and field observations.

Source map units: meters

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Original USGS DLG data were overlaid on DOQs and scanned topographic maps to verify stream locations and update and/or make corrections to the original data using ArcView. Using ArcView's hydrologic tools extension (version 1.1), the Strahler and Shreve stream orders were calculated for each stream segment.

<u>Coordinate System Description:</u>

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svstreamsf.dbf (ArcView Feature Attribute Table)

SHAPE	Polyline
ID	ArcView internal ID
SHREVE_ORD	Shreve stream order number
STRAHLER_O	Strahler stream order number
LENGTH_M	Length, in meters, of stream segments
LENGTH_FT	Length, in feet, of stream segments
FORK	Fork of Squaw Creek that the segment is found in
CHECK	Field checked by Becky Maholland
	Y
	N

ArcView Shapefile Names: svsubbasinsf.shp, svsubbasinsf.dbf, svsubbasinsf.shx

Coverage description: The svsubbasinsf shapefile is a polygon feature shapefile of the subbasins (subwatersheds) in the Squaw Creek watershed.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/12/02

Feature type: polygon

Data source: 10 meter DEM

Source map units: meters

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Mosaicked 10 meter DEM of the Squaw Creek watershed was used as input into ArcView's hydrologic tools extension (version 1.1). A flow direction grid was calculated from the DEM which was then used to derive a watershed grid with a specified minimum cell size per basin. This grid was then converted into a polygon shapefile. The result was a total of 44 subwatersheds calculated for the Squaw Creek basin.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svsubbasinsf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
ID	Sequential count of subwatersheds
GRIDCODE	Original gridcode calculated for each subwatershed
BASINID	Id assigned to each subwatershed polygon
CENTROIDX	X coordinate of each subwatershed polygon centroid
CENTROIDY	Y coordinate of each subwatershed polygon centroid
BASINAREA	Area, in square meters, of each subwatershed polygon
PERIMETER	Perimeter, in meters, of each subwatershed polygon
MFDIST	Flow length along flow path in each subwatershed
MEANELEV	Mean elevation, in meters, of each subwatershed
MEANSLOP	Mean slope, in degrees, of each subwatershed

ArcView Shapefile Names: sv_xsection.shp, sv_xsection.dbf, sv_xsection.shx

Coverage description: The sv_xsection shapefile is a line feature shapefile of the cross section sample locations in the Squaw Creek meadows.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/18/02

Feature type: polyline

Data source: Digitized from field GPS data and notes.

Source map units: feet

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Stream cross sections were established and monumented in the field during the 2001 field season. Cross section locations were then digitized using mosaicked DOQs, topographic contours derived from 10 meter digital elevation models, and GPS meadow stream attributes in ArcView.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: sv_xsection.dbf (ArcView Feature Attribute Table)

SHAPE	Polyline
ID	Internal ArcView identification number
SITE_ID	Site identification number
LENGTH_FT	Length of cross section in feet
LENGTH_M	Length of cross section in meters

ArcView Shapefile Names: svgeomorphf.shp, svgeomorphf.dbf, svgeomorphf.shx, svgeomorphf.sbn, svgeomorphf.sbx

Coverage description: The svgeomorphf shapefile is a polygon feature shapefile of the geomorphology of Squaw Creek in the lower meadow of the watershed.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/18/02

Feature type: polygon

Data source: Digitized from feature map produced during 2001 field mapping and aerial photographic analysis.

Source map units: meters

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Geomorphic feature mapping of the meadow portion of Squaw Creek was completed during the 2001 field season. Geomorphic features were then transferred and digitized from field maps using mosaicked DOQs, aerial photographs, topographic contours derived from 10 meter digital elevation models, and GPS meadow stream attributes in ArcView. Areas for each geomorphic polygon were computed from the digitized layer using ArcView.

