Introduction

This report presents the findings of California Department of Conservation's California Geological Survey (CGS) in a reconnaissance geologic and geomorphic study of the Gualala River watershed as part of the California Resource Agency's North Coast Watershed Assessment Program (NCWAP). NCWAP is a combined effort of five state entities; Department of Forestry and Fire Protection (CDF), Department of Conservation (CGS), Department of Fish and Game (DFG), Department of Water Resources (DWR), and the North Coast Regional Water Quality Control Board (NCRWQCB) to assess watershed conditions in the northern California coastal area. Each agency contributed its expertise to the overall watershed assessment.

Gualala River watershed is a 298 square mile drainage basin located about 70 miles north of San Francisco in the southwestern portion of Mendocino County and northwestern portion of Sonoma County, Figure 1. Historically, the Gualala River watershed provided important fishery habitat for a variety of fish including the Coho salmon and steelhead trout. These species are listed as endangered. Stream surveys done in 2001 for NCWAP by DFG biologists indicate that in-stream sediment is a limiting factor for salmon recovery. Pools were undesirably shallow and spawning gravels were deleteriously embedded within fine sediment. The watershed has been listed under Section 303(d) of the Clean Water Act by the California State Water Resources Control Board as being impaired due to non-point source sediment pollution. Logging activities from 1950-1970 resulted in considerable erosion and alteration of stream conditions. The subsequent passage of the Forest Practices Rules in 1971 restricted some logging practices to reduce adverse impacts. The NCWQCB surveyed the effects of current land use in the Gualala River watershed and developed a Total Maximum Daily Load (TMDL) for sediment as required by the Clean Water Act.

Natural processes, specifically large-scale landslides and smaller, more numerous debris slides and debris flows, create a high background level of sediment yield in the Gualala River watershed. Climate driven natural events such as widespread landsliding and flooding can greatly disturb aquatic habitat by altering in-stream sediment conditions. Land use can worsen the effects of natural disturbances.

CDF's review of land use in the Gualala River watershed for NCWAP found that prior to the Forest Practices Rules, logging activities substantially damaged the watershed. Roads, landings, and skid trails were constructed in watercourses. Improperly constructed fills, abandoned crossings, and the lack of erosion control structures resulted in excessive sedimentation in the stream channels. In response to the winter rains of the late 1950's and early 1960's, sediment accumulated in many of the upper reaches–the transport reaches. Subsequently, the accumulated sediment in the active transport channels generally has been dispersed downstream, to the response reaches.

For the Gualala River watershed, CGS evaluated, compiled, and mapped landslides, geomorphic features related to landsliding, and fluvial geomorphic features related to sediment transport and storage. Mapping was done through interpretation of aerial photographs from two periods, 1984 and 1999/2000, and calibrated with limited field studies. In limited areas of special interest, older aerial photos were examined. Geologic and geomorphic maps were compiled into an Arc/Info and ArcView geographic information system (GIS) and produced as paper maps at a scale of 1:24,000 and as digital GIS files and databases.

This report describes and maps much of the background geologic and geomorphic conditions, which both 1) define the sensitivity of an area to erosion and disturbance and 2) reveal the complexity of the long-term evolution of background conditions. The new data and analysis demonstrate good spatial correlations between in-stream sediment conditions and upland landsliding. Strong spatial correlations were also found between fluvial conditions in 1984 and historic (i.e., constructed between 1950-1970) in-stream roads as mapped by CDF. Because of the lack of historic monitoring of landslide activity and stream channel sediment load rates and the lack of an undisturbed area for comparison, this study can only provide a rough estimate of sediment potential and can not definitively separate long-term natural conditions from land use impacts. A long-term monitoring program is needed to conclusively determine whether the watershed is recovering from past land uses.

While this mapping is reconnaissance, it can serve as a valuable starting point for evaluating watershed conditions and trends in stream recovery, and for locating potential long-term monitoring stations. This report and the accompanying geomorphic data document spatial and temporal characteristics of the Gualala River watershed that are critical for the development of refined sediment budget analyses. The sediment yield in the Gualala River watershed (1,000-4,000 tons/square mile/year) was estimated by four independent methods that produced similar results. The estimate is explained in detail in Appendix C.

The 1984 photos were taken soon after the record wet year of 1983. A nearby precipitation gage (DWR #F80 3161 00) at Fort Ross recorded 65.70 inches of rainfall for water-year (WY)1983, a 25-year return period event based on the gage's 126 year record (Goodridge, J., 1998). The 1999/2000 photos also followed a high precipitation year with 65.78 inches as recorded at Fort Ross, another 25-year return period event. Channel characteristics that indicate disturbance are generally more widespread in the 1984 photos than in the 1999/2000 photos. Over the entire watershed, there was a reduction during the 15-16 years of approximately 47 percent in the mapped length of channel characteristics indicative of stored channel sediment or sources of sediment. However, the extent and type of geomorphic changes during this period were highly varied. This may indicate a general trend toward recovery from past disturbances. This apparent recovery may also be a consequence of milder storm conditions between 1984 and 1999/2000. At the Fort Ross precipitation gage only water-year 1995 exceeded the long-term mean annual precipitation of 43.36 inches. Future storms may interrupt or reverse this apparent trend towards recovery.

Various fluvial geomorphic trends occur across the watershed. Review of time-series of aerial photos dating back to 1936 show degradation at the confluence of the Wheatfield and South Forks, possibly steady aggradation in the North Fork, and apparently static sediment conditions along the South and Wheatfield Forks. Some of these photos are annotated in Appendix A. Numerous channel bars indicative of excess sediment are visible in these photos that predate widespread logging in the watershed. This suggests that periodic aggradation and sediment storage in these lower reaches reflects background conditions.

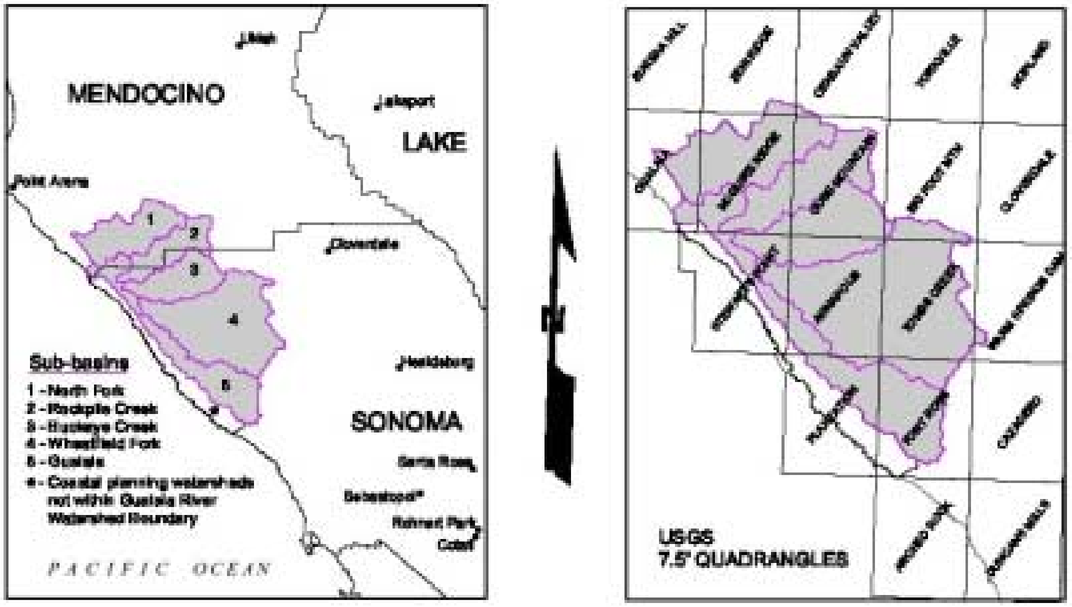


Figure 1: Index maps of Gualala River watershed showing planning watersheds and USGS 7-1/2 minute topographic quadrangle names.

Previous Work

The Little North Fork and South Forks of the Gualala River follow the San Andreas Fault. Studies of the fault commenced with investigation of the effects of the 1906 earthquake (Lawson and others, 1908). Later Brown and Wolfe (1972) mapped the 1906 fault breaks. Prentice (1989) studied the offset along the San Andreas Fault and remains involved in continuing studies. Baldwin and others (2000) described the penultimate event near Fort Ross in the southern portion of the Gualala River watershed. Students, through the Keck Geology Consortium, conducted several other studies of local paleoseismicity and crustal deformation. For example, Richardson (2000) estimated the Quaternary uplift rate of marine terraces mapped originally by Bauer (1952).

Previous geologic mapping of Higgins (1960) who described and mapped the Ohlson Ranch Formation, Wentworth (1966, 1997) who described and mapped rocks west of the San Andreas Fault, Huffman (1972), and, Huffman and Armstrong (1980) were compiled into a regional geologic map at the scale of 1:250,000 (Wagner and Bortugno, 1999). Gaudemer and others (1989) and Brown (1990) described the relationships between fault movements and offset streams in the Gualala River system. Subsurface data is very limited. Luhdorff and Scalmanini (1998) and Bailey (1996) characterized the subsurface alluvial valley of the lower North Fork of the Gualala River at Elk Prairie.

Prior landslide mapping in the Gualala River watershed did not cover the entire area. Previous landslide mapping in the watershed are as follows. Davenport (1984) and McKittrick (1995) mapped landslides and geomorphic features related to landsliding at the scale of 1:24,000 in the Gualala 7.5' quadrangle and in the North Fork Gualala River subbasin, respectively. Huffman and Armstrong (1980) mapped geology, landslides, and geologic hazards for the portion of the watershed that falls within Sonoma County at a scale of 1:62,500. The principal mapping that this report has depended on are shown in Figure 2. Other mapping efforts that focused on the coastal zone in the Gualala area were Williams and Bedrossian (1976a), Williams and Bedrossian (1976b), Williams and Bedrossian (1977) and Huffman (1972). Dwyer, Noguchi, and O'Rourke (1976) provided reconnaissance landslide mapping of Tombs Creek and Fort Ross 7.5' quadrangles at the scale of 1:24,000.

Sediment studies include: sediment source inventories of the Fuller Creek subbasin of the Wheatfield Fork of the Gualala River (Pacific Watershed Associates, 1997a, 1997b), North Coast Regional Water Quality Control Board (2001), Brown and Jackson (1974), Kleinfleder Incorporated (1998,1999), and Monschke (1998).

Figure 2: Map showing primary geologic and geomorphic references

Conceptual Background

The Coast Ranges in general and the Gualala River watershed in particular are areas of naturally high background levels of landslide activity due to high rainfall amounts coupled with the uplift that produced steep slopes, sheared weak rock, and seismic shaking. Natural disturbances such as large storms, earthquakes, and fires are triggers for episodes of widespread landsliding. Stream sedimentation trends fluctuate with the episodic recurrence of natural disturbances. Many studies show a sequence of channel change and therefore habitat transformation in response to large punctuated sediment inputs such as landsliding (Miller and Benda, 2000; Sutherland and others, 2002).

Many landslides, especially streamside landslides, directly shed (or deliver) sediment of various qualities to streams. That sediment, dependent on its characteristics, may enhance or impact stream habitat. The effects of the landslide are greatest at the point of entry to the stream and diminish downstream and with time. The local effects of a sudden landslide, such as a debris slide, in forested terrain consist of the input of a large amount of soil, rock, downed trees, and nutrients. This debris may immediately alter the stream flow, occasionally to the point of creating dams that are usually short-lived. Debris dams can inhibit fish passage, which can be critical if access to upstream habitat is lost (DeLaFuente and others, 1996).

Once the landslide debris enters a stream, the effects vary from beneficial to deleterious for fish habitat. Large wood brought (recruited) into the channel is an important habitat element. The large woody debris (LWD) and newly delivered rock can improve channel complexity, channel substrate, and pool formation (Naiman and others, 1992). However, excess volumes can lead to channel instabilities and adverse substrate changes. Landslide debris typically contains a significant, but highly variable, proportion of fine-grained (sand size or less) sediment that can, dependent on flow conditions, fill critical pools, bury and smother spawning gravels, and increase turbidity to unhealthy levels for fish. The proportion of fine-grained material in landslide deposits is primarily controlled by the underlying geologic conditions and is therefore somewhat predictable with geologic information. For example, earthflows within the mélange of the Franciscan Complex consist dominantly of a relatively fine-grained matrix with few blocks of hard rock. Consequently, earthflows will deliver primarily fine-grained sediment to streams.

When landsliding is especially widespread and abundant, as during the record setting December 1964 flood, sediment delivery may generally exceed transport across entire basins creating widespread impacts to fish habitat. The amount of time that these sediment effects persist is a function of several variables including the magnitude and composition of the sediment, storage capacity of the stream network, energy of subsequent stream flow, frequency and magnitude of subsequent disturbance(s), and others (Naiman and others, 1992). Recovery may be delayed during periods of drought such as from 1959-1962, 1976-1977, and 1987-1988. Conversely if the interval between repeated disturbances is too short, complete recovery may not occur.

United States Geological Survey (USGS) sediment gages throughout the north coast show that, annually and decadally, the vast majority of sediment is transported over a brief period of peak flows associated with flooding (Ritter and Brown, 1971). That sediment is in part what was already in the channel and in part new material from landsliding and runoff from bare slopes. After the peak flow, the river loses capacity to carry the sediment load and deposits the excess. Some of this excess sediment remains in the channel; whereas, some is stored on floodplains out of reach of lower flows in the active channel. The gage records further show that sediment transport may remain elevated for several years, diminishing rapidly from year to year as the excess sediment stored in the channel is gradually transported downstream mainly during the highest annual flows (Ritter and Brown, 1971). The excess sediment in channels form a variety of transient geomorphic features such as various bars and channel adjustments. This is part of what is referred to as recovery in this report. These stream channel (fluvial) geomorphic features are illustrated in Appendix B.

CGS mapped, at a scale of 1:24,000, landslides and fluvial geomorphic features, as well as other geomorphic features related to landsliding from aerial photos taken in 1984 and 1999/2000. That mapping has allowed for comparison of landslide activity to in-stream sediment accumulations and comparison of in-stream sediment levels between 1984 and 1999/2000. In general, sediment levels were diminished, especially in reaches with gradients greater than four percent, indicating effective downstream transport.

This likely indicates that while in-stream sediment was scoured from upstream storage and deposited somewhere downstream, basin-wide net sediment transport exceeded resupply in most of the streams.

Topography

The Gualala River drains 298 square miles along the coast of southern Mendocino and northern Sonoma Counties. The topography consists of steep slopes, moderate rolling hills, flat-topped hills, and marine terraces. Elevations range from sea level to 2,602 feet above sea level at Gube Mountain. Steep slopes are found throughout the watershed. The coastal and steeper inland areas are forested; whereas, the rolling hills are generally grassy. Drainage networks are largely fault controlled and vary from very long linear reaches (as along the Little North Fork and the South Fork) to regions of rectilinear patterns (as along Rockpile Creek) to deranged convoluted patterns (as in the eastern Wheatfield Fork)(see Figure 3). The Gualala River watershed is elongated (about 32 miles long by 20 wide) such that the entire basin is within 20 miles of the ocean. A relatively straight and continuous ridgeline separates the Gualala River from the ocean (Figure 4). The river crosses the ridge in a saddle and flows northward to its mouth at the town of Gualala. The inland boundaries of the watershed and sub-basins are dominantly defined by a disconnected series of northwest oriented groups of ridges. Based on general geomorphology, the watershed is divisible into three distinctive regions; a northern, a southern, and a western as exemplified by drainage patterns (Figure 3). A general geomorphologic description of these subdivisions is presented below.

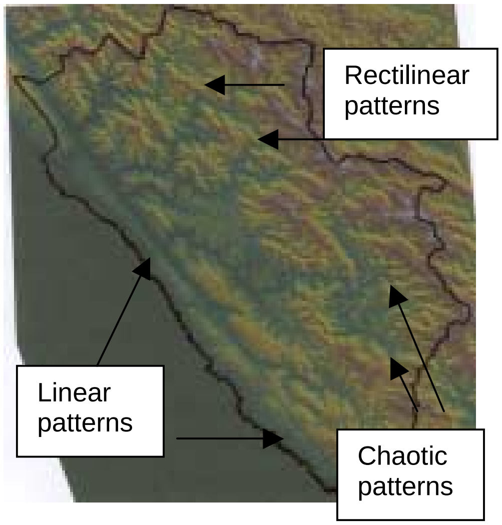


Figure 3: Triangular Integrated Network (TIN) image generated from 30-m DEM illustrates the complexity of drainage patterns in the Gualala River Watershed

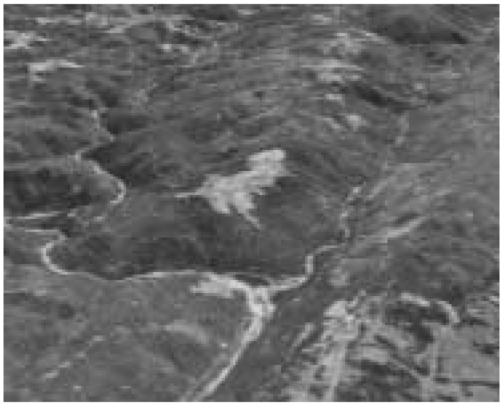


Figure 4: View southward above South Fork of the Gualala River. The informally named Gualala Ridge separates the river from the Pacific Ocean as it flows within the rift zone of the San Andreas Fault. Note the low sinuosity of the river. The confluence with the Wheatfield Fork is in foreground.

Geologic setting

The northern coast of California evolved dramatically over the last 23 million years in response to changes in the convergence of the Pacific and North American Plates (Atwater, 1989). This major plate reorganization changed coastal conditions throughout the circum-Pacific and coincided with, if not created the opportunity for, the evolution of the five species of Pacific Salmon (Montgomery, 2000). A broad, extensive system of strike-slip faults known collectively as the San Andreas Fault System formed to accommodate the crustal stresses caused by the change in plate motion. The San Andreas Fault System profoundly deformed the Coast Ranges of California.

In the Gualala River watershed, deformation probably peaked between one and a half to five million years ago and reshaped the basic landscape. During the Pleistocene (10,000- 500,000 years ago), varying rates of uplift coupled with alternating rise and fall in sea level further modified the landscape. The Gualala River and its tributaries incised into bedrock, especially along fault zones, during periods of low sea level. During prolonged periods of relatively high sea levels, waves carved terraces into the coastline and the lower valleys were likely flooded with seawater and terrestrial sediments. Remnants of that sediment are preserved as the linear terraces and flood plains. The marine terraces were subsequently uplifted to their current position above sea level.

The after effects of deformation include increased sediment yield as weakened and uplifted rocks erode and streams downcut. Erosion and susceptibility to natural disturbance is enhanced because of 1) intense rainfall, 2) continued downcutting of streams which undercuts slopes, 3) the weakness of deformed rocks, and 4) shaking during episodic earthquakes. Increased mass wasting related to uplift generally lags 2-10 million years behind uplift and deformation episodes (Burbank and Anderson, 2001 and references therein). Thus, erosion rates in the Gualala River watershed may still be elevated as a result of past deformation.

Lithology exerts an additional fundamental control over erosion rates. Significant variation in material strength occurs among the different rock types in the Gualala River watershed. Differing bedrock units were juxtaposed and deformed as fault bounded blocks during accretion onto the Pacific edge of the continent. Formation of these units and subsequent accretion occurred prior to the landscape forming processes that remain in evidence in the Gualala River watershed. The variable erosion of the different rock types results in a complex geomorphology expressed in the current landscape.

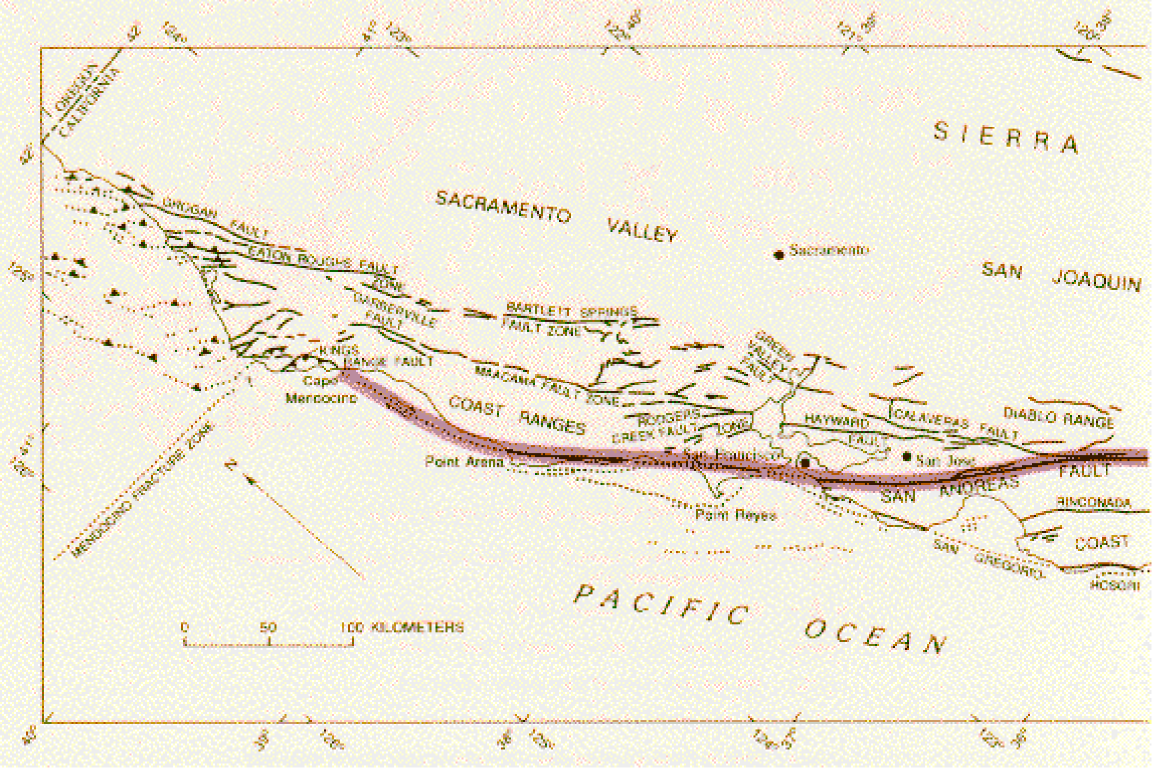


Figure 5: Map of northern San Andreas Fault System. The Gualala River watershed occupies the area between Points Arena and Reyes and between the Maacama Fault and the coast. Image from USGS Professional Paper 1515.

Deformation

The current drainage network is an artifact of deformation that occurred as 1) at least two phases or distinct episodes of uplift and subsidence beginning no later than about 5 million years ago, plus 2) regional uplift, and 3) lateral slip along the San Andreas Fault. The Gualala River watershed resides wholly in the San Andreas Fault System and is bounded on the west and east by the San Andreas and the Maacama Faults respectively (see Figure 5). The Maacama Fault lies about 25 miles east of the watershed. Both faults are active, sub-parallel, right lateral strike-slip faults. Three of the strike-slip faults are the active San Andreas Fault and the Quaternary Tombs Creek and Mount Jackson Faults (Huffman and Armstrong, 1984). Many inactive faults criss-cross the region between the San Andreas and Maacama Faults. The dominant trend of these inactive faults is sub-parallel to the San Andreas Fault. Many show a history of strike-slip movement and are considered to be a part of the San Andreas Fault System. The rocks across this entire zone are generally intensely sheared, a contributing factor in their instability.

The modern topography in the Gualala River watershed developed through a series of subsidence and uplift probably associated with the lateral faulting. The subsidence and uplift was not a simple up and down episode, but varied in different parts of the watershed. As areas subsided, other areas were uplifted. The central portion of the watershed subsided and was sub-marine as recently as 2 million years ago. Fossils in the deposits indicate deposition during the Pliocene (2-5 million years ago). The Pliocene marine sediments are now elevated up to 800 feet above sea level on ridges within a couple miles of the ocean. The gravelly, silty, and sandy Ohlson Ranch Formation was deposited into the basin and is now found capping many flat-topped ridges located throughout the Annapolis and Stewarts Point 7.5 minute quadrangles.

Similarly, much of the modern topography in the Clear Lake area formed about the same time also in probable response to the development of the San Andreas Fault System. There, more detailed studies show that during the last 2 million years, two major episodes of basin deformation occurred. The first is initiated about 1.5 million years; and the second began about 600,000 years ago (Sims, 1988 and references therein). Recent studies in New Zealand found that similar basins formed by strike-slip faulting can be developed and destroyed during plate boundary evolution on a time scale of 10,000- 1,000,000 years (Barnes and others, 2001).

Localized uplift is further recognized in the area of northern (Gube and Snook Mountains) and southern (in the area of Morhardt and Kings Ridges) portions of the watershed. These uplifted areas are parallel, similar sized blocks that appear to be structurally alike. These twinned uplifts are tentatively interpreted as compression ridge. Higgins (1960) described north trending thrust faults along Kings Ridge. Fluvial conglomerate along Kings Ridge at an elevation of approximately 1,600 feet above sea level reveals the last vestiges of a fossil river that presumably flowed from the south into the Pliocene basin. No headwaters are recognized for this river. This indicates significant subsequent uplift. Similarly, the formation of the northern compression ridge (the current watershed divide) cut-off another significant ancient river that had flowed from the northeast into the basin through the area around Flat and Bear Ridges as revealed by fluvial sediments there (Higgins, 1960). Stacked low angle faults that trend to the north are exposed in roadcuts along the northern divide.

The vertical changes to the landscape resulted in the abandonment of the older stream network that drained into the Pliocene basin. In contrast, another deformation had a more dominant lateral component. The evidence for that deformation includes 1) offset streams along the San Andreas Fault and Tombs Creek Fault and 2) right lateral offsets of the compression ridge in several places as seen in abrupt jogs in the northern watershed boundary. These vertical and horizontal changes may have resulted from either a single progressive deformation or by separate episodes of deformation.

As mentioned, the effects of episodic lateral shifts along the San Andreas Fault System are preserved in the modern stream network as abrupt realignments of parts of the stream network. Prentice (1989) and Gaudemer et. al. (1989) described the complex response of the stream channels to lateral shifts along the San Andreas Fault. The South Fork and Little North Fork of the Gualala River flow (as does the South Fork of the Garcia River to the north) within a continuous linear valley that marks the trace of the San Andreas Fault. Older literature refers to the valley as the San Andreas Rift Zone. Prentice proposed that the Gualala River once drained through the mouth of the Garcia River to the north, i.e. the Gualala and Garcia River systems originated as one but subdivided due to multiple episodes of stream piracy and capture. If so, the present geometry of the drainages in relationship with the San Andreas Fault zone indicates at least 8 miles of stream diversion (Figure 6). Across the divide in the Navarro River and Rancheria Creek watersheds, Manson (pers. comm. 2000) described similar repeated cycles of stream capture and beheading.

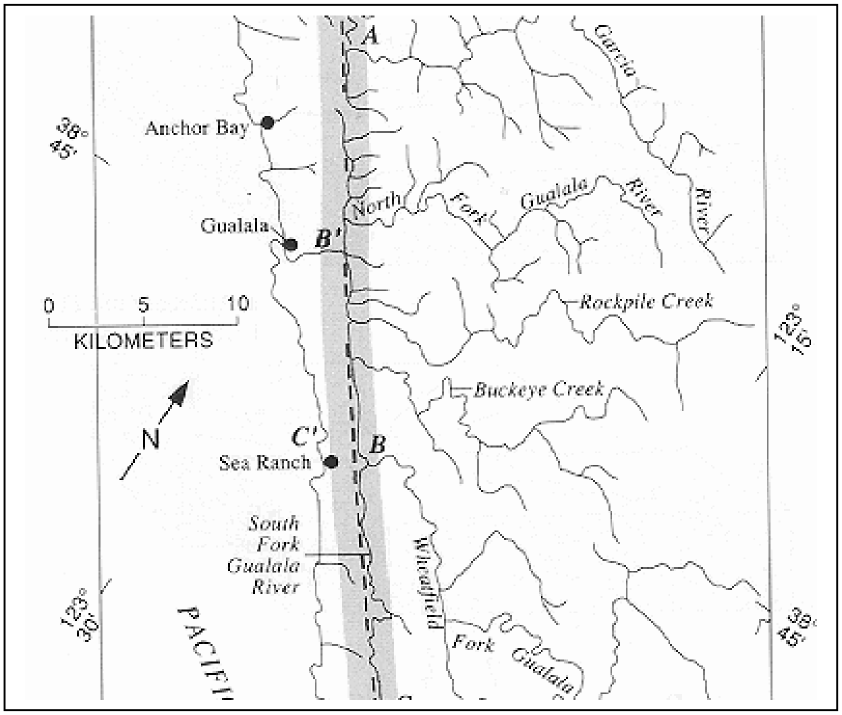


Figure 6: Sketch map of major tributaries of the Gualala watershed and the San Andreas Fault. Drainages were diverted right-laterally on the fault (dashed and solid line). Possible offsets of 8.4 miles are indicated for the Garcia River (A-A'), the Wheatfield Fork of the Gualala River (B-B'), and the South Fork of the Gualala River (C-C'). Figure from USGS Professional Paper 1515.

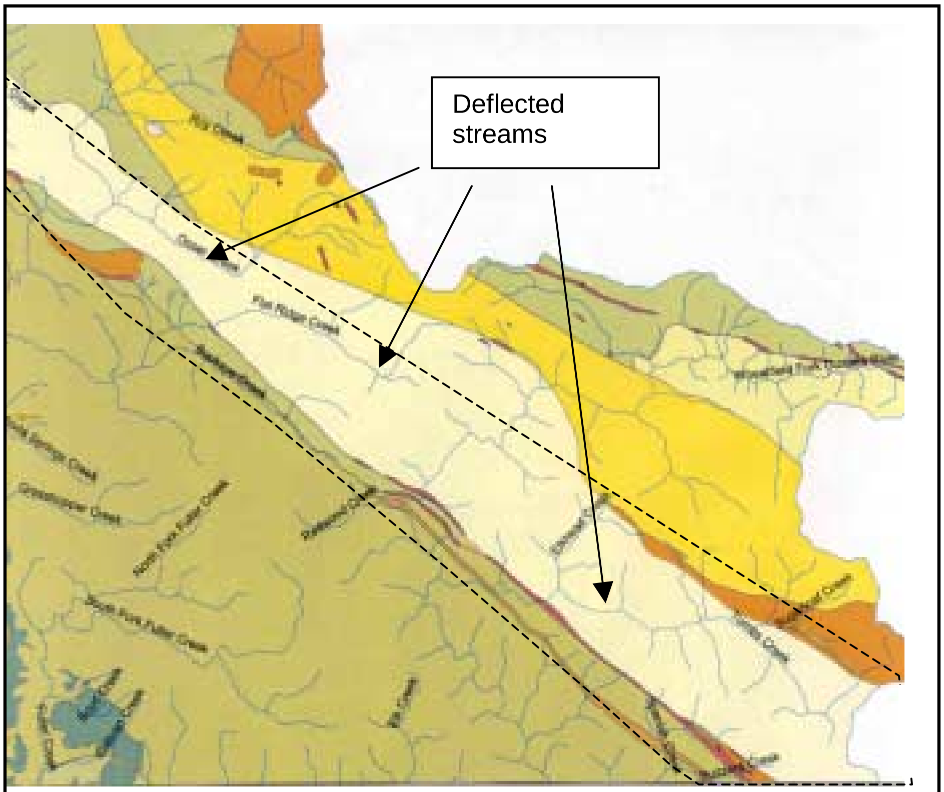


Figure 7: Detail geologic map showing stream deflection along the Tombs Creek Fault zone shown as dashed lines.

Latest significant ground movements in the vicinity occurred along the San Andreas Fault in 1906 with the San Francisco Earthquake. Near Fort Ross, ground was displaced right laterally up to 12 feet and uplifted three feet. Along the South Fork of the Gualala River, numerous landslides occurred and entered the river (Lawson, 1908). The Maacama Fault is actively creeping and has generated many low magnitude earthquakes. The area around the Clear Lake volcanic field, less than 40 miles east of the Gualala River basin, is also seismically active.

Significance of Sea Level Changes

Sea level fluctuated in response to global climatic changes. Sea level changes during the Pleistocene occurred in response to a series of glaciations (ice ages) and interglacials. Prodigious volumes of seawater were locked in glaciers at times in the past; thus lowering the sea level. Approximately 15,000 years ago, during the latest marine low stand (known as the Wisconsin Glaciation) sea level had fallen as much as 390 feet (120m) (Grove and Niemi, 1999). The rivers incised in response to falling sea level. During interglacials, sea levels rose and at times were higher than present.

The sea level rise, beginning 125,000 years ago, probably flooded the river valleys that gradually filled with sediment and created a distribution of alluvium similar to current conditions along the North Fork Gualala River, Rockpile Creek and Buckeye Creek. However, it is likely that most of the older deposits were removed during Wisconsin aged incision. The valley fill present in the deeply incised valleys likely represents mainly the latest rise of sea level.

The well logs at Elk Prairie and adjacent to the estuary both show considerable history of clay deposition indicative of low energy environments, possibly estuarine, which may have extended from the ocean to at least Elk Prairie. Based on this assumption, the estuary may have migrated back and forth from at least Elk Prairie to somewhat off the modern shoreline depending on the interplay of sea level rise and tectonic uplift. Subsurface well logs are not available for the South Fork. However, the estuary may have extended upstream on the South Fork as well as the North Fork.

The valley of the mainstem is the only watergap across the otherwise continuous ridge that separates the watershed from the ocean. Flow through the mainstem was probably established during the low stand of the Wisconsin Glaciation. One well located about 100 feet south of and 20 feet higher than the mainstem was drilled to 50 feet in depth and revealed brown, black, and blue clay throughout the length of the boring. Bedrock was not encountered.

Subsurface information at Elk Prairie (about one mile upstream) at the mouth of the North Fork reveals that the alluvial filled paleo-valley there is nearly 200 feet deep (Luhdorff and Scalmanini, 1998 and Bailey Scientific, 1996). This depth corresponds to the elevation of a submerged marine terrace just off shore (Bauer, 1952), which probably defined base level at the time of paleo-valley development. The alluvium was probably deposited over the last 15,000 years somewhat synchronously with sea level rise. The borings show the alluvium as alternating layers of blue clay, gravel, and brown silt indicating dramatic changes in transport energy for the North Fork of the Gualala River. The blue clay may represent estuary deposits. If so, that may indicate that at times sea level rise outpaced aggradation. Alternately, the fill may represent alternating flood deposits.

The main stem cross-cuts the series of Pleistocene marine terraces. The marine terraces record one stage of late-Pliocene to early Quaternary uplift with considerable local deformation and at least three stages of regional uplift during the Quaternary. Localized folding that occurred until the mid-Quaternary is evident in those terraces (Wentworth, 1966).

The marine terraces record of crustal deformation is as follows:

> Late Pliocene-Early Quaternary (500,000- 5,000,000 years old)- uplift and topographic inversion of a Pliocene basin in which Ohlson Ranch Formation accumulated. This forms flat-topped ridges throughout central basin.
>
> Older Quaternary (500,000 years old) - regional uplift along the San Andreas Fault with local vertical deformation elevated marine terraces to over 600 feet above current sea level (Richardson, 2000).
>
> Subsequently or concurrently, those strata were folded or faulted such that terraces north of the mainstem are 200 feet higher than presumably equivalent terraces on the south side. Folds may correlate across the San Andreas Fault with uplifted and subsided areas. An anticline, north of the main stem, predates an older Quaternary terrace that cuts across both the fold core (Anchor Bay Formation) and carapace (German Rancho Formation); however, continued folding may have occurred (Davenport, 1984). The west face of the anticline north of the river is deeply incised with close-spaced gulches while the east face is steeper and has fewer drainages that are not incised. This anomalous pattern may indicate additional fold growth since emergence.
>
> Younger Quaternary (83,000-100,000 years old) – regional uplift elevated the lowest emerged marine terrace 130 feet above current sea level without additional local vertical deformation; fold growth had ceased. At Fort Ross, slip along the San Andreas Fault since the formation of this terrace has been estimated at 0.9 miles (Prentice and others, 2000).
>
> Late Quaternary and early Holocene (about 20,000-10,000 years ago)-sea level dropped during the last global ice age. Bauer (1952) reported that a possible wave-cut terrace lies offshore about 200 feet below current sea level and its elevation is approximately the same as the estimated depth of the paleo-valley of the Russian River, just south of the Gualala River watershed. This is consistent with the depth of the paleo-valley of the North Fork of the Gualala River, as described above. It is undetermined how much uplift has occurred since the formation of the terrace.