<u>Coordinate System Description:</u>

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svgeomorphf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
ID	Internal ArcView identification number
AREA_SQM	Area, in square meters, of each geomorphological feature
SECTOR	Study sector each feature is found in
FEATURE_TY	Type of geomorphological feature
	Mid-channel bar
	Point bar
	Terrace

ArcView Shapefile Names: svstream_meadowf.shp, svstream_meadowf.dbf, svstream_meadowf.shx

Coverage description: The svstream_meadowf shapefile is a line feature shapefile of the meadow portion of Squaw Creek.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/31/02

Feature type: polyline

Data source: In-field mapping using differentially corrected Global Positioning System (GPS) input.

Source map units: feet

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Stream banks and stream thalweg in the meadow portion of Squaw Creek were mapped using a differentially corrected Global Positioning System (GPS) unit during 2001. Stream bank and thalweg features then were checked and adjusted using mosaicked DOQs in ArcView to correct reception problems encountered by the GPS unit that occurred when mapping portions of the creek under dense canopy.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svstream_meadowf.dbf (ArcView Feature Attribute Table)

SHAPE	Polyline
CATEGORY	Description of stream bank characteristics Left bank Right bank Thalweg

ArcView Shapefile Names: svsamplesitesf.shp, svsamplesitesf.dbf, svsamplesitesf.shx

Coverage description: The svsamplesites shapefile is a point feature shapefile of the sample sites Becky Maholland evaluated. They include both erosion pin and fence samples.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/30/02

Feature type: point

Data source: Digitized from data collection field notes, aerial photography and Global Positioning System (GPS) data.

Source map units: feet

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Sample data sites were established in the field during the 2001 field season. Data site locations were then digitized using mosaicked DOQs, topographic contours derived from 10 meter digital elevation models, and aerial photographs in ArcView.

<u>Coordinate System Description:</u>

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svsamplepointsf.dbf (ArcView Feature Attribute Table)

SHAPE	Point
SITE_ID	Site identification number
SECT	Study sector
GEOLOGY	Geological unit found at sample point
SLOPE_DEG	Slope, in degrees, found at sample point
METHOD	Method of sampling Erosion Pin/Fence Erosion Pin Rill Transect Silt Fence

ArcView Shapefile Names: svboundaryf.shp, svboundaryf.dbf, svboundaryf.shx, svboundaryf.prj, svboundaryf.sbx, svboundaryf.sbn

Coverage description: The svboundaryf shapefile is a polygon feature shapefile of the Squaw Creek watershed hydrographic basin.

Coverage type: Arcview shapefile

Coverage extent: Truckee River watershed

Coverage creator: DRI

Creation date: 1/12/02

Feature type: polygon

Data source: USGS DLG data modified with subsequent analysis of scanned topographic maps.

Source map units: meters

Source map scale: 1:100,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: USGS Digital Line Graph (DLG) data were modified to better fit the topography of the Squaw Creek hydrographic basin using the scanned, rectified topographic maps.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svboundaryf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
SSHD_	Basin number

ArcView Shapefile Names: svdirtroadsf.shp, svdirtroadsf.dbf, svdirtroadsf.shx, svdirtroadsf.sbx, svdirtroadsf.sbn

Coverage description: An Arcview line feature shapefile of the dirt roads in the Squaw Creek watershed.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/12/02

Feature type: line

Data source: Tahoe National Forest (TNF) roads database from 1986 USGS quads, Updated 1998; USGS DLGs at 1:100,000; updated with aerial photographs and 1998 DOQs.

Source map units: meters

Source map scale: 1:24,000; 1:100,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: The dirt roads database was derived from the original TNF data, which was updated with aerial photographs and the USGS DOQ from 1998.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svdirtroadsf.dbf (ArcView Feature Attribute Table)

SHAPE	Polyline
ID	ArcView internal identification number
LENGTH	Length of road segments
SECTOR	Study sector number
GEO_TYPE	Geology unit road segment is found in
SLOPE_DEG	Mean slope, in degrees, for road segment
LENGTH	Length of road segment, in meters
ROAD_TYPE	Type of road, based on width
	Double-track
	Single-track

ArcView Shapefile Names: svpavedroadsf.shp, svpavedroadsf.dbf, svpavedroadsf.shx, svpavedroadsf.sbx, svpavedroadsf.sbn

Coverage description: An Arcview line feature shapefile of the paved roads in the Squaw Creek watershed.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/12/02

Feature type: line

Data source: Tahoe National Forest (TNF) roads database from 1986 USGS quads, Updated 1998; USGS DLGs at 1:100,000; updated with 1998 DOQs.

Source map units: meters

Source map scale: 1:24,000; 1:100,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: The paved roads database was derived from the original TNF data, which was updated with the USGS DOQ mosaic from 1998.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svpavedroadsf.dbf (ArcView Feature Attribute Table)

SHAPE	Polyline
LENGTH	Length of road segments
GEO_TYPE	Geology unit road segment is found in
ROAD_TYPE	Type of paved road, based on width and traffic load Primary Secondary

ArcView Shapefile Names: svpaved_prime_buf.shp, svpaved_prime_buf.dbf, svpaved_prime_buf.shx

Coverage description: An Arcview polygon feature shapefile of the calculated area around primary paved roads in the Squaw Creek watershed, based on a fixed road width.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/12/02

Feature type: polygon

Data source: Paved roads database described above.

Source map units: meters

Source map scale: 1:24,000; 1:100,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Using the paved roads database described above, a buffer operation was run on the data using ArcView. The buffer distance from the road was based on an estimate of total road width (including shoulder) for the four kinds of roads classified in the basin; primary paved roads (30 ft. width), secondary paved roads (26 ft.), single-track dirt roads (20ft.), and double-track dirt roads (40 ft.). The result of the calculations are a set of polygons around all the roads in each category which represent the total area, with buffer, for the roads.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svpaved_prime_buf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
BUFFERDIS	Buffer distance, in feet, out from road centerline
AREA	Total Area, in meters, for all buffered roads
PERIMETER	Total Perimeter, in meters, for all buffered roads

ArcView Shapefile Names: svpaved_second_buf.shp, svpaved_second_buf.dbf, svpaved_second_buf.shx

Coverage description: An Arcview polygon feature shapefile of the calculated area around secondary paved roads in the Squaw Creek watershed, based on a fixed road width.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/12/02

Feature type: polygon

Data source: Paved roads database described above.

Source map units: meters

Source map scale: 1:24,000; 1:100,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Using the paved roads database described above, a buffer operation was run on the data using ArcView. The buffer distance from the road was based on an estimate of total road width (including shoulder) for the four kinds of roads classified in the basin; primary paved roads (30 ft. width), secondary paved roads (26 ft.), single-track dirt roads (20ft.), and double-track dirt roads (40 ft.). The result of the calculations are a set of polygons around all the roads in each category which represent the total area, with buffer, for the roads.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svpaved_second_buf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
BUFFERDIS	Buffer distance, in feet, out from road centerline
AREA	Total Area, in meters, for all buffered roads
PERIMETER	*Total Perimeter, in meters, for all buffered roads*

ArcView Shapefile Names: svdirt_single_buf.shp, svdirt_single_buf.dbf, svdirt_single_buf.shx

Coverage description: An Arcview polygon feature shapefile of the calculated area around single-track dirt roads in the Squaw Creek watershed, based on a fixed road width.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/12/02

Feature type: polygon

Data source: Paved roads database described above.

Source map units: meters

Source map scale: 1:24,000; 1:100,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Using the paved roads database described above, a buffer operation was run on the data using ArcView. The buffer distance from the road was based on an estimate of total road width (including shoulder) for the four kinds of roads classified in the basin; primary paved roads (30 ft. width), secondary paved roads (26 ft.), single-track dirt roads (20ft.), and double-track dirt roads (40 ft.). The result of the calculations are a set of polygons around all the roads in each category which represent the total area, with buffer, for the roads.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svdirt_single_buf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
BUFFERDIS	Buffer distance, in feet, out from road centerline
AREA	Total Area, in meters, for all buffered roads
PERIMETER	Total Perimeter, in meters, for all buffered roads

ArcView Shapefile Names: svdirt_double_buf.shp, svdirt_double_buf.dbf, svdirt_double_buf.shx

Coverage description: An Arcview polygon feature shapefile of the calculated area around double-track dirt roads in the Squaw Creek watershed, based on a fixed road width.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/12/02

Feature type: polygon

Data source: Paved roads database described above.