Rock Formations

The geologic map illustrates many geologic units within the Gualala River Watershed (see Plate 1 of the Gualala River Watershed Assessment Report showing Geologic and Geomorphic Features Related to Landsliding: Gualala River Watershed). The vast majority of the Gualala River watershed is underlain by the Franciscan Complex. Blake and others (1984, 1989) subdivided the Franciscan Complex, in the Gualala River watershed, into five fault-bounded terranes; Rio Nido, Pickett Peak, Yolla Bolly, Coastal, and Central (Figure 8). In general, the terranes of the Franciscan Complex have been variably fractured, faulted and folded by tectonic processes associated with regional uplifting and transpression. The rocks were formed in the accretionary prism that developed within the subduction zone between North American and Pacific Plates during the Mesozoic. The terranes were accreted to the leading edge of the North American Plate prior to the deposition of the overlying Pliocene Ohlson Ranch Formation. These tectonic processes have weakened the Franciscan Complex, contributing to landsliding and debris flows. The Franciscan Complex and the Ohlson Ranch Formation are the most important geologic units in regard to landsliding in the Gualala River watershed. Their lithology and relative slope stability are described below. The mapping and descriptions of the rock types are derived from literature review, regional in nature, and may not accurately represent conditions within local areas of the Gualala River watershed.

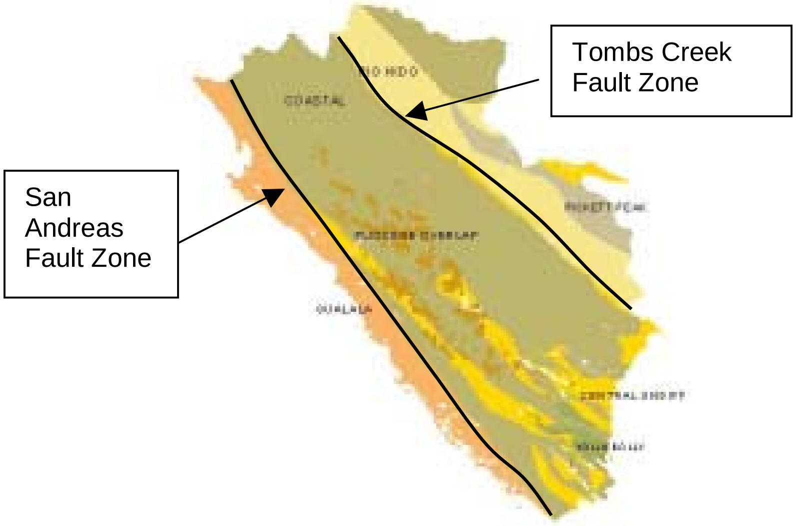


Figure 8: Generalized Terrane Map of Gualala Watershed based on Blake and others, 1984 and Blake and others, 1989.

Rio Nido Terrane

The late Cretaceous-aged Rio Nido terrane of the Franciscan Complex (TKfs) extends in a Northwest orientated belt along the west side of the Tombs Creek Fault Zone (Huffman and Armstrong, 1980, and Blake, Howell and Jayko, 1984). Regionally, this terrane generally consists of massively bedded, medium-grained, graywacke with interbedded siltstone, shale and conglomerate. In areas, the rock consists of severely sheared clayey gouge. Much of this terrane is locally fractured, with the tectonic deformation obscuring the original structure. The sandstone is fine to medium grained, dark gray where fresh, light brown where weathered, and moderately hard to hard. Bedding, where present, is up to five feet thick and the fracture spacing was closely to very closely-spaced. In general, the Rio Nido terrane has been variably fractured, faulted and folded by tectonic processes associated regional uplifting and transpression (Haydon, 2002, pers. comm.; Ellen and Wentworth, 1995; Blake and others, 1984, Blake and others, 1989). Many active earthflows are found in association with this formation in Gualala River watershed consistent with the presence of severely sheared clayey gouge.

Pickett Peak Terrane

The early Cretaceous-aged Pickett Peak terrane (KJfm, KJfss) of the Franciscan Complex forms a belt adjacent to and in some places across the Rio Nido terrane. The Pickett Peak terrane underlies the area northeast of the Tombs Creek Fault Zone. The Pickett Peak terrane consists of a melange of clayey gouge with severely sheared blocks and small shattered masses of metamorphic semischistose meta-graywacke, meta-shale, and meta greenstone. Blocks have a diameter of >100-feet and the shattered masses are as much as 0.1 to 0.2 miles in length, and together constitute about half of the units mass. Gouge and the severely sheared masses are firm to soft, lack bedding and are very closely fractured. Blocks are typically hard, have moderate to widely spaced fractures, bedding is thick to thin in the meta-graywacke (Haydon, 2002, pers. comm.; Ellen and Wentworth, 1995; Blake and others, 1984, Blake and others, 1989). Many large active earthflow complexes are found in association with this formation in Gualala River watershed.

Coastal Terrane

Late Jurassic to early Cretaceous aged Coastal terrane of the Franciscan Complex (KJFs, Kfgs) underlies the vast majority of the Gualala River watershed. The unit predominantly consists of graywacke type sandstone and shale with minor greenstone, conglomerate, chert and limestone (Blake and others, 1971; Huffman and Armstrong, 1980; Wagner and Bortugno, 1982; Ellen, and Wentworth, 1995). The sandstone is generally massive to locally thin-bedded. Much of this unit is not sheared; whereas, other portions are severely sheared and may contain hard blocks. Fresh sandstone is hard, but weathered portions are firm to hard. This formation forms steep slopes throughout the McGuire Ridge quadrangle and on Oak Ridge and Fuller Mountain in the Annapolis quadrangle. However, the topography is more subdued in the southern areas of occurrence. Where steep, debris slides and debris flows are common. Large dormant translational/rotational rockslides are also common.

Central Terrane

The late Jurassic to early Cretaceous aged Central terrane of the Franciscan Complex (Huffman and Armstrong, 1980) interfingers with the Coastal terrane in the southern portions of the watershed. The Central terrane consists largely of a melange of variably abundant hard, resistant blocks and small shattered masses of chert, “high grade” metamorphic rocks, sandstone, greenstone, metagreenstone and serpentinite suspended in sheared shale and sandstone gouge matrix. Discrete blocks range in size from less than one foot to greater than 5 miles. This sandstone is medium-grained, moderately to thickly bedded, moderately hard and strong, gray where fresh and light brown where weathered (Haydon, 2002, pers. Comm.; Ellen and Wentworth, 1995; Blake and others, 1984, Blake and others, 1989). Many active earthflows are found in association with this formation in Gualala River watershed. This strong relationship is further discussed and illustrated below in the Mass Wasting History section.

Yolla Bolly Terrane

The late Jurassic to early Cretaceous aged Yolla Bolly terrane of the Franciscan Complex interfingers with the Central terrane in the southern part of the Gualala River watershed. The Yolla Bolly terrane consists variably of quartzofeldspathic metagraywacke, argillite, radiolarian chert, and minor greenstone. Blocks of blueschist and amphibolite, together with serpentinite are scarce. The rocks have been severely sheared through multiple deformations (Blake and others, 1989). Historically active earthflows are common.

Ohlson Ranch Formation

The Pliocene Ohlson Ranch Formation caps flat to slightly undulating ridge tops found extensively throughout the Annapolis and Stewarts Point 7.5’ quadrangles. This geologic unit consists mostly of poorly consolidated marine sandstone, with small exposures of conglomerate. The Ohlson Ranch Formation is deeply weathered, fossiliferous, and generally soft, and the sandstones are very fine-grained. The sediments were deposited on marine terrace surfaces that later were uplifted by regional tectonic forces. This unit is generally less than 100 feet thick. Limited fieldwork and map relations suggest that failures occur primarily where slopes steepened along stream channels and at the edges of the flat-topped ridges. This relationship is further discussed and illustrated below in the Mass Wasting History section. Failures occur primarily as small discrete slumps, rotational slides, and earthflows.

The following rock types occur on the west side of the San Andreas Fault. The descriptions are excerpts from Huffman, 1972, Geology for Planning on the Sonoma County coast between the Russian and Gualala Rivers: The California Division of Mines and Geology Preliminary Report 16. The descriptions are modifications of Wentworth 1966 and 1972.

“Spilite (spilitic basalt) near Black Point (Ksb)

Spilitic basalt is exposed in the core of an anticline north of Black Point in The Sea Ranch, where it is in fault contact with the Upper Cretaceous “strata of Stewarts Point”. Structurally it underlies the sedimentary rocks and, for this and other reasons, is presumed to be the basement of the section. In the study area, it is within the San Andreas Fault zone. Exposures are poor but apparently are complexly faulted.

Strata of Stewarts Point (Ks)

The rocks are massive marine sandstone and conglomerate, inter-bedded sandstone, and mudstone, and thinly to thickly interbedded sandstone and mudstone. Sparse microfossils and stratigraphic relationships indicate they are of Upper Cretaceous age. Porosity is very low.

The rocks have an exposed thickness of 4400 feet on the south limb of the anticline in The Sea Ranch. They interfinger with or are overlain conformably by the “strata of Anchor Bay”.

Strata of Anchor Bay (KA)

These are thin to thick interbeds of marine sandstone and mudstone, interspersed with massive sandstone and conglomerate. Mega fossils indicate they are of Upper Cretaceous age. Porosity is very low. Thickness of the unit is 2500 – 3300 feet in the limbs of the anticline in The Sea Ranch. The rocks interfinger with and overlie the “strata of Stewarts Point” and are overlain conformably by the “strata of German Rancho”.

Strata of German Rancho (TG)

These rocks consist of massive marine sandstone, conglomerate and thin to thick interbeds of sandstone and mudstone. Sparse fossils indicate their age’s range from Paleocene to middle Eocene. Some sandstone beds have significant porosity. An incomplete, faulted section north of Fort Ross is 20,000 feet thick. The unit is overlain concordantly by basalt of Miocene age north of the study area. Strata on intervening Oligocene and Upper Eocene age are absent, although no erosional unconformity is evident.

Undifferentiated Strata of German Rancho, Anchor Bay and Stewarts Point (Tku)

These strata are within the San Andreas Fault zone and probably have been disrupted by faults associated with the San Andreas (see Geologic Structure).

Gallaway Formation (?) (Tsm)

These rocks, tentatively assigned to the Gallaway Formation, are interbedded marine mudstone and sandstone with some orange-weathering concretions, glauconitic sandstone, and black fissile, clayey siltstone. Microfossils indicate a Miocene age. The Fort Ross section is in fault contact with adjacent units.

Tertiary Basalt (Tb)

These rocks occur as two low, weathered knobs that rise above terrace deposits overlying the Gallaway Formation (?). Contacts with adjacent bedrock are not exposed. Blocks of the basalt occur also in a shear zone north of Fort Ross Reef. "

Quaternary Units

Unconsolidated Quaternary deposits overlie the bedrock units, particularly along the lower Gualala River. Fluvial and marine deposits are included in the geologic base map and defined below. However, mass wasting features mapped for this program are described in the following section, "Landslide Types and Associated Geomorphic Features". Quaternary units are generally mapped primarily on the basis of geomorphic relationships. Units mapped in the Gualala River watershed and depicted on Plate 1 are shown in Table 1.

Name	**Description**
af	Artificial Fill
Qal	(Holocene) Undifferentiated alluvial deposits of unconsolidated sand and silty sand with lesser clay, cobbles and boulders; may include/interfinger with colluvial deposits along the base of adjacent slopes.
Qsc	(Holocene) Active stream channels (undifferentiated) .
1-4	Number indicates relative age and transport of deposit associated with flood stage when known: - 1 youngest and most mobile (5 years or younger, bankfull movement) - 2 estimated stage/return period of 5-20 years - 3 estimated stage/return period of 20-50 years - 4 estimated stage/return period between 50-100 years; includes flood plain deposition
Qf	(Holocene) Alluvial Fans: Characteristic fan-cone shapes at the mouths of eroding stream canyons; includes debris fans.
Qoal	(Early Holocene to Pleistocene) Older Alluvium: Unconsolidated sand and silty sand with lesser clays, cobbles and boulders, commonly forming terraces above and outside the 100-year flood plain (if known). Vegetation is characteristically well-established.
Qrt	(Holocene-Pleistocene) River Terraces: Flat-lying to gently-inclined platforms typically overlain by alluvium deposited during higher stands of major streams and rivers; elevated above flood level stage, not likely to be inundated by major storm events; typically contains some level of soil profile development.
Qc	(Holocene-Pleistocene) Colluvium, talus and slope wash deposits.
Qbs	(Holocene) Beach Sand: Marine-laid deposits of well-sorted fine-coarse grained sands and gravels; may migrate seasonally.
Qds	(Holocene) Dune Sands: Unconsolidated, loose to medium dense, medium- to fined-grained well-sorted sands subaerially deposited adjacent to coast. Bare to grassy vegetation, often dependent on distance from coastline.
Qods	(Holocene-Pleistocene) Older Dune Sands: Unconsolidated, medium dense to very dense, medium- to fine-grained well-sorted sands subaerially deposited adjacent to coast. Vegetation is typically well-established (brush and/or trees), and the deposits may contain varying degrees of oxidation and/or cementation, and immature soil profile development.
Qmt	(Holocene-Pleistocene) Marine Terrace Deposits: Clast-supported deposits of relatively uniform grain size overlying wave-cut benches. The degree of consolidation, amount of soil profile development and elevation of the unit above sea level increases with age of the deposit.
Qe	(Holocene-Pleistocene) Estuarine deposits: undifferentiated
Ql	(Holocene-Pleistocene) Lacustrine deposits: undifferentiated.

Table 1: Quaternary units

Geomorphic subdivisions

As discussed above, the watershed is divisible into three distinctive geomorphic subdivisions; a northern, a southern, and a western (Figure 9). Profound differences in 1) drainage patterns, 2) steepness, and 3) overall orientation of the ridges and streams make these subdivisions distinct. These younger (Paleogene-Recent) subdivisions differ from the older (Late Mesozoic) terranes of Blake and others, 1984.

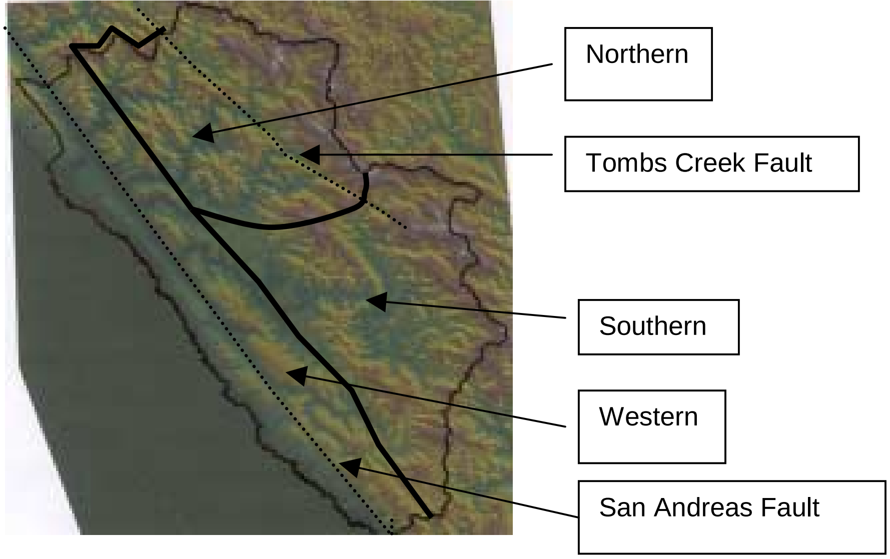


Figure 9: Map showing geomorphic subdivisions. Boundary locations are not rigidly defined and may be more diffuse than illustrated. For example, the western edge of the Northern subdivision is overprinted by the younger topography related to the San Andreas Fault.

Northern subdivision

The northern region is distinct because it is 1) occupied by rectilinear drainages such as Rockpile Creek and the North Fork of the Gualala River, 2) is underlain with the Coastal Terrane of the Franciscan Formation, and 3) contains the steepest slopes in the watershed. The geologic history and these immature geomorphic conditions imply that this subdivision was uplifted above sea level more recently than the remainder of the watershed. In addition to recent uplift, the western portion of this area has subsided creating a low region at the confluence of Rockpile Creek and the North Fork. The drainage networks of the Little North Fork, Robinson Creek, the North Fork, Rockpile Creek, and Buckeye Creek all in a general sense drain radially toward a common low region (Figure 10). A series of NW trending strike-slip faults have offset drainages in a uniform manner forming “twinned” drainage networks in the Rockpile Creek and North Fork Gualala River sub-basins. Tributaries join trunk streams orthogonally producing a zig-zag pattern with a strong NNW orientated fabric. Secondary tributaries that flow westward across the regional NNW grain are far more numerous and longer than those that flow eastward across the grain, indicating westward tilting.

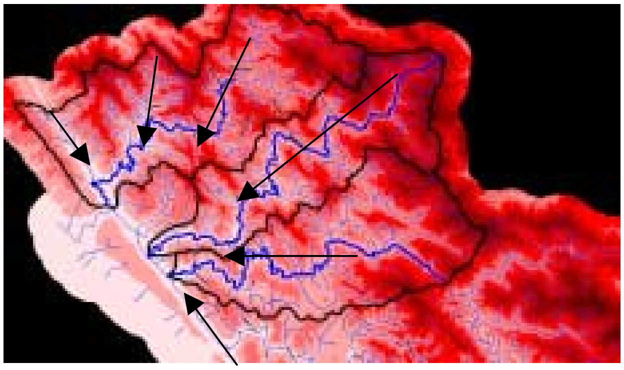


Figure 10: Digital elevation model showing the general radial drainage pattern. From a 11:00 position moving clockwise, the major drainages are the Little North Fork, Stewart Creek, North Fork, RockPile Creek, and Buckeye Creeks.

The formation in this region, although broken (tectonically crushed but not significantly sheared), forms steep slopes and is relatively more stable and coherent (bedding is recognizable) than it is in the rest of the watershed. However, slopes failures are common and occur dominantly as debris slides and flows (Figure 11).

Figure 11: Photo series of a debris flow in the McGuire Ridge Quadrangle. From left to right, photos show the debris flow across the river, a close-up of the torrent track, and its deposit along the riverside road. Note the truck for scale. Photos by Mike Fuller and Wayne Haydon.

Southern subdivision

The southern subdivision has experienced the most complex history of deformation and drainage. This subdivision extends almost from the Gube Mountain area southward to Fort Ross and comprises most of the watershed. The youngest consolidated geologic formation in this subdivision is the Ohlson Ranch Formation. The relatively young marine sediments of this formation are poorly consolidated sands, silts, and gravels that tend to slump or flow when saturated on slopes such as those near the contact with the underlying Franciscan Formation. In the southern subdivision, the Central Terrane Franciscan generally flanks the Coastal Terrane, except in the Fort Ross quadrangle where complex faulting has shuffled both terranes. The Central Terrane is largely a tectonic mélange (tectonically crushed and highly sheared rock) of generally resistant hard blocks in a weak fine-grained matrix and forms slopes mantled with creeping colluvium and deeper earthflows. Many deep-seated rockslides also occur; some appear to be intermittently active. The blocks consist of serpentinite, metacehert, and metavolcanic rock. Serpentinite, however, is especially prone to deep-seated and shallow failure. Hard metavolcanic blocks form bold outcrops that dot the landscape. The topography is rounded and grasslands are common. Figure 12 is a photograph taken from Oak Mountain showing the characteristic topography of the Southern subdivision.

Figure 12: Photo from Oak Mountain showing typical topography of the Southern subdivision. Note hummocky slopes, gullies, and earthflows.

Along the Wheatfield Fork of the Gualala River, large horizontal movements on NW-WNW strike-slip faults stretched out many of the streams along the faults even to the point of detachment from their headwaters in a process generally illustrated in Figure 13. Abandoned headwaters were blocked until finding favorable passage (typically an abandoned trunk stream) around obstacles. Slip along the strike-slip faults caused the west side to move relatively northward.

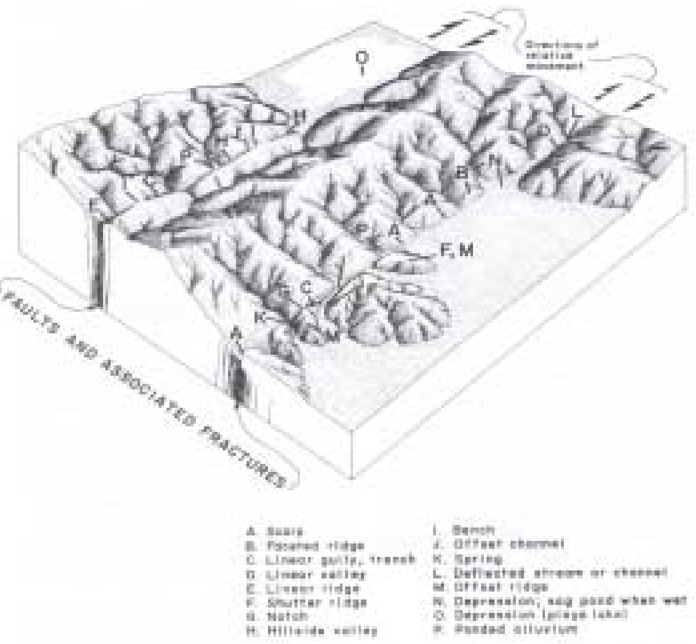


Figure 13: Schematic diagram illustrating the origin of various tectonic geomorphic features typical of the region.

For example, drainage diverts southward along the east side of Oak Mountain. On the west face of Oak Mountain is the upper Fuller Creek watershed. The main forks of Fuller Creek developed over terrain that is probably ancient landslide deposits. The northwestward translation or uplift along the Tombs Creek Fault Zone and ancillary faults likely placed Oak Ridge in its current position that appears to block drainage from the east (Figure 14).

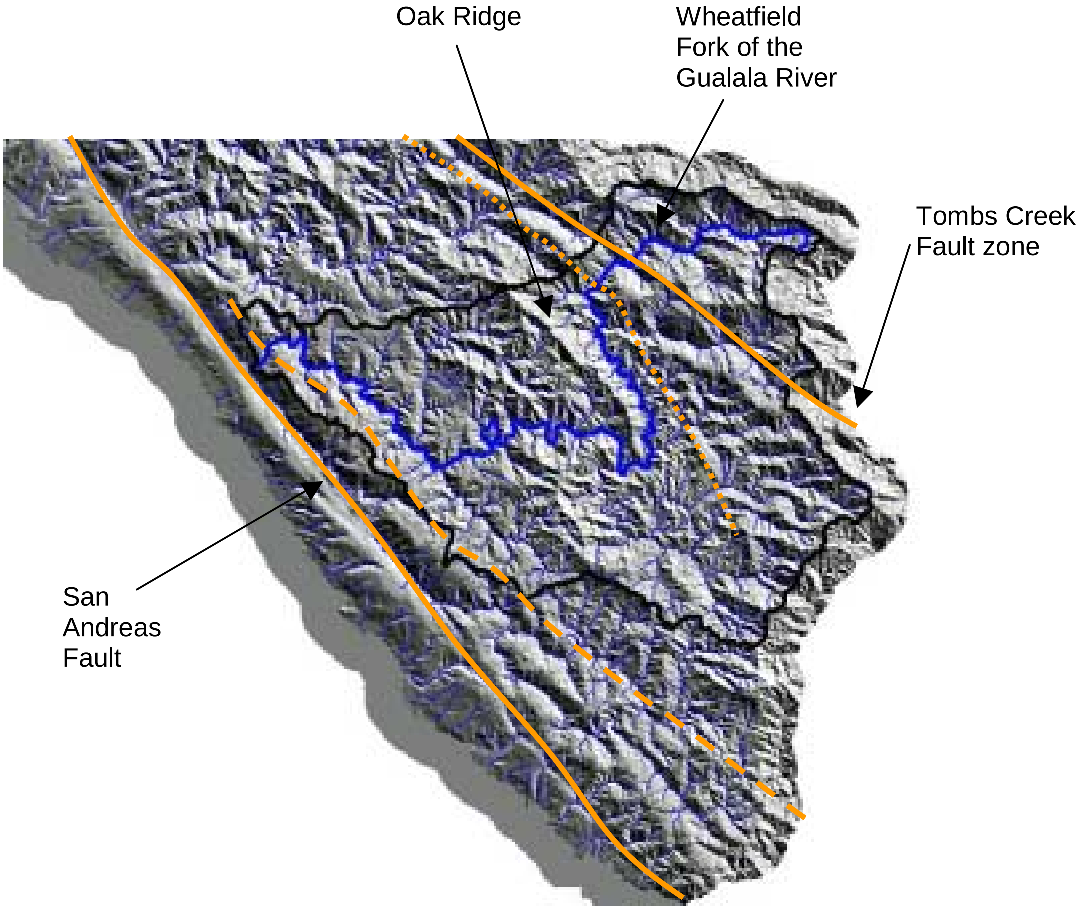


Figure 14: Diversions of the Wheatfield Fork. Parallel ridges probably translated northward along parallel, dextral -slip faults (orange) appear to control drainage. The ridges shunt drainage along their NW trending, east facing range fronts. Flow is generally westward from right to left.

In several areas, streams that cross strike-slip faults follow abrupt deflections along the fault zone. This may indicate co-development of stream and fault. Osser and Flat Ridge Creeks are two examples. The amount of stream deflection across a fault is related to many factors including channel age relative to fault activity. Generally, diverted streams that existed prior to faulting will show the greatest offset and the youngest streams the least offset. Some profound age differences are evident in the Wheatfield Fork sub-basin and record a complex chronology of deformation and fluvial response. Probably as a result of multiple deformations, the complicated drainage pattern in this region developed highly disordered networks.

Western subdivision

In the western subdivision, the drainage network is dominated by the San Andreas Fault. Stream beheading, capture, and blockage by ridges are common and were a focus of a study by Prentice (1989). She concluded that through those processes an earlier single drainage system transformed into both the modern Gualala and Garcia Rivers. While migrating northwesterly, the informally named Gualala Ridge in the German Rancho progressively blocked the drainage of the South Fork of the Gualala River, then the Wheatfield Fork of the Gualala River; such that the river now flows northward along the fault until reaching an outlet at the town of Gualala (refer back to Figure 14). Within the San Andreas Fault Zone, the divide between the Little North Fork Gualala River and South Fork Garcia River is a gentle 350-foot rise, largely composed of coalesced landslides (Plate 1 of Gualala Basin Assessment Report). However, the divide is dominantly defined by the more broadly elevated surrounding area.

In general, the valley walls along the San Andreas Fault are moderate to steep, benched and show a complex history of seismic deformation and abundant landsliding. Different rock units occur on either side of the fault with the Coastal Terrane Franciscan on the east and the German Rancho and Gualala Formations on the west. Moderate to large relic landslides are abundant and small active landslides are common on both sides of the valley. In several areas, numerous landslide and fault features overlap into a dense pattern that complicates interpretation regarding their generation. Debris slides and debris flows are especially common near the San Andreas Fault where topography exhibits well defined benches and "lumps."(Figure 15).

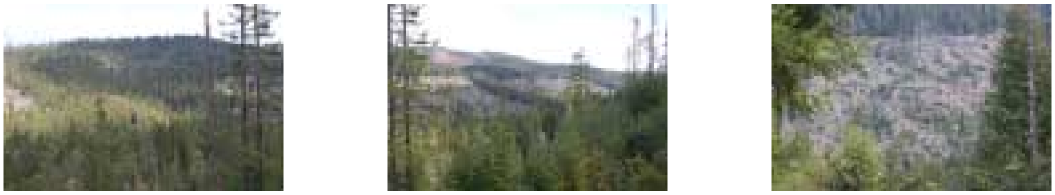


Figure 15: Photo series showing terrain of western subdivision. Note dominant midslope bench in middle photo and mounded ground in close-up photo of clearcut area in right photo.

Landslide Distribution

Very large dormant rotational/translational landslides are found in the following areas:
  Along the San Andreas Fault zone in the western subdivision
  Along the Tombs Creek Fault zone and Oak Ridge in the southern subdivision

Very large active and dormant earthflow complexes are found in the following areas:
  Within or partly within the Central, Rio Nido, Pickett Peak, and Yolla Bolly terranes of Franciscan Complex in the eastern and southern subdivisions

Debris slides are found in the following areas:
  Steep terrain with incised streams such as North Fork, South Fork, Wheatfield Fork, Buckeye Creek, Rockpile Creek, and Fuller Creek. Debris slides also occur along on road cuts and fills. Debris slides are especially abundant in the Coastal terrane on the steepest slopes in watershed.

Debris flows are found in:
  Moderate-steep terrain –prominent in North Fork of Fuller Creek, North Fork of the Gualala River and South Fork of the Gualala River. Debris flows also occur on road cuts and fills. Debris flows are especially abundant in the Coastal terrane on the steepest slopes in watershed.

Inner Gorges are found in:
  Scattered stretches along incised streams, such as the South and North Forks of the Gualala River and Buckeye, Rockpile, Haupt, and Fuller Creeks.

Many large relic and dormant slides throughout the watershed remain important in the landscape. About forty per cent of small (less than 1/5 of an acre) historically active landslides occur within a large dormant landslide. Some of these dormant slides may be historic and others may be thousands of years old. Within that time span the climate was significantly wetter and cooler, geologic uplift rates were considerably more rapid, and earthquakes were probably more common. Paleoclimatic information derived from cores in Clear Lake and approximately 20 miles off the coast from Fort Ross are consistent with other regional studies and show that precipitation was at least 2.5-3 times greater during the Pleistocene (Adam and West, 1983; Adam, 1988,Gardner and others, 1988). All of these factors could have triggered the formation of many of the dormant old landslides. These dormant features have been highly eroded which occasionally makes recognition questionable. The size distribution of relic slides is probably skewed toward larger features because the long history of erosion has obliterated signs of the smaller features. Relic slides are important today because they influence modern stream and hillslope processes. For example, they continue to influence stream channel planform and profile due to their effect on the distribution of hard versus soft and erodible material. Massive features on the flanks of Oak Ridge define the path of major tributaries; i.e., the North and South Forks of Fuller Creek. Those features are interpreted to be ancient landslides (Figure 16). Ancient features, probably landslides, on the east flank of Oak Ridge similarly seem to cause realignment of the Wheatfield Fork (Figure 17).

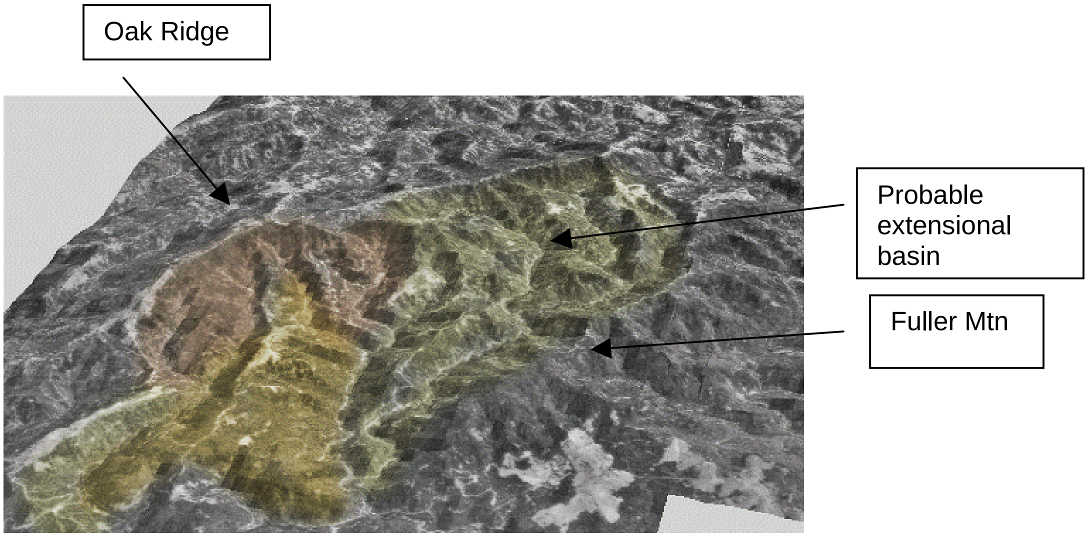


Figure 16: View southeastward at Oak Ridge. The west face of Oak Ridge is highly deformed and is tentatively interpreted as pull-apart basin (green highlight). A probable large ancient landslide (yellow highlight) appears to have collapsed into possible extensional basin leaving a bowl (brown highlight) in the side of the ridge. The remainder of the extensional basin may be occupied by older, less recognizable landslide deposits. Image is digitally enhanced aerial photos.

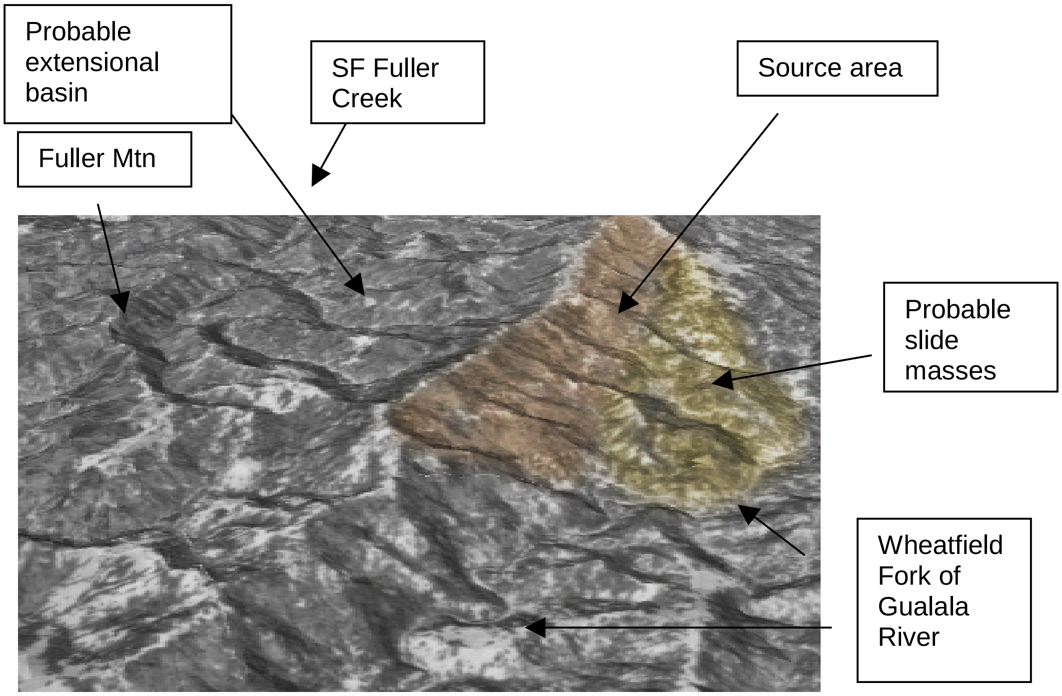


Figure 17: NW view above Oak Ridge of ancient features landslides possibly shed from the east face of ridge. Wheatfield Fork of the Gualala River is seen winding its way from upper right hand corner of image southward along flanks of probable slide masses. On left side of image, three concentric drainages within the pull-apart merge into the South Fork of Fuller Creek and flow northward. The ridgelines of Fuller Mtn and Oak Ridge form semiparallel borders to the probable extensional basin marked with the trio concentric ridges and valleys. Image is digitally enhanced aerial photos.