Source map units: meters

Source map scale: 1:24,000; 1:100,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Using the paved roads database described above, a buffer operation was run on the data using ArcView. The buffer distance from the road was based on an estimate of total road width (including shoulder) for the four kinds of roads classified in the basin; primary paved roads (30 ft. width), secondary paved roads (26 ft.), single-track dirt roads (20ft.), and double-track dirt roads (40 ft.). The result of the calculations are a set of polygons around all the roads in each category which represent the total area, with buffer, for the roads.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svdirt_double_buf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
BUFFERDIS	Buffer distance, in feet, out from road centerline
AREA	Total Area, in meters, for all buffered roads
PERIMETER	*Total Perimeter, in meters, for all buffered roads*

ArcView Shapefile Names: ***svlandusef.shp, svlandusef.dbf, svlandusef.shx, svlandusef.sbn, svlandusef.sbx***

Coverage description: An Arcview polygon feature shapefile of the land use/land cover categories in the Squaw Creek watershed.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 1/21/02

Feature type: polygon

Data source: Manual interpretation of 1998 USGS DOQ, as well as aerial photography.

Source map units: meters

Source map scale: 1:24,000; 1:100,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Sixteen land use/land cover categories were manually interpreted for the Squaw Creek watershed using the 1998 USGS DOQ. A modified Anderson level land cover classification was used, with an emphasis on land cover types that are significant in composition relative to erosion/sediment source potential.

<u>Coordinate System Description:</u>

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svlandusef.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
ID	ArcView internal identification number
LU_TYPE	Land use/land cover type Alpine meadow Bare rock Bridge Chaparral Forbs and grasses Golf course Graded ski run High density urban Landslide Low density urban Mixed conifer Mixed conifer/bare rock SEZ Transportation corridor Water Woody riparian
LU_CODE	Numerical code attached to each land use/land cover type

ArcView Shapefile Names: Landcoverf.shp, Landcoverf.dbf, Landcoverf.shx, Landcoverf.prj

Coverage description: An Arcview polygon feature shapefile of the land cover of the Truckee River watershed.

Coverage type: Arcview shapefile

Coverage extent: Truckee River watershed

Coverage creator: DRI

Creation date: 1/31/01

Feature type: polygon

Data source: The land cover database was derived from a combination of a TNF timber type data set, a UNR-Biological Resource Research Center (BRRC) vegetation database, the USFWS Gap vegetation data set, and image interpretation of a Landsat Enhanced Thematic Mapper (ETM) scene of the study area acquired in August of 1999.

Source map scale: TNF Timber type - 1:24,000, BRRC vegetation map - 1:24,000, USFWS Gap data – 1 km minimum mapping unit, 15 meter Landsat ETM satellite imagery.

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: The development of the land cover database involved the integration and merging of the TNF, BRRC, and USFWS vegetation data sets, as no one vegetation data set covered the entire study area. The Landsat satellite data were used to update burn and regrowth areas and determine accurate land cover at the intersection of the input data sets. Some of the data sets, in particular the TNF timber data, were rather old (the TNF timber type data were originally created in 1979-1980 by the Forest Service). The resultant, integrated attribute tables of land cover had to then be edited and checked for completeness and consistency with respect to land cover categories and canopy cover percentage classes.

The metadata descriptions for the TNF timber type database can be found in the veg80.rtf document on the Data Product CD. The BRRC (NPR) vegetation map metadata can be found in the nprveg and nprveg.apx files (rich text format) on the CD. Please note that the BRRC document and appendices are drafts and should be cited accordingly. The data dictionary for the California Gap data can be found at the following web site:
http://www.biogeog.ucsb.edu/projects/gap/data/meta/landcovdd.html.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: Landcoverf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
ID	Arcview grid identification number
GRIDCODE	Original gridcode id for land cover type 1 – Lodgepole; Forest 2 – White Fir, Ponderosa Pine, Mixed Forest, Forest Clearcuts (partial regrowth); Forest 3 – Red Fir, White Pine; Forest 4 – Nonwoody vegetation (meadows) 5 – Woody shrubs (sagebrush) 6 – Barren and Rocks 7 – Water bodies 8 – Plantations 9 – Bare ground and clearcut areas 10 – Urban Developed 11 – Miscellaneous hardwoods
LANDCOVER	Land cover descriptions

ArcView Shapefile Names: Canopycoverf.shp, Canopycoverf.dbf, Canopycoverf.shx, Canopycoverf.prj

Coverage description: An Arcview polygon feature shapefile of the canopy cover, by percentage, of the Truckee River watershed.