Younger dormant landslides were identified based on an overall more juvenile appearance and appear scattered throughout the Gualala River watershed but follow the same distribution pattern of historically active slides. Again, due to the effects of continued erosion, there may be a detection bias toward larger features.

Historically active landslides occur throughout the Gualala River Watershed. The landslides are mapped and are shown on Plate 1 of the Gualala River Watershed Assessment. The map, Geologic and Geomorphic Features Related to Landsliding in the Gualala River Watershed, is at a scale of 1:24,000. Landslides as large as a fifth acre are mapped as single points; those larger are mapped as polygonal areas. The distribution of historically active landslides in the watershed is partly controlled by lithology. The following maps show the spatial relationships between active landslides and lithology (Figures 18 and 19).

The Central, Rio Nido, and Pickett Peak terranes of the Franciscan Complex consist of weak rock and large landslide complexes can form therein. There is high correlation between active slides and this rock.

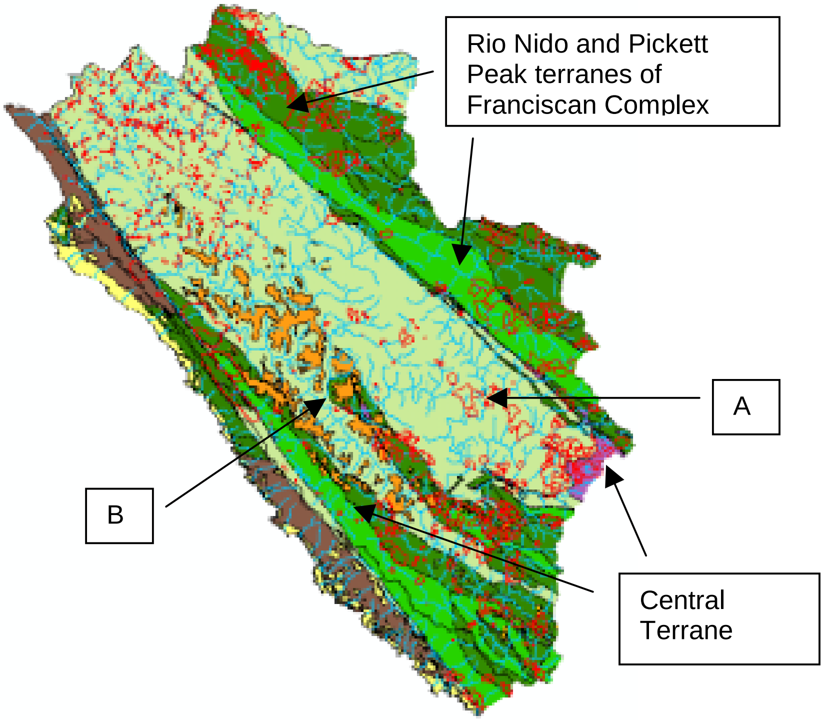


Figure 18:Geologic map overlain with large active landslides (red polygons). Note the high correlation of large landslides with the Central, Pickett Peak, and Rio Nido terranes of the Franciscan Complex (shown in darker greens). Arrow A refers to a Northwest trending string of large landslides that do not seem to correlate with the terranes. However, this string does follow disrupted topography that has been tentatively interpreted, based on other criteria, as a shear zone. Figure 19 zooms into the area indicated by Arrow B.

The Ohlson Ranch Formation is poorly consolidated weak rock that sits atop flat-topped ridges found throughout the Annapolis Quadrangle and adjoining areas. The Ohlson Ranch Formation is stable on relatively flat slopes, but is unstable on steeper slopes generally occurring along its contact with underlying formations and along stream channels.

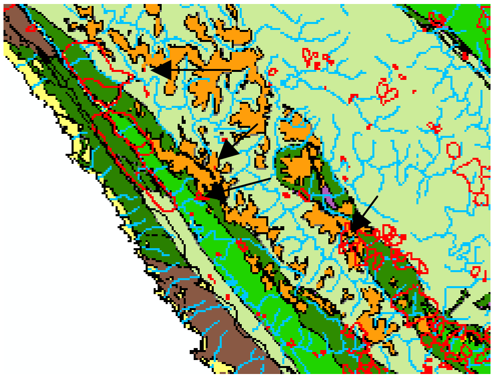


Figure 19: Geologic Map overlain with active landslides.The Ohlson Ranch Formation is shown as orange. Historically active landslides are shown as red polygons.Black arrows show the occurrence of landslides along the margins of the Ohlson Ranch Formation.

Certain portions in the Gualala River Watershed are more active in terms landslides and have a higher potential of future landsliding. These are represented in Plate 2 of the Gualala River Watershed Assessment: Relative Landslide Potential Map. A simplified version of the potential map is illustrated in Figure 20. The distribution of active landslides and landslide potential in the watershed is described in further detail below. The impacts of the landslides on stream conditions are considered in the Fluvial Geomorphology section of this report.

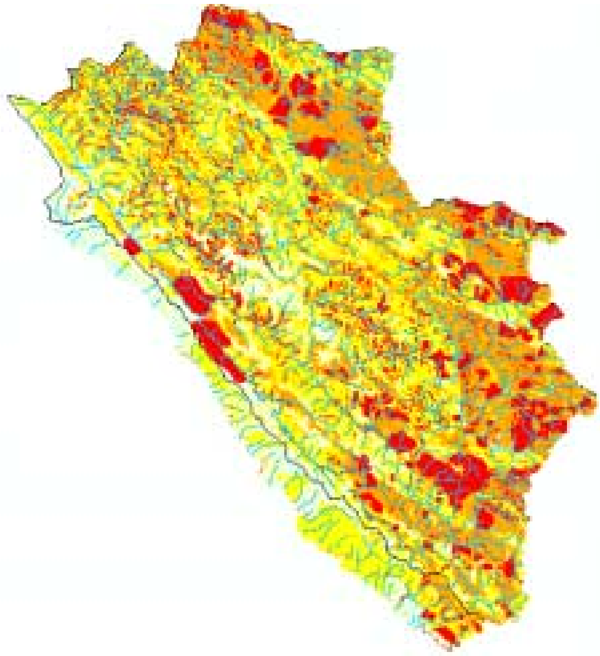


Figure 20: Landslide Potential Map with streams. The colors indicate landslide potential ranked from highest to lowest as follows: red, orange, brown, and yellow.

The areas of high landslide potential are probably areas of long-term sediment sources that may impact stream habitat.

Sediment Yield

1) A 20 year record of suspended sediment measurements on Dry Creek tributary to the Russian River was used as a proxy to the Gualala River watershed due to close proximity, similar geology, and similar land use history as the upper Gualala River (Figure 21).

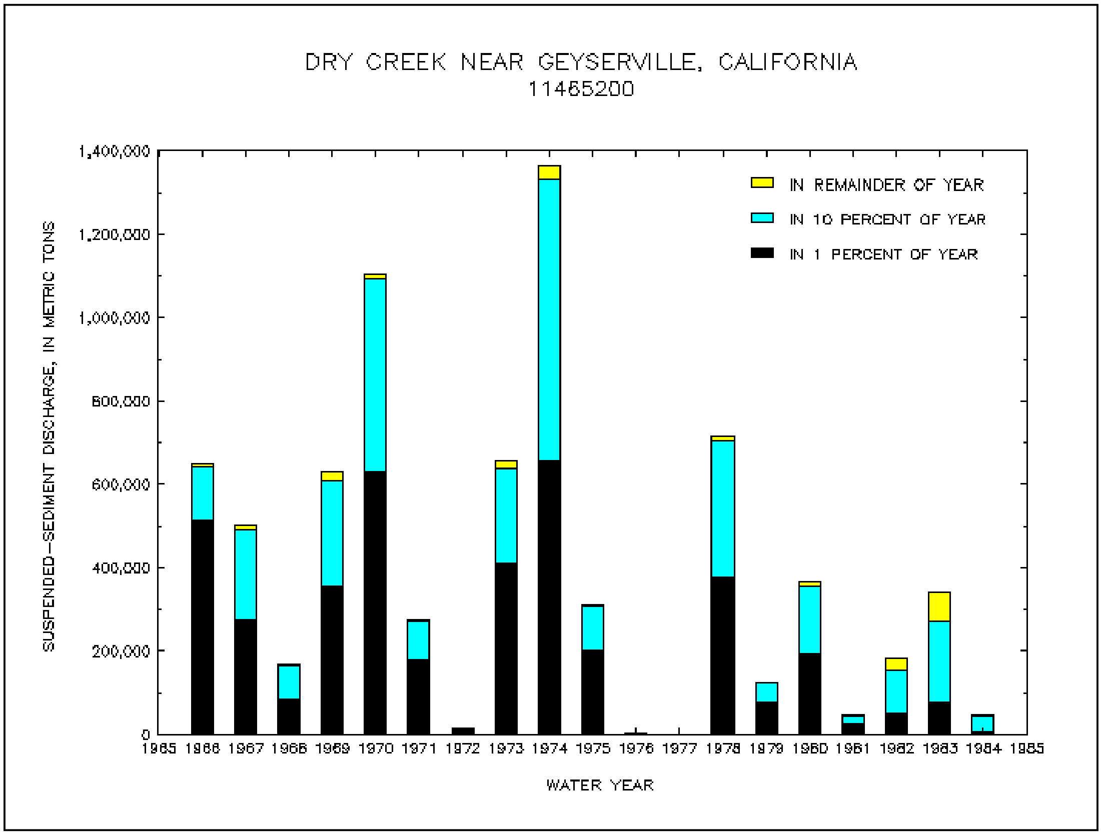


Figure 21: Suspended sediment discharge on Dry Creek measured at USGS sediment gage 11465200. This 20 year record begins in water year 1966 and ends in water year 1984 when flows became regulated by Warm Springs Dam. Dry Creek drains the area immediately east of the Gualala watershed. This graph was retrieved from the USGS web site.

2) Recently established uplift rates based on marine terraces (Table 1) were used as a proxy for long-term erosion rates based on an assumption that long-term uplift and erosion are within an order of magnitude of each other since the terrain is neither excessively steep nor excessively flat. Following this reasoning, long-term erosion rate is estimated at 1,200 to 2,900 US tons per square mile per year (Appendix C).
3) Measured movement rates of deep-seated landslides and calculated yields from similar watersheds within the Coast Range were used as a proxy for the unknown rates in the Gualala River watershed (Table 1). These published studies indicate a range of 1,000 to 70,000 US tons per square mile per year.
4) Recalculation of a published sediment budget for the Gualala River watershed (NCRWQCB,2001) using recently developed CGS landslide data and rates shown in Table 1 instead of estimates that were employed (Appendix C).

That these different methods produced similar results suggests that the estimate is reasonable. Consideration of bedload and dissolved load should be made when comparing the measured suspended sediment discharge values. Bedload was approximately 20% of suspended load during the one year that it was measured at the Dry Creek gage. The dissolved load of Gualala River is approximately 160 US tons per square mile per year (Appendix C).

VARIABLE	VALUES	REFERENCE
Tectonic uplift rate	0.24-0.58 mm/yr	Richardson, 2000
Measured movement rates of earthflows in Van Duzen basin	2,400-4,000 mm/yr. Average: 3,100 mm/ yr	Kelsey, 1978 and 1980
Annual sediment yield from Van Duzen earthflow movement	71,214 US tons/ sq. mi/yr	Kelsey, 1978,1980, 1987
Annual sediment yield from gullies on earthflows in Van Duzen	75,218 US tons/sq/yr	Kelsey, 1978,1980, 1987
Measured movement rate of two landslides in Redwood Creek	Up to 15,300 mm/yr.	Nolan and Janda, 1995
Annual sediment yield of two landslides in Redwood Creek	From 1979-1982, 2,000-71,800 US tons/ sq. mi/yr	Nolan and Janda, 1995
Measured suspended sediment yield of Russian River above Guerneville	From 1965-1968, 4,370 tons/ sq. mile/yr from 1,340 sq. mi. drainage area	Ritter and Brown, 1971
Measured suspended sediment yield of Dry Creek tributary to Russian River	From 1965-1968, 5,770 tons/ sq. mi/yr from 128 sq. mi. drainage area ranging from 1,150 to 14,100 tons/ sq. mi./yr.	Ritter and Brown, 1971
Measured annual sediment yield on Dry Creek for water year 1980 with annual water yield = 61,955 cubic feet	Suspended sediment: 313 tons/ sq. mi/yr Bedload sediment: 80 tons/ sq. mi/yr Total sediment yield: 392 tons/sq. mi/yr	USGS Gage 11465200 records
Measured annual sediment yield on Pena Creek for water year 1980 with annual water yield = 8,366 cubic feet	Suspended sediment: 532 tons/sq. mi/yr Bedload sediment: 106 tons/sq. mi/yr Total sediment: 640 tons/ sq. mi/yr	USGS Gage 11465150 records
Total suspended annual sediment yield for water year 1970 on Dry Creek with annual water yield =111,342 cubic feet	Suspended sediment : 1,866 tons/sq. mi/yr	USGS Gage 11465200 records
Measure movement rates of earthflows from 1974-1982	0-2,500 mm/yr.	Harden and others, 1995 Harden and others, 1978
Measured creep rate of earthflows in Redwood Creek	3-130 mm/yr.	Swanston and others, 1995
Measured rate of movement of an active earthflow	488 mm/yr.	Madej, 1999 and references therein
Calculated yield from an active earthflow in Redwood Creek	29,280 US tons/sq. mi/yr.	Madej, 1999

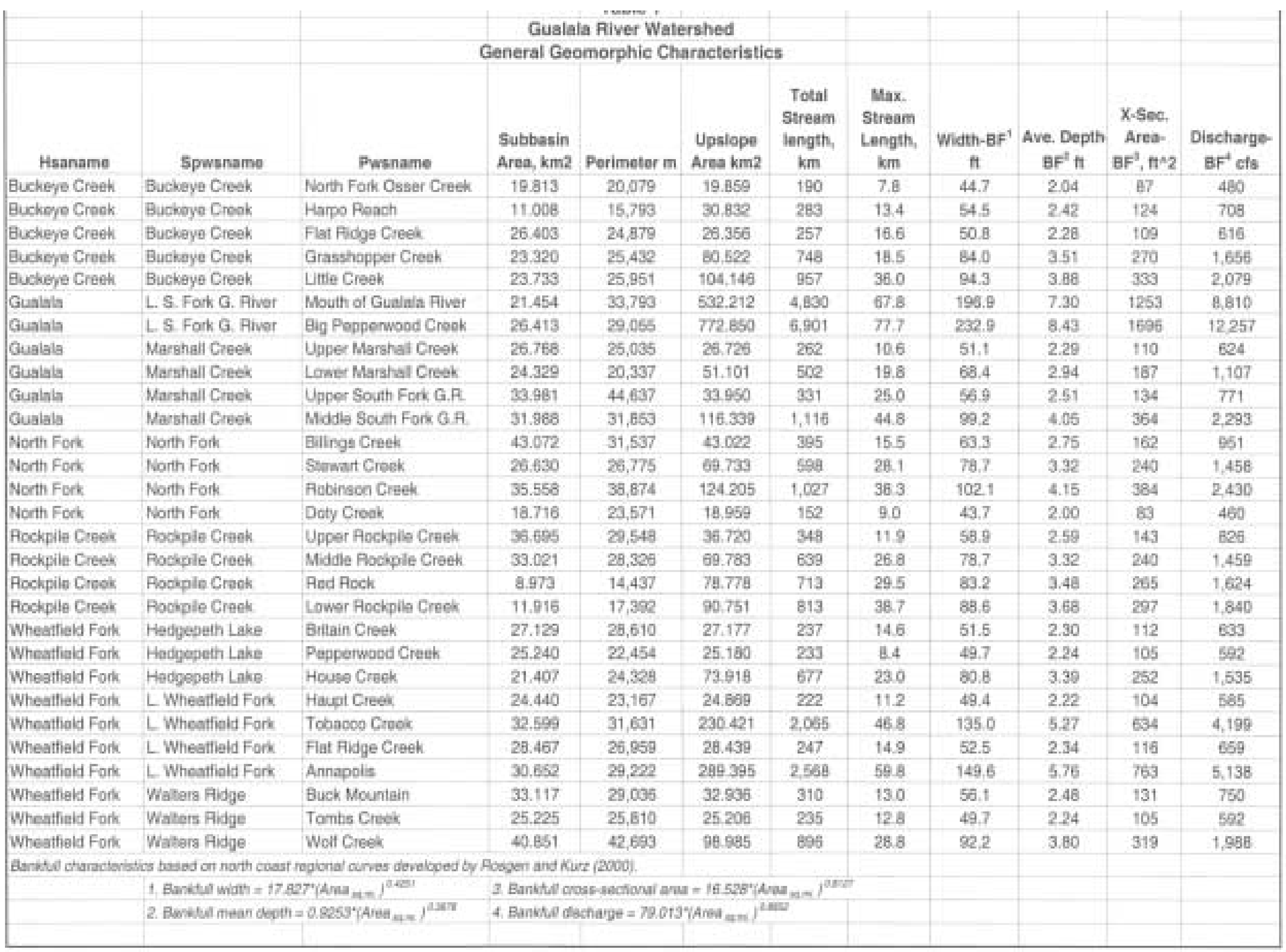
Table 2: Variables and values considered in estimation of sediment yield.

General Stream Geomorphic Characteristics

General stream geomorphic characteristics were evaluated using the 10-meter DEM to simulate the entire Gualala River watershed drainage network. A DEM-based network was produced assuming a minimum drainage area for a zero-order basin of 1 hectare. Comparison of DEM stream network with the USGS topographic and digital orthophoto maps found the 1-hectare minimum area produced a reasonable representation of the drainages, although there was some misalignment of the smaller drainages with the contour crenulations. The stream order of USGS blue-line streams was higher for the DEM-based network than would be calculated from the USGS line work alone. A DEM-based network using a minimum drainage area of 10 hectares produces a drainage network similar to the USGS 1:24,000 topographic map’s blue-line streams, although some of the smaller drainages were missed in the USGS network. The higher-order simulated streams compared favorably with the USGS 1:24,000 blue-line stream network except where the angularity of the DEM network deviated at sharp bends. Network-generated sub-basin boundaries generally agree with the CalWater boundaries except where CalWater boundaries are not drawn based on hydrologic characteristics, mainly at the planning watershed level.