Coverage type: Arcview shapefile

Coverage extent: Truckee River watershed

Coverage creator: DRI

Creation date: 1/31/01

Feature type: polygon

Data source: The canopy cover database was derived from a combination of a TNF timber type data set, a UNR-Biological Resource Research Center (BRRC) vegetation database, the USFWS Gap vegetation data set, and image interpretation of a Landsat Enhanced Thematic Mapper (ETM) scene of the study area acquired in August of 1999

Source map scale: TNF Timber type - 1:24,000, BRRC vegetation map - 1:24,000, USFWS Gap data – 1 km minimum mapping unit, 15 meter Landsat ETM satellite imagery.

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: The development of the canopy cover database involved the integration and merging of the TNF, BRRC, and USFWS vegetation data sets, as no one vegetation data set covered the entire study area. The Landsat satellite data were used to update burn and regrowth areas and determine accurate land cover at the intersection of the input data sets. Some of the data sets, in particular the TNF timber data, were rather old (the TNF timber type data were originally created in 1979-1980 by the Forest Service). The resultant, integrated attribute tables of canopy cover percentage had to then be edited and checked for completeness and consistency with respect to land cover categories and canopy cover percentage classes.

The metadata descriptions for the TNF timber type database can be found in the veg80.rtf document on the Data Product CD. The BRRC (NPR) vegetation map metadata can be found in the nprveg and nprveg.apx files (rich text format) on the CD. Please note that the BRRC document and appendices are drafts and should be cited accordingly. The data dictionary for the California Gap data can be found at the following web site:
http://www.biogeog.ucsb.edu/projects/gap/data/meta/landcovdd.html.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: Canopycoverf.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
ID	Arcview grid identification number
GRIDCODE	Original gridcode Id for canopy cover percentage 1 – 0% 2 – less than 20% 3 – 20 to 39% 4 – 40 to 69% 5 – 70% and above 6 – variable canopy cover (mixed percent cover within the same polygon)
CANOPYCOV	Canopy cover percentage classes

ArcView Shapefile Names: svstreammigration.shp, svstreammigration.dbf, svstreammigration.shx

Coverage description: The svstreammigration shapefile is a line feature shapefile of Becky Maholland's multi-year stream migration analysis in the Squaw Creek meadow.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 5/31/02

Feature type: polyline

Data source: Historic stream meander pattern was evaluated within the meadow portion of Squaw Creek using aerial photographic analysis, digital orthophotoquads (DOQs), and a GIS.

Source map units: meters

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Aerial photographs from 1939, 1987, and 1997 were scanned as TIF files and imported into the GIS. Stream thalwegs within the meadow portion of the channel were digitized from each photo as polylines. The thalweg polylines were overlain onto mosaicked 1998 DOQs and then manually rotated, enlarged and aligned with reference features. Average stream migration was calculated by computing the average migration distances between 1939 and 2001 mapped thalwegs for sections of the creek.

<u>Coordinate System Description:</u>

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: svstreammigration.dbf (ArcView Feature Attribute Table)

SHAPE	Polyline
YEAR	Year of stream migration analysis
SINUOSITY	Stream Length divided by valley length

ArcView Shapefile Names: sv_high_erosion.shp, sv_high_erosion.dbf, sv_high_erosion.shx, sv_high_erosion.sbx, sv_high_erosion.sbn

Coverage description: The sv_high_erosion shapefile is a polygon feature shapefile of Becky Maholland's erosion hazard analysis for high erosion susceptibility areas of the Squaw Creek watershed.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 6/6/02

Feature type: polyline

Data source: 10 meter USGS DEM; field data and observations; aerial photographs, applicable parameters related sediment movement processes; and information from other studies.