Table 3 lists general watershed and stream geomorphic characteristics based on the 10-meter DEM drainage network. Values in the table are based on the lowermost point in the named planning watershed and represent cumulative upstream values. Table 3 also includes estimates of bankfull stream geomorphology that were made using regional equations developed by Rosgen and Kurz (2000) from USGS stream gage data on several north coast rivers. Stream gages used in their study were located on major rivers where upslope drainage area was greater than 28 square miles (18,000 acres). The channels studied included B, C and F Rosgen types, with channel sediment size ranging from gravel to cobble (Rogen class types 3 and 4). The addition of twelve field measurements by Mendocino County Forest Lands of bankfull width in the Gualala River watershed found general agreement with the Rosgen and Kurz regional bankfull width curve. The bankfull geomorphic channel characteristics listed in Table 3 should be considered approximate and are derived from relatively stable channel reaches. Geomorphic characteristics of reaches with high sediment deposition and/or variable channel hydraulics will likely differ from these values.

CGS’s fluvial geomorphic mapping concentrated on identifying features indicative of stored channel sediment or sources of sediment that could be identified on the available aerial photographs. Two periods were mapped, 1984 and 1999/2000, in order to document recent channel conditions and to provide an estimate of changes in channel geomorphology since the mid-1980’s. The fluvial mapping efforts developed GIS layers for each of the two ages of aerial photo. The older 1984 black-and-white photo set was taken by WAC Corporation (WAC) at a nominal scale of approximately 1:32,000. The more recent set is a combination of two WAC flight series, a color set for Sonoma County taken in 1999 at a scale of 1:24,000 and a second black-and-white set for Mendocino County taken in 2000 at a scale of 1:24,000.



Gualala River Watershed

General Geomorphic Characteristics

Hsaname	Spwsname	Pwsname	Subbasin Area, km2	Perimeter m	Upslope Area km2	Total Stream length, km	Max. Stream Length, km	Width-BF^1 ft	Ave. Depth BF^2 ft	X-Sec. Area-BF^3, ft^2	Discharge-BF^4 cfs
Buckeye Creek	Buckeye Creek	North Fork Osser Creek	19.813	20,079	19.859	190	7.8	44.7	2.04	87	480
Buckeye Creek	Buckeye Creek	Harpo Reach	11.008	15,793	30.832	283	13.4	54.5	2.42	124	708
Buckeye Creek	Buckeye Creek	Flat Ridge Creek	26.403	24,879	26.356	257	16.6	50.8	2.28	109	616
Buckeye Creek	Buckeye Creek	Grasshopper Creek	23.320	25,432	80.522	748	18.5	84.0	3.51	270	1,656
Buckeye Creek	Buckeye Creek	Little Creek	23.733	25,951	104.146	957	36.0	94.3	3.88	333	2,079
Gualala	L. S. Fork G. River	Mouth of Gualala River	21.454	33,793	532.212	4,830	67.8	196.9	7.30	1253	8,810
Gualala	L. S. Fork G. River	Big Pepperwood Creek	26.413	29,055	772.850	6,901	77.7	232.9	8.43	1696	12,257
Gualala	Marshall Creek	Upper Marshall Creek	26.768	25,035	26.726	262	10.6	51.1	2.29	110	624
Gualala	Marshall Creek	Lower Marshall Creek	24.329	20,337	51.101	502	19.8	68.4	2.94	187	1,107
Gualala	Marshall Creek	Upper South Fork G.R.	33.981	44,637	33.950	331	25.0	56.9	2.51	134	771
Gualala	Marshall Creek	Middle South Fork G.R.	31.988	31,653	116.339	1,116	44.8	99.2	4.05	364	2,293
North Fork	North Fork	Billings Creek	43.072	31,537	43.022	395	15.5	63.3	2.75	162	951
North Fork	North Fork	Stewart Creek	26.630	26,775	69.733	598	28.1	78.7	3.32	240	1,458
North Fork	North Fork	Robinson Creek	35.558	38,874	124.205	1,027	38.3	102.1	4.15	384	2,430
North Fork	North Fork	Doty Creek	18.716	23,571	18.959	152	9.0	43.7	2.00	83	460
Rockpile Creek	Rockpile Creek	Upper Rockpile Creek	36.695	29,548	36.720	348	11.9	58.9	2.59	143	826
Rockpile Creek	Rockpile Creek	Middle Rockpile Creek	33.021	28,326	69.783	639	26.8	78.7	3.32	240	1,459
Rockpile Creek	Rockpile Creek	Red Rock	8.973	14,437	78.778	713	29.5	83.2	3.48	265	1,624
Rockpile Creek	Rockpile Creek	Lower Rockpile Creek	11.916	17,392	90.751	813	38.7	88.6	3.68	297	1,840
Wheatfield Fork	Hedgepeth Lake	Britain Creek	27.129	28,610	27.177	237	14.6	51.5	2.30	112	633
Wheatfield Fork	Hedgepeth Lake	Pepperwood Creek	25.240	22,454	25.180	233	8.4	49.7	2.24	105	592
Wheatfield Fork	Hedgepeth Lake	House Creek	21.407	24,328	73.918	677	23.0	80.8	3.39	252	1,535
Wheatfield Fork	L. Wheatfield Fork	Haupt Creek	24.440	23,167	24.869	222	11.2	49.4	2.22	104	585
Wheatfield Fork	L. Wheatfield Fork	Tobacco Creek	32.599	31,631	230.421	2,065	46.8	135.0	5.27	634	4,199
Wheatfield Fork	L. Wheatfield Fork	Flat Ridge Creek	28.467	26,959	28.439	247	14.9	52.5	2.34	116	659
Wheatfield Fork	L. Wheatfield Fork	Annapolis	30.652	29,222	289.395	2,568	59.8	149.6	5.76	763	5,138
Wheatfield Fork	Walters Ridge	Buck Mountain	33.117	29,036	32.936	310	13.0	56.1	2.48	131	750
Wheatfield Fork	Walters Ridge	Tombs Creek	25.225	25,610	25.206	235	12.8	49.7	2.24	105	592
Wheatfield Fork	Walters Ridge	Wolf Creek	40.851	42,693	98.985	896	28.8	92.2	3.80	319	1,988

Bankfull characteristics based on north coast regional curves developed by Roegen and Kurz (2000).

1. Bankfull width = 17.827(Area$_{sq.mi.}$)$^{0.4251}$*

2. Bankfull mean depth = 0.9253(Area$_{sq.mi.}$)$^{0.3679}$*

3. Bankfull cross-sectional area = 16.528(Area$_{sq.mi.}$)$^{0.8127}$*

4. Bankfull discharge = 79.013(Area$_{sq.mi.}$)$^{0.8852}$*

Table 3: General Fluvial Geomorphic Characteristics of Gualala River watershed.

Fluvial mapping in the Gualala River watershed encompassed all of the 1:24,000 USGS blue-line steam network and occasionally extended into non-blue-line tributaries if significant channel disturbance was observed. Thirty-two fluvial geomorphic attributes were available in the GIS database. Appendix B contains a more detailed discussion of the fluvial mapping methodology, the GIS database structure, and a stream characteristics photomapping dictionary showing examples of the 32 fluvial geomorphic attributes.

For each mapped fluvial feature, up to 4 of the 32 attributes along with a 40-characters of comment text were recorded in the GIS database. Several of these attributes were considered probable indicators of excess sediment in storage or sediment sources that might be detrimental to optimum habitat for anadromous salmonids (see Appendix B for listing of detrimental attributes). While many of these features were associated with apparent increases in channel sediment or impaired channel conditions, the degree of impairment above natural background conditions could not be quantified using aerial photo interpretation alone. The significance of these detrimental channel characteristics on the habitat of anadromous salmonids likely varies with position in the watershed and channel order. Field studies should be undertaken to quantify impacts of these fluvial geomorphic changes to fishery habitat in specific reaches. Limited field reconnaissance found a good spatial correlation between the probable detrimental channel geomorphic characteristics identified on aerial photos and the on-the-ground evidence of channel instability or excess channel sediment.

Channel conditions such as the lack of riparian, excessive channel bars, multi-thread channels, channel bank erosion, shallow landslides adjacent to or blocking channels were often associated with areas of moderate to high landslide potential even in areas where historically active sediment sources were not identified in aerial photos. This suggests that control of sediment yield and channel deposition in some reaches may in part reflect a natural sediment loading condition resulting from mass wasting or fluvial erosion of the adjacent large unstable terrains. The sedimentation from these deep-seated landslides is likely the result of small rates of erosion and mass movement combined with their large area to create a significant chronic contribution of sediment to the adjacent channel. The inability to identify a localized source area for this sediment is a characteristic expected from a true non-point source. For example, reaches mapped as a “wide channel” correspond with stream reaches that have abundant sediment deposits and often lie along the toe of deep-seated landslides, both historically active and/or dormant. While a large landslide mass is mapped adjacent to these “wide channels” there is often a lack of adjacent smaller historically active slides to provide a clearly identifiable source of sediment adjacent to the stream deposits.

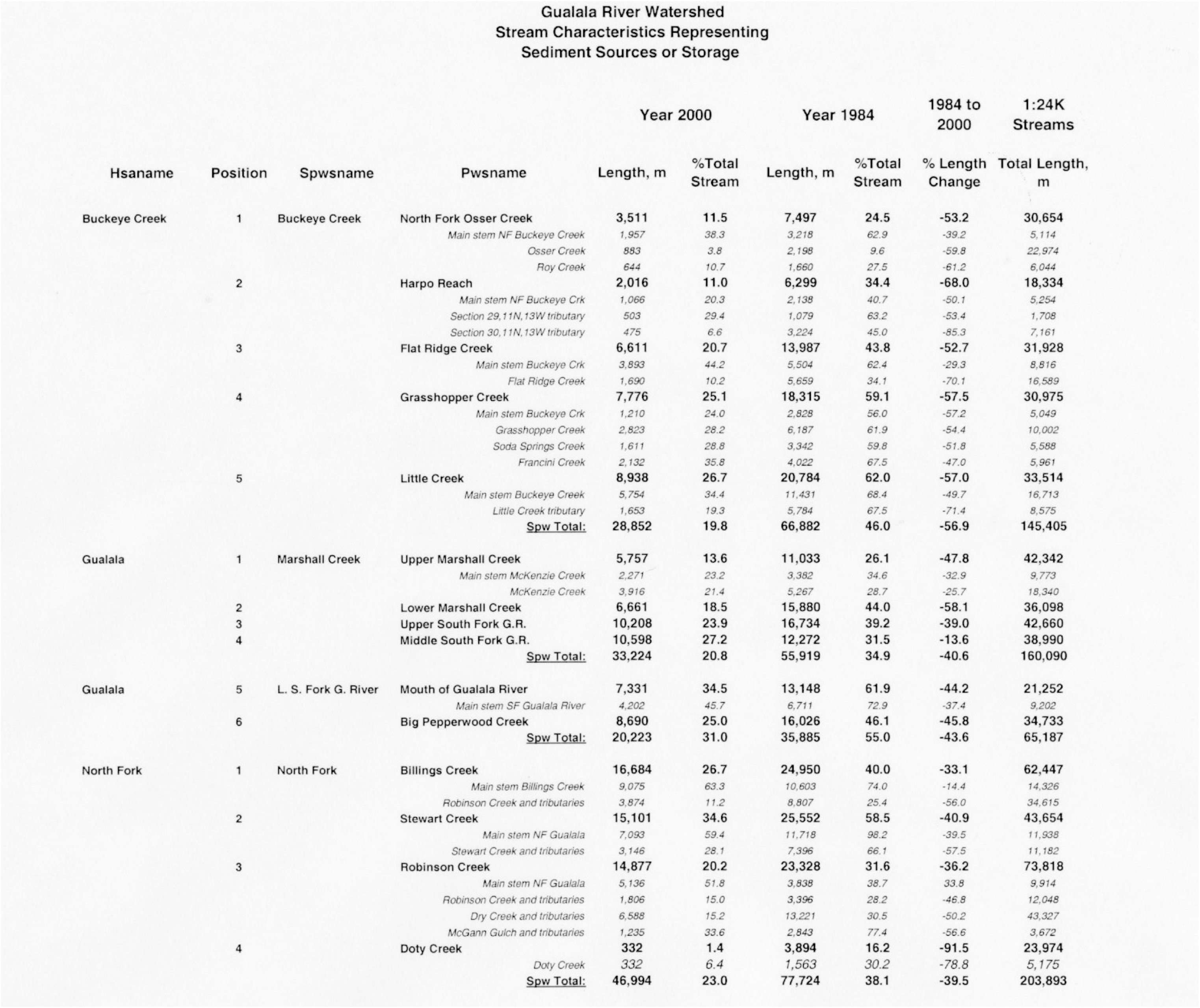
The wide channel characteristic appears to be the result of deposits of excess sediment that prevented riparian vegetation from re-establishing either because of continued burial by new sediment, periodic vegetation removal by flood events made more damaging because of channel aggradation, or the depth of channel sediment prevents the shallow rooted riparian vegetation from obtaining sufficient water. Some active channels in disturbed reaches were narrower and more deeply incised than channels mapped stable in reaches reflecting ongoing degradation as the channel attempts to establish a pre-disturbance condition. These channel characteristics are consistent with observations of others (James, 1999; Madej and Ozaki, 1996) regarding the geomorphic changes as a channel tries to re-establish a stable configuration by eroding excess sediment stored in bars or channel banks. Additional GIS analysis of the associations between mapped channel features unstable terrains is given below in the report section on Analysis of Mapped Data.

Table 4 lists for each planning watershed the lengths and percentage change mapped from aerial photos from 1984 to 1999/2000 in 1:24,000 USGS blue-line streams having characteristics interpreted as representing sediment sources or storage that may be detrimental to optimum habitat for anadromous salmonids. In addition, channel length change statistics are listed for several individual reaches under their respective planning watershed where other NCWAP investigators have identified a particular interest.

In general, from 1984 to 2000, the portions of channels mapped as having probably detrimental fluvial sediment conditions decreased, although some reaches apparently increased. Overall, a watershed wide decrease in detrimental sediment stream length of approximately 47 percent was mapped. The reduction in mapped channel sediment was greatest in the steeper reaches. In some areas, reduction in mapped sediment within the upper, steeper gradient tributaries is accompanied with an increase in mapped sediment in lower gradient main channel. At the planning watershed scale, reductions in mapped channel sediment characteristics ranged from a low of approximately 14 percent for the Middle South Fork of the Gualala River, to a high of approximately 90 percent for Doty Creek and Tombs Creek. The range of channel recovery for individual reaches was greater with an increase in length of detrimental channel characteristics of approximately 29 percent for the main stem of North Fork Gualala River in Robinson Creek Planning

Watershed, to an approximate 89 percent decrease in detrimental sediment length in a tributary of Sections 15 and 23 of Township 11 North, Range 14 West in the Middle Rockpile Creek Planning Watershed. The reader should refer to the individual ArcView shape files for specific information about a channel reach. The reader should keep in mind that the estimates given in Table 4 are approximate as they are derived from mapping done at a regional scale of 1:24,000 and do not measure historic changes in channel cross-section.

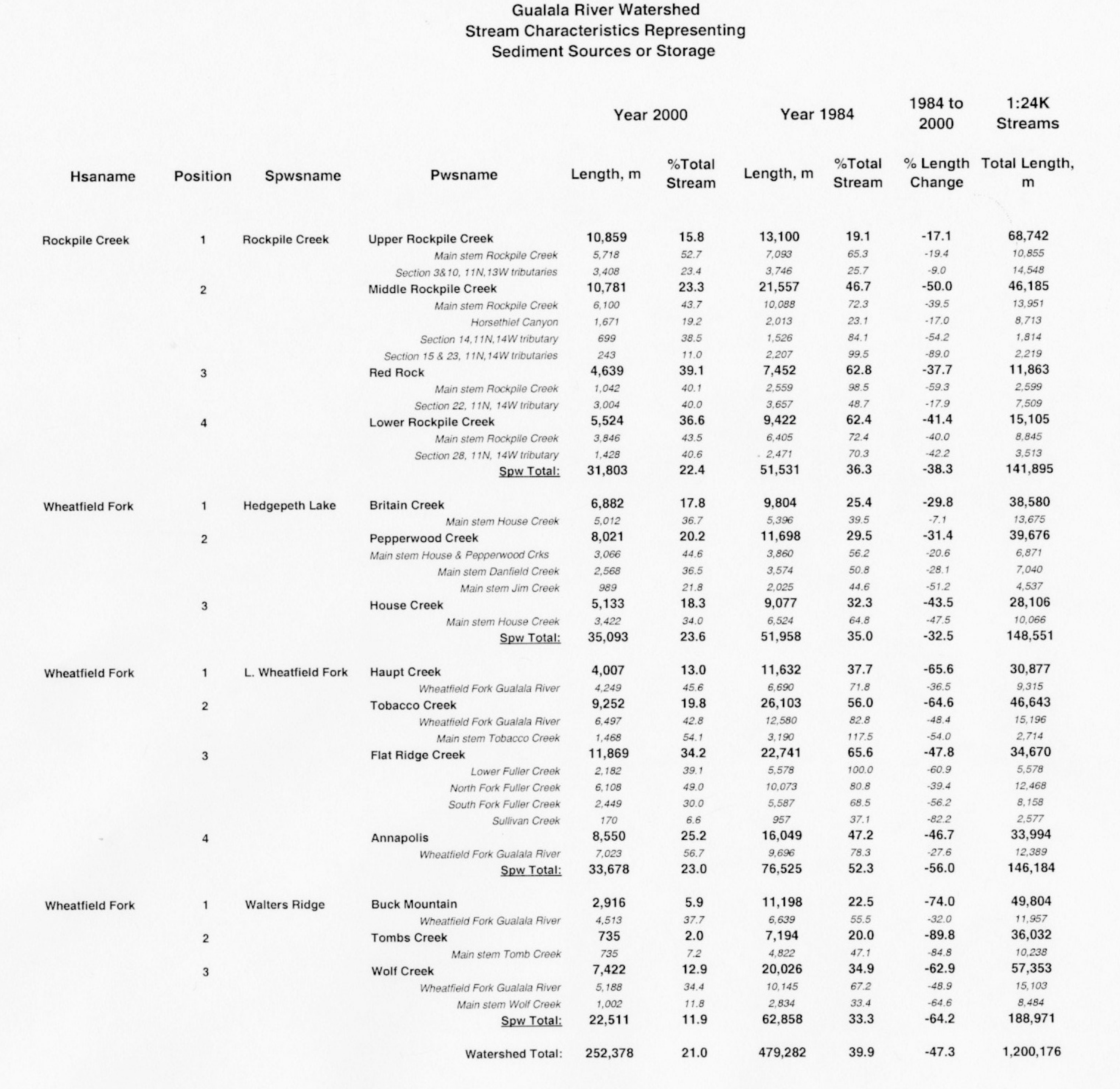
The results of this 15-year aerial photos time series mapping of fluvial geomorphic change in the Gualala River watershed are consistent with other channel change field studies done in Redwood Creek watershed by Madej (1987, 1995) and Pitlick (1995). Using channel cross-section data, Madej (1987) found that 60 to 100 percent of the sediment stored in steeper, low-order tributaries to Redwood Creek watershed was transported out of the channel within 10 years of initial deposition, except where trapped by logjams. The extent of tributary recovery corresponded roughly with channel gradient with all reaches steeper than 12 percent showing substantial recovery. Channel recovery occurred even with moderate flow conditions that did not exceed the 5-year recurrence interval. However, tributary channel recovery was not simultaneous or uniform. Madej (1987, 1995) also found that the lower gradient tributaries with approximately 1 percent slope often showed good recover whenever logjams were not present. Channel recovery in the main stem of Redwood Creek varied from 4 to 70 percent for the upper reach, and 0 to 13 percent for the middle and lower reach reflecting a residence time of 10 to 50 years for sediments in the active (within the 1-5 year flood stage) and semi-active (within the 5 to 20 year flood stage) channel (Madej, 1987). Pitlick (1995) found that in Redwood Creek watershed the lower 50 percent of the tributary reaches store 95 percent of the sediment. Whereas, in the main stem channel 95 percent of the sediment is stored in 75 percent of the channel length. Consistency between the Gualala River watershed aerial photo mapping done for this report with the more detailed field studies done in the Redwood Creek watershed supports the conclusion that the watershed wide mapping of fluvial geomorphic characteristics can be used to develop a reconnaissance assessment of the general conditions of channels, document channel changes, and provide locations for site specific studies.



Gualala River Watershed
Stream Characteristics Representing Sediment Sources or Storage

				Year 2000		Year 1984		1984 to 2000	1:24K Streams
Hsaname	Position	Spwsname	Pwsname	Length, m	%Total Stream	Length, m	%Total Stream	% Length Change	Total Length, m
Buckeye Creek	1	Buckeye Creek	North Fork Osser Creek	3,511	11.5	7,497	24.5	-53.2	30,654
			Main stem NF Buckeye Creek	*1,957*	*38.3*	*3,218*	*62.9*	*-39.2*	*5,114*
			Osser Creek	*883*	*3.8*	*2,198*	*9.6*	*-59.8*	*22,974*
			Roy Creek	*644*	*10.7*	*1,660*	*27.5*	*-61.2*	*6,044*
	2		Harpo Reach	2,016	11.0	6,299	34.4	-68.0	18,334
			Main stem NF Buckeye Crk	*1,066*	*20.3*	*2,138*	*40.7*	*-50.1*	*5,254*
			Section 29,11N,13W tributary	*503*	*29.4*	*1,079*	*63.2*	*-53.4*	*1,708*
			Section 30,11N,13W tributary	*475*	*6.6*	*3,224*	*45.0*	*-85.3*	*7,161*
	3		Flat Ridge Creek	6,611	20.7	13,987	43.8	-52.7	31,928
			Main stem Buckeye Crk	*3,893*	*44.2*	*5,504*	*62.4*	*-29.3*	*8,816*
			Flat Ridge Creek	*1,690*	*10.2*	*5,659*	*34.1*	*-70.1*	*16,589*
	4		Grasshopper Creek	7,776	25.1	18,315	59.1	-57.5	30,975
			Main stem Buckeye Crk	*1,210*	*24.0*	*2,828*	*56.0*	*-57.2*	*5,049*
			Grasshopper Creek	*2,823*	*28.2*	*6,187*	*61.9*	*-54.4*	*10,002*
			Soda Springs Creek	*1,611*	*28.8*	*3,342*	*59.8*	*-51.8*	*5,588*
			Francini Creek	*2,132*	*35.8*	*4,022*	*67.5*	*-47.0*	*5,961*
	5		Little Creek	8,938	26.7	20,784	62.0	-57.0	33,514
			Main stem Buckeye Creek	*5,754*	*34.4*	*11,431*	*68.4*	*-49.7*	*16,713*
			Little Creek tributary	*1,653*	*19.3*	*5,784*	*67.5*	*-71.4*	*8,575*
			Spw Total:	28,852	19.8	66,882	46.0	-56.9	145,405
Gualala	1	Marshall Creek	Upper Marshall Creek	5,757	13.6	11,033	26.1	-47.8	42,342
			Main stem McKenzie Creek	*2,271*	*23.2*	*3,382*	*34.6*	*-32.9*	*9,773*
			McKenzie Creek	*3,916*	*21.4*	*5,267*	*28.7*	*-25.7*	*18,340*
	2		Lower Marshall Creek	6,661	18.5	15,880	44.0	-58.1	36,098
	3		Upper South Fork G.R.	10,208	23.9	16,734	39.2	-39.0	42,660
	4		Middle South Fork G.R.	10,598	27.2	12,272	31.5	-13.6	38,990
			Spw Total:	33,224	20.8	55,919	34.9	-40.6	160,090
Gualala	5	L. S. Fork G. River	Mouth of Gualala River	7,331	34.5	13,148	61.9	-44.2	21,252
			Main stem SF Gualala River	*4,202*	*45.7*	*6,711*	*72.9*	*-37.4*	*9,202*
	6		Big Pepperwood Creek	8,690	25.0	16,026	46.1	-45.8	34,733
			Spw Total:	20,223	31.0	35,885	55.0	-43.6	65,187
North Fork	1	North Fork	Billings Creek	16,684	26.7	24,950	40.0	-33.1	62,447
			Main stem Billings Creek	*9,075*	*63.3*	*10,603*	*74.0*	*-14.4*	*14,326*
			Robinson Creek and tributaries	*3,874*	*11.2*	*8,807*	*25.4*	*-56.0*	*34,615*
	2		Stewart Creek	15,101	34.6	25,552	58.5	-40.9	43,654
			Main stem NF Gualala	*7,093*	*59.4*	*11,718*	*98.2*	*-39.5*	*11,938*
			Stewart Creek and tributaries	*3,146*	*28.1*	*7,396*	*66.1*	*-57.5*	*11,182*
	3		Robinson Creek	14,877	20.2	23,328	31.6	-36.2	73,818
			Main stem NF Gualala	*5,136*	*51.8*	*3,838*	*38.7*	*33.8*	*9,914*
			Robinson Creek and tributaries	*1,806*	*15.0*	*3,396*	*28.2*	*-46.8*	*12,048*
			Dry Creek and tributaries	*6,588*	*15.2*	*13,221*	*30.5*	*-50.2*	*43,327*
			McGann Gulch and tributaries	*1,235*	*33.6*	*2,843*	*77.4*	*-56.6*	*3,672*
	4		Doty Creek	332	1.4	3,894	16.2	-91.5	23,974
			Doty Creek	*332*	*6.4*	*1,563*	*30.2*	*-78.8*	*5,175*
			Spw Total:	46,994	23.0	77,724	38.1	-39.5	203,893

Table 4: Gualala River watershed stream characteristics representing sediment sources or storage, 1984 to 2000.



Gualala River Watershed
Stream Characteristics Representing
Sediment Sources or Storage

				Year 2000		Year 1984		1984 to 2000	1:24K Streams
Hsaname	Position	Spwsname	Pwsname	Length, m	%Total Stream	Length, m	%Total Stream	% Length Change	Total Length, m
Rockpile Creek	1	Rockpile Creek	Upper Rockpile Creek	10,859	15.8	13,100	19.1	-17.1	68,742
			Main stem Rockpile Creek	*5,718*	*52.7*	*7,093*	*65.3*	*-19.4*	*10,855*
			Section 3&10, 11N,13W tributaries	*3,408*	*23.4*	*3,746*	*25.7*	*-9.0*	*14,548*
	2		Middle Rockpile Creek	10,781	23.3	21,557	46.7	-50.0	46,185
			Main stem Rockpile Creek	*6,100*	*43.7*	*10,088*	*72.3*	*-39.5*	*13,951*
			Horsethief Canyon	*1,671*	*19.2*	*2,013*	*23.1*	*-17.0*	*8,713*
			Section 14,11N,14W tributary	*699*	*38.5*	*1,526*	*84.1*	*-54.2*	*1,814*
			Section 15 & 23, 11N,14W tributaries	*243*	*11.0*	*2,207*	*99.5*	*-89.0*	*2,219*
	3		Red Rock	4,639	39.1	7,452	62.8	-37.7	11,863
			Main stem Rockpile Creek	*1,042*	*40.1*	*2,559*	*98.5*	*-59.3*	*2,599*
			Section 22, 11N, 14W tributary	*3,004*	*40.0*	*3,657*	*48.7*	*-17.9*	*7,509*
	4		Lower Rockpile Creek	5,524	36.6	9,422	62.4	-41.4	15,105
			Main stem Rockpile Creek	*3,846*	*43.5*	*6,405*	*72.4*	*-40.0*	*8,845*
			Section 28, 11N, 14W tributary	*1,428*	*40.6*	*2,471*	*70.3*	*-42.2*	*3,513*
			Spw Total:	31,803	22.4	51,531	36.3	-38.3	141,895
Wheatfield Fork	1	Hedgepeth Lake	Britain Creek	6,882	17.8	9,804	25.4	-29.8	38,580
			Main stem House Creek	*5,012*	*36.7*	*5,396*	*39.5*	*-7.1*	*13,675*
	2		Pepperwood Creek	8,021	20.2	11,698	29.5	-31.4	39,676
			Main stem House & Pepperwood Crks	*3,066*	*44.6*	*3,860*	*56.2*	*-20.6*	*6,871*
			Main stem Danfield Creek	*2,568*	*36.5*	*3,574*	*50.8*	*-28.1*	*7,040*
			Main stem Jim Creek	*989*	*21.8*	*2,025*	*44.6*	*-51.2*	*4,537*
	3		House Creek	5,133	18.3	9,077	32.3	-43.5	28,106
			Main stem House Creek	*3,422*	*34.0*	*6,524*	*64.8*	*-47.5*	*10,066*
			Spw Total:	35,093	23.6	51,958	35.0	-32.5	148,551
Wheatfield Fork	1	L. Wheatfield Fork	Haupt Creek	4,007	13.0	11,632	37.7	-65.6	30,877
			Wheatfield Fork Gualala River	*4,249*	*45.6*	*6,690*	*71.8*	*-36.5*	*9,315*
	2		Tobacco Creek	9,252	19.8	26,103	56.0	-64.6	46,643
			Wheatfield Fork Gualala River	*6,497*	*42.8*	*12,580*	*82.8*	*-48.4*	*15,196*
			Main stem Tobacco Creek	*1,468*	*54.1*	*3,190*	*117.5*	*-54.0*	*2,714*
	3		Flat Ridge Creek	11,869	34.2	22,741	65.6	-47.8	34,670
			Lower Fuller Creek	*2,182*	*39.1*	*5,578*	*100.0*	*-60.9*	*5,578*
			North Fork Fuller Creek	*6,108*	*49.0*	*10,073*	*80.8*	*-39.4*	*12,468*
			South Fork Fuller Creek	*2,449*	*30.0*	*5,587*	*68.5*	*-56.2*	*8,158*
			Sullivan Creek	*170*	*6.6*	*957*	*37.1*	*-82.2*	*2,577*
	4		Annapolis	8,550	25.2	16,049	47.2	-46.7	33,994
			Wheatfield Fork Gualala River	*7,023*	*56.7*	*9,696*	*78.3*	*-27.6*	*12,389*
			Spw Total:	33,678	23.0	76,525	52.3	-56.0	146,184
Wheatfield Fork	1	Walters Ridge	Buck Mountain	2,916	5.9	11,198	22.5	-74.0	49,804
			Wheatfield Fork Gualala River	*4,513*	*37.7*	*6,639*	*55.5*	*-32.0*	*11,957*
	2		Tombs Creek	735	2.0	7,194	20.0	-89.8	36,032
			Main stem Tomb Creek	*735*	*7.2*	*4,822*	*47.1*	*-84.8*	*10,238*
	3		Wolf Creek	7,422	12.9	20,026	34.9	-62.9	57,353
			Wheatfield Fork Gualala River	*5,188*	*34.4*	*10,145*	*67.2*	*-48.9*	*15,103*
			Main stem Wolf Creek	*1,002*	*11.8*	*2,834*	*33.4*	*-64.6*	*8,484*
			Spw Total:	22,511	11.9	62,858	33.3	-64.2	188,971
			Watershed Total:	252,378	21.0	479,282	39.9	-47.3	1,200,176

Analysis of Mapped Data

Preliminary analysis of the mapped data was done using the ArcView GIS by making spatial comparisons of the landslide and stream characteristic data. Analysis of GIS data of mapped stream characteristic, landslide types and landslide potential found strong correlations between mapped stream geomorphic characteristics suggesting sediment deposition and erosion with geologically unstable lands, i.e. active and dormant deep seated landslides, debris slide slopes, or combined in CGS's landslide potential zones 4 and 5 (Plate 2 of the NCWAP Gualala River Watershed Assessment).

Spatial and temporal associations developed from map comparisons of geologic, landslide and stream channel characteristics and discussed below do not imply or otherwise demonstrate the underlying physical causes of the mapped features. The importance of this reconnaissance mapping is to guide in the selection of investigation sites, help inform landowners of historic changes in geomorphology, and aid in the selection of monitoring stations and types of monitoring. Further investigation for site specific projects or studies is needed to develop an accurate estimate of the biological response or effects of the mapped stream and landslide geomorphic features.

In the Gualala River watershed, approximately thirty-nine percent of the 1:24,000 blue line streams have a gradient of less than four percent based on estimates of channel slope taken from the USGS 10-meter grid digital elevation models (DEM), provided by California Department of Forestry and Fire Protection. Approximately thirty-seven percent of the channels are transport reaches with gradients between four and twenty percent. The remaining twenty-four percent of channel are considered source reaches with gradients greater than twenty percent. Figure 22 shows the distribution of the response, transport and source reaches for the Gualala River watershed. Figure 23 shows that most, greater than ninety percent, of the 1999/2000 mapped channel geomorphic characteristics that suggest a potential for high sediment deposition, bank erosion and sediment delivery occur in and adjacent to response and transport reaches.

Anomalous accumulations of in-stream sediment are highly correlated throughout the Gualala River watershed with areas of unstable slopes. Correlation between mapped channel characteristics and upslope mass wasting characteristics are shown in Figures 24 to 30. In Figure 24, seventy percent of the 1999/2000 mapped stream reaches that have characteristics showing a potential for high sediment deposition and sediment delivery are within fifty meters of an active or dormant deep seated landslide.

Small slides mapped as points occur dominantly within larger landslides, active and dormant, or debris slide slopes, areas sculpted by numerous debris slides or debris flows. Fifty-nine percent of the shallow landslides mapped as points features for the period of 1984 to 2000 are found to intersect with the deep seated active and dormant landslides or debris slide slopes, as seen in Figure 25. Similarly, thirty-five percent the small slides mapped as points by the NCRWQCB for the Gualala Technical Support Document (TSD) were within CGS's active or dormant deep-seated landslides, and an additional twenty-nine percent were within CGS's areas of debris slide slopes. Forty-four percent of the small slides mapped as points by CGS probably delivered sediment to the mapped stream reaches in 1999/2000, as shown in Figure 26. Sediment derived from these landslides is eventually transported downstream and becomes disconnected from the source area.

If the areas of high and very high landslide potential, as defined by CGS's zones 4 and 5, are compared to the stream reaches with sediment deposition and erosion characteristics, seventy-two percent of the 1999/2000 mapped reaches are within ten meters, Figure 27. Similarly, eight-two percent of the small landslides mapped as points by the NCRWQCB for the Gualala TSD fell within ten meters of CGS's landslide potential zones 4 and 5.

Of the 1999/2000 mapped stream reaches with eroding banks, sixty-eight percent were within ten meters of a mapped active or dormant deep seated landslide, Figure 28.

A comparison of the mapped gullies with active and dormant deep seated landslides found that seventy-five percent intersected these long-term geologically unstable lands, Figure 29.

Mapped channel characteristic attributes can provide insight into transport processes. For example, Figure 30 shows a portion of Billings Creek planning watershed within the North Fork Gualala River super planning watershed. This mapping demonstrates the complex relationships between mapped channel segments, transport and response reaches, and different periods of mapping. In some reaches, features mapped in 1984 were apparently transported out of the reach by 1999/2000. While in other reaches sedimentation was observed in 1999/2000 that was not seen in 1984.

Preliminary analysis suggests that, in general, for transport reaches the length of mapped characteristics were reduced from 1984 to 1999/2000. While response reaches generally show similar percentages of mapped channel sediment features, particularly in the lower portions of the watershed. In those lower watershed areas, the rate of sediment delivery likely either matches or exceeds downstream transport. Exceptions to this are often found in reaches near areas of high landslide activity, such as active deep seated slides and new or reactivated shallow landslides.