Source map units: meters

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Areas of high erosion susceptibility were derived by calculating all slopes greater than 30º using the Squaw Creek 10 meter digital elevation model (DEM).. These slopes were categorized as "steep". Areas of chaparral and bare or marginally vegetated rock and soil that intersected steep slopes were designated as high susceptibility. However, granite outcrops were excluded due to the higher degree of resistance to erosion for this rock type in relation to the other dominant rock types occurring within the Squaw Creek watershed. Moderately steep slopes (15º – 30º) were next identified and categorized. Areas of chaparral, graded ski runs, and bare or marginally vegetated "very high erosion hazard" soils (as classified in the SCS/Tahoe National Forest Soil Survey, 1994) that intersected steep or moderately steep slopes and were intersected by significant road networks were categorized as having high erosion susceptibility. Lastly single and double track roads and major landslide scars were also categorized as high erosion susceptibility, regardless of slope.

<u>Coordinate System Description:</u>

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866

Datum NAD 27

Description of Database Attributes:

File: sv_high_erosion.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
ID	ArcView identifier
AREA_SQKM	Area, in square kilometers, of each high erosion susceptibility area
AREA_SQM	Area, in square meters, of each high erosion susceptibility area

ArcView Shapefile Names: sv_low_erosion.shp, sv_low_erosion.dbf, sv_low_erosion.shx, sv_low_erosion.sbx, sv_low_erosion.sbn

Coverage description: The sv_low_erosion shapefile is a polygon feature shapefile of Becky Maholland's erosion hazard analysis for low erosion susceptibility areas of the Squaw Creek watershed.

Coverage type: Arcview shapefile

Coverage extent: Squaw Creek watershed

Coverage creator: DRI

Creation date: 6/6/02

Feature type: polyline

Data source: 10 meter USGS DEM; field data and observations; aerial photographs, applicable parameters related sediment movement processes; and information from other studies.

Source map units: meters

Source map scale: 1: 24,000

Source map projection: UTM zone 10

Source map datum: NAD 27

Input/Transfer method and History: Areas of low erosion susceptibility were determined by calculating all slopes less than 20º using the Squaw Creek 10 meter DEM. These slopes were categorized as "moderate". Areas of mixed conifer and forbs and grasses land cover classifications that occurred on moderate slopes were determined to be of low erosion susceptibility. Additionally, alpine meadow and non-flowing water body land cover classifications were identified as low erosion susceptibility, since these features act as storage sites for sediment transported to them.

Coordinate System Description:

Projection	UTM
Zone	10
Units	meters
Spheroid	Clarke 1866
Datum	NAD 27

Description of Database Attributes:

File: sv_low_erosion.dbf (ArcView Feature Attribute Table)

SHAPE	Polygon
ID	ArcView identifier
AREA_SQM	Area, in square meters, of each low erosion susceptibility area
AREA_SQKM	Area, in square kilometers, of each low erosion susceptibility area

APPENDIX E

Historic Aerial Photographs Used in the Squaw Creek Study

Number in parentheses indicates number of photographs from each flight line

Date	Flight Line	Photograph Number
06/27/39	CDJ	12-39, 12-40 (2)
06/27/39	CDJ	12-36, 12-37 (2)
06/28/39	CDJ	13-20,13-53 (2)
06/28/39	CDJ	13-18, 13-19, 13-20, 13-55 (4)
08/22/55	TA	2-5, 2-6, 2-7, 2-8, 2-9, 2-10, 2-11, 2-12, 2-13 (9)
07/15/66	EQL	9-268, 9-270, 9-271 (3)
07/16/66	EQL	11-78 (1)
07/16/66	EQL	11-75, 11-76, 11-16, 11-17 (4)
07/17/66	EQL	10-115, 10-116 (2)
07/21/66	EQL	14-113 (1)
07/12/72		1472-197, 1472-199, 1472-200 (3)
08/04/72		1972-170 (1)
09/12/72		0872-153, 0872-154, 0872-155, 0872-212, 0872-214 (5)
08/31/77	USDA 615170	377-94, 377-95, 377-96 (3)
09/06/83		1582-39, 1582-40, 1582-42, 1582-43 (2), 1582-71, 1582-74, 1782-125, 1782-127, 1782-169, 1782-171 (10)
07/16/87		487-147, 487-148, 487-204 (3)
07/31/92		692-83, 692-85, 692-115, 692-116, 692-122, 692-123, 692-124, 692-155, 692-163 (9)
07/12/97		1-1, 1-2, 1-3, 1-4, 1-5, 1-6, 1-7, 1-8, 1-9, 2-1, 2-2, 2-3, 2-4, 2-5, 2-6, 2-7, 2-8, 3-1, 3-2, 3-3 (20)
08/15/97		1097-15 (1)
08/15/97		997-37, 997-38, 997-66, 997-68 (4)

APPENDIX F

Monitoring And Management Recommendations

During periods of base flow; which probably represents about 75 to 85% of the year, the sediment loads from Squaw Creek appear to be relatively low, not unlike those from watersheds like Sagehen and General creeks. However, during peak discharge and extreme events, sediment discharge from Squaw Creek may be several factors to an order of magnitude higher than Sagehen during similar events. This is interpreted to reflect excessive erosion from controllable sources within the Squaw Creek watershed that, if left unchecked could result in continued sediment problems in the watershed.

Primary considerations to developing an effective program to reduce sediment loading to Squaw Creek involving monitoring, and mitigation, and restoration. Monitoring is needed to acquire long-term sediment yield from sub-watersheds to better define load reductions from specific sources.

The following are recommendations for monitoring and management.

1. Stream and sediment discharge – the lack of sediment yield data for the Squaw Creek watershed demands more direct measurement from sediment sources. This should be accomplished by
    a. Install automatic recording stream gauges on the north fork, south fork, and main stem of Squaw Creek (outlet).
    b. Install automatic sediment sampling/monitoring equipment at the site of the three gauges mentioned above.
    c. Smaller-scale discharge and sediment monitoring from upstream and downstream of road crossing to better evaluate rates of sediment discharge from roads and roadside ditches.
    d. Hillslope monitoring of sediment movement and installation of sediment traps, such as erosion boxes on graded ski runs, selected undisturbed areas, and dirt roads (if feasible) to gain better estimate of sediment yield from sources.
2. Unpaved roads – these probably constitute the single-most detrimental factor relating to sediment discharge in the watershed. Therefore, a number of actions should be considered.
    a. Decommission a number of roads such that the density of roads throughout the watershed are similar to the Sagehen Creek reference watershed.
    b. Carefully assess drainage ditches and culverts and make improvements that will help to reduce the velocity and discharge reaching the main stem of the south fork of Squaw Creek.
    c. Plant low-canopy vegetation along the sides of roads and on roadbeds (or consider placing a thick layer of gravel on the roadbed) to stabilize shoulders and road surface.
    d. Redesign and vegetate road cuts and drainage ditches at the base of problem road cuts.

3. Instream sources – these are potential sources of sediment that contribute to Squaw Creek. The sources within the streambed largely represent sediment that is in temporary storage while in transit. However, the stream banks, which are comprised of alluvial that has filled Squaw Valley and of engineered fill in certain areas on the mountain, have the potential to provide large amounts of sediment if the stream should access the banks with greater frequency. Erosion of the stream banks is a natural process as a stream system evolves and constantly adjusts to changing water and sediment load conditions. Inadvertent modifications to the stream channel can, however, have extreme consequences on the behavior of the stream. For example, straightening the channel causes increased stream velocity that has greater erosive power; reinforcing banks with rip rap has the same effect by redirecting the flow into the outside banks of meanders, resulting in increased bank erosion. And increased sediment in the stream also provides an additional source of abrasive material to erode the bank and bed of the stream.

    a. Attempt to avoid altering the natural configuration of the stream without first consulting a qualified fluvial geomorphologist and civil engineer
    b. Avoid intentional or unintentional increases in sediment to streams without a careful assessment of consequences of increased sediment load not only on aquatic life, but also on the behavior of the stream.