Figure 22. Gualala River watershed showing channel type as response (light blue), transport (violet) or source (gray). Response reaches are approximately 459 km (39%) of the total 1188 km USGS 1:24,000 blue line streams. Transport reaches are approximately 439 km (37%) of the USGS channels. Source reaches are the remaining 290 km (24%). Response reaches are those with a blue line channel gradient of less than 4 percent. Transport reaches have gradients of between 4 and 20 percent. Source reaches have gradient above 20 percent. Channel gradients are calculated from USGS 10 meter grid DEMs. Green grid is USGS topographic 7-1/2 minute boundaries. Black dashed line are CalWater2.2 planning watershed boundaries.

Figure 23. Gualala River watershed showing in red mapped channel characteristics for 1999 and 2000 that suggest excess deposition or sediment delivery, and in blue other mapped channel sediment deposits. Light blue lines are response reaches, slope less than 4 percent, and violet lines are transport reaches, slopes between 4 and 20 percent. Green grid is USGS topographic 7-1/2 minute boundaries. Black dashed line are CalWater2.2 planning watershed boundaries.

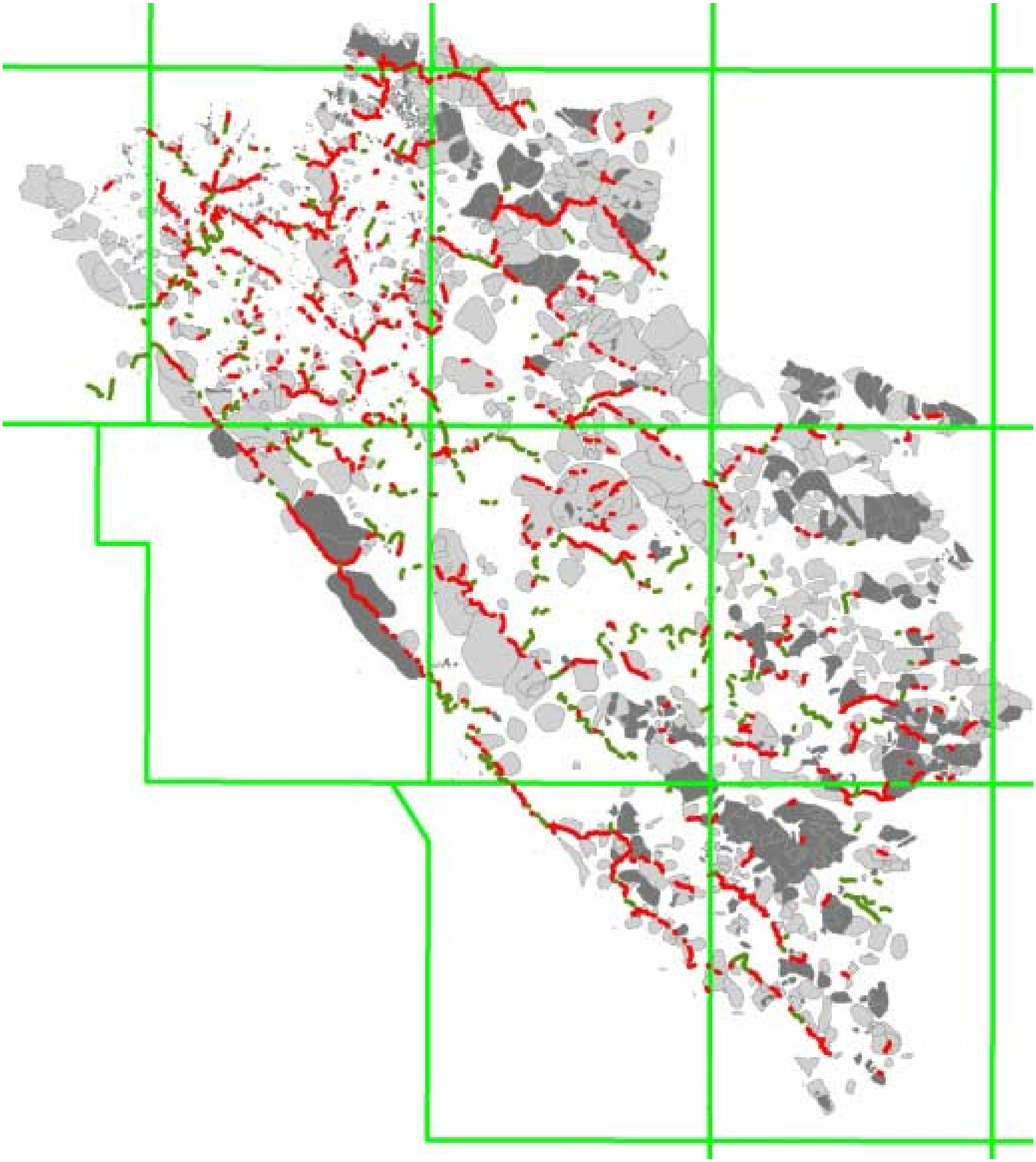


Figure 24. Gualala River watershed showing in red the 70% of 1355 mapped reaches with sediment deposition and erosion stream characteristics are within 50 meters of an active or dormant deep seated landslide. Other mapped stream reaches are shown in green. Light gray polygons are dormant and dark gray are active deep seated landslides. Green grid is USGS topographic 7-1/2 minute boundaries.

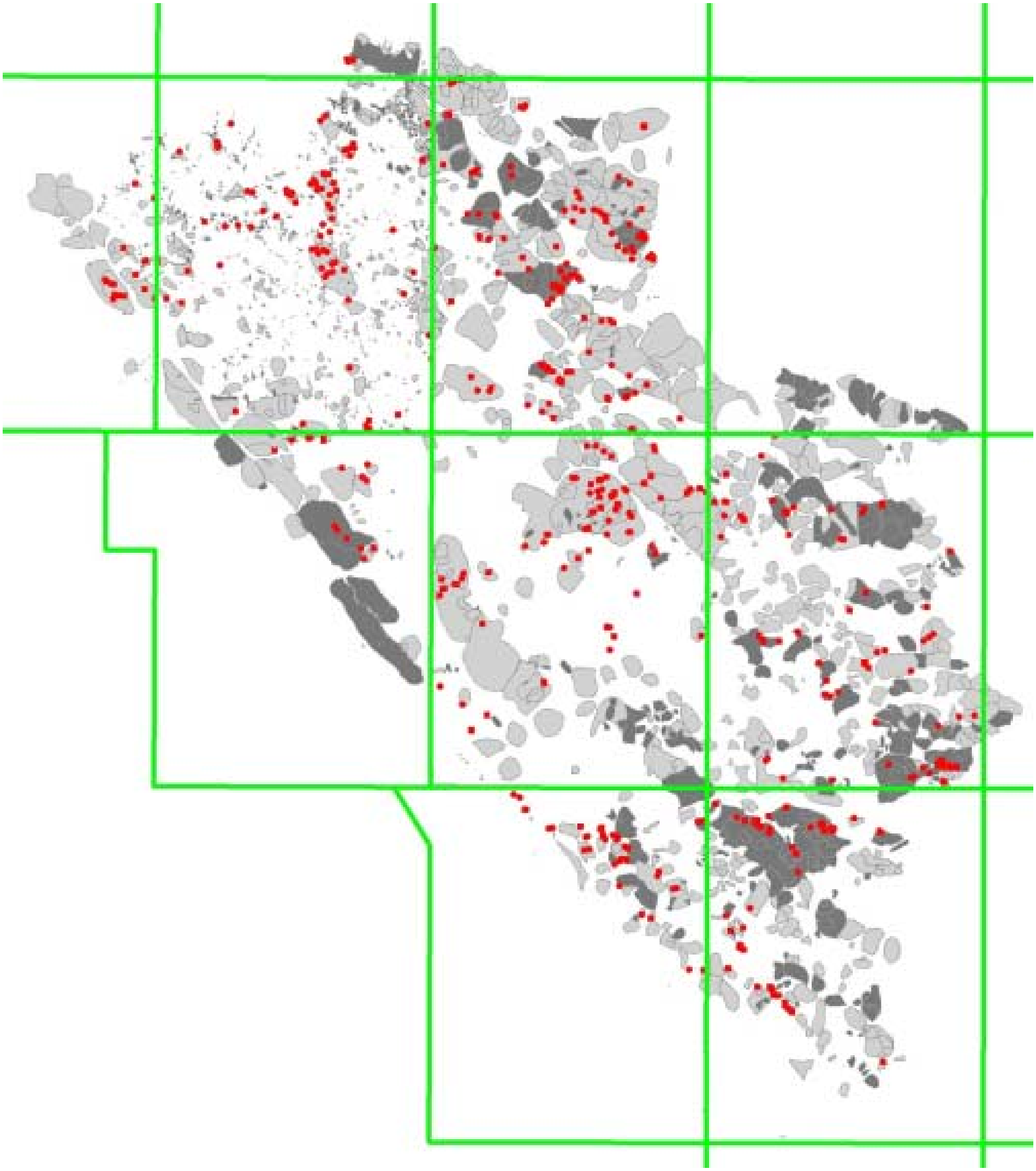


Figure 25. Gualala River watershed showing the 552 of 2190 (25%) mapped shallow point slides that lie within an active or dormant deep seated landslide. The additional 872 point slides (40%) that lie on debris slide slopes are also shown. Light gray polygons are dormant and dark gray are active deep seated landslides. For clarity, the debris slide slope polygons are not shown on this figure. Green grid is USGS topographic 7-1/2 minute boundaries.

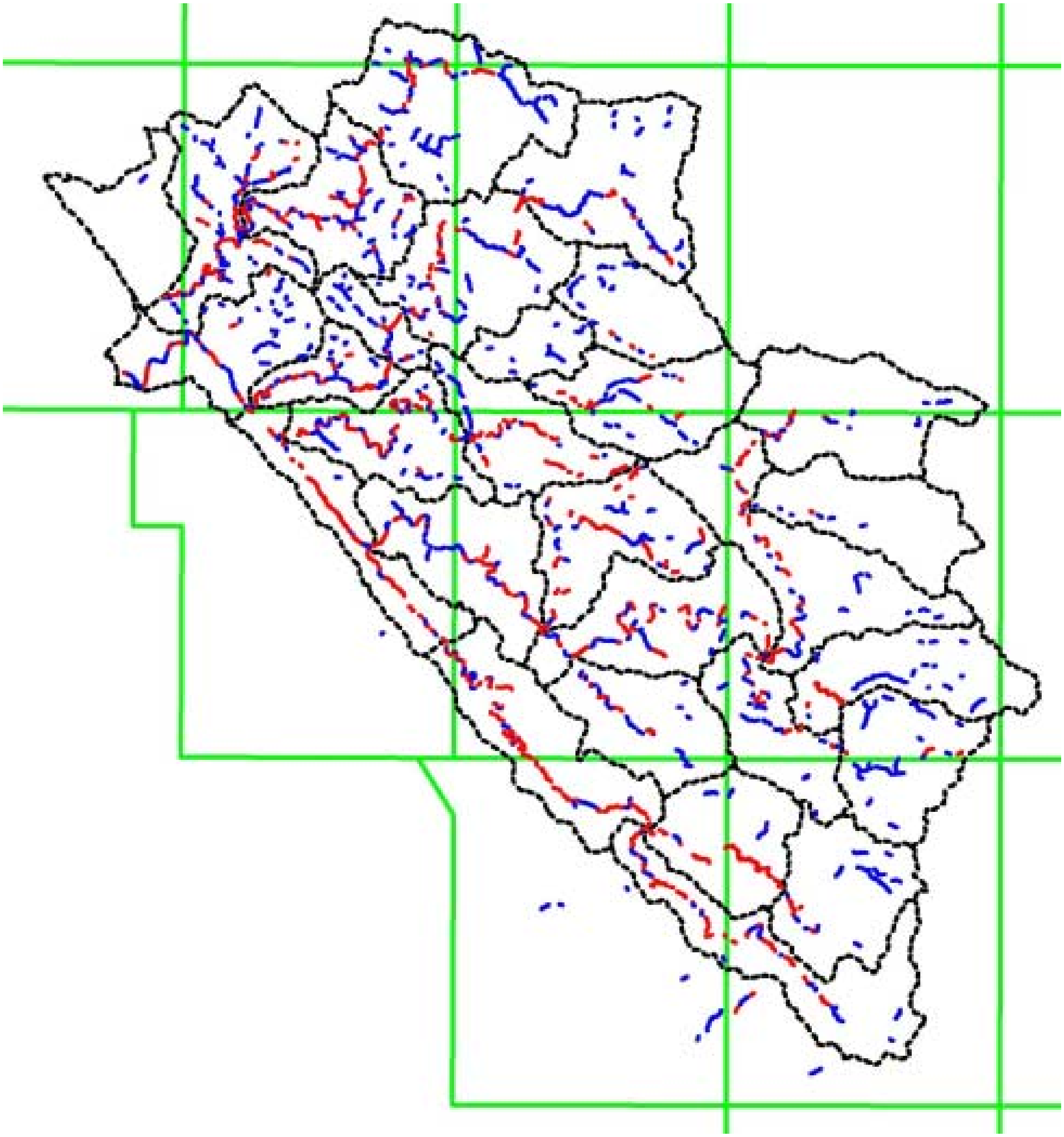


Figure 26. Gualala River watershed showing 44% (599 of 1352) of the mapped stream reaches that have active or older shallow landslides delivering sediment to the channel. Red channels have delivering landslides and blue the other mapped channels. Green grid is USGS topographic 7-1/2 minute boundaries. Black dashed line are CalWater2.2 planning watershed boundaries.

Figure 27. Gualala River watershed showing 72% of mapped stream characteristics lie within 10 meters of CGS's zone 4 and 5 landslide potential polygons. Red channels lie within 10 meters and green lie outside. CGS's zones 4 and 5 polygons not shown on figure for clarity. Green grid is USGS topographic 7-1/2 minute boundaries. Black dashed line are CalWater2.2 planning watershed boundaries.

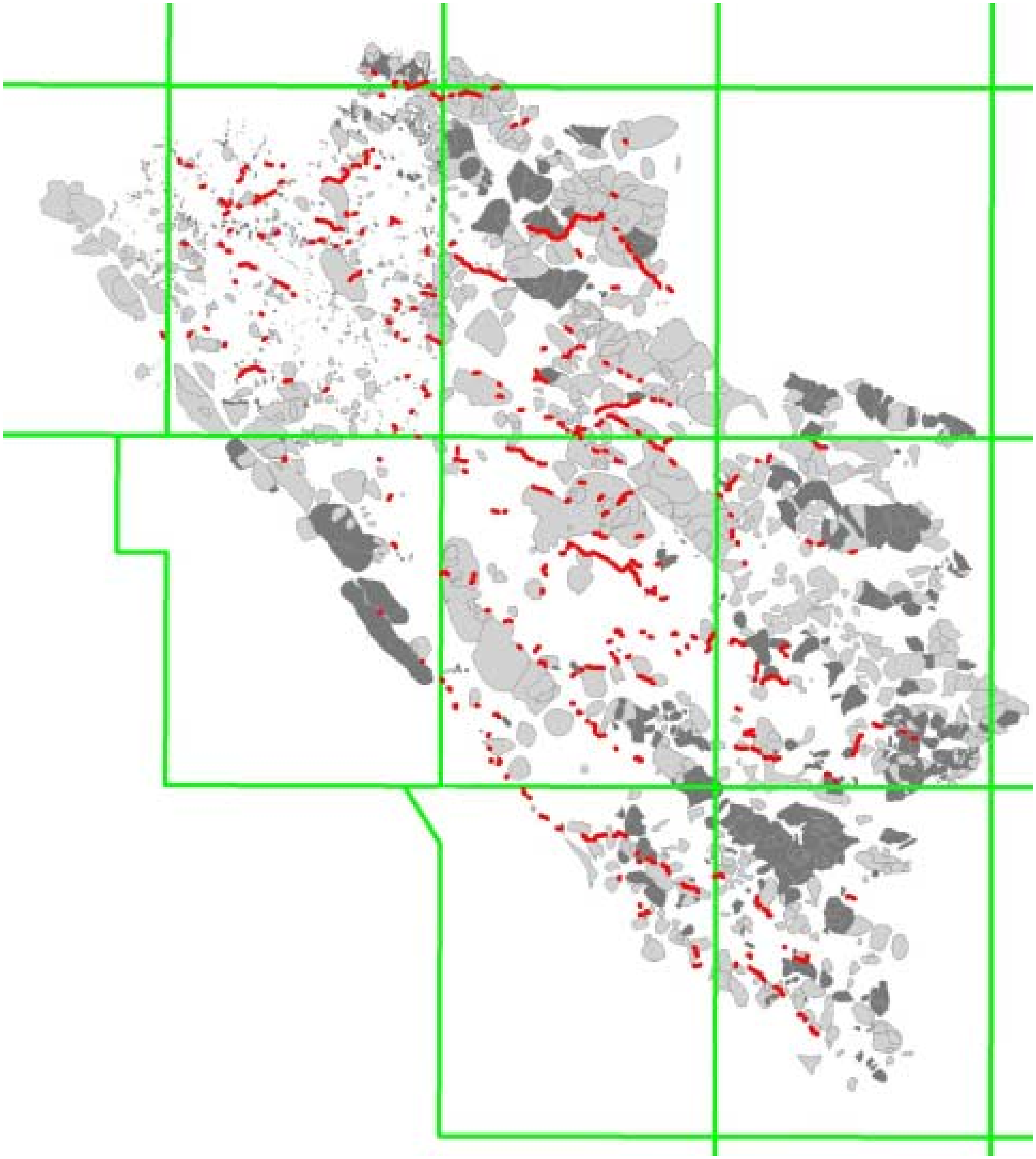


Figure 28. Gualala River watershed showing in red the 68% (252 of 370) of the mapped stream characteristics that have eroding banks and lie within 10 meters of an active or dormant deep seated landslide. Light gray polygons are dormant and dark gray are active deep seated landslides. Green grid is USGS topographic 7-1/2 minute boundaries.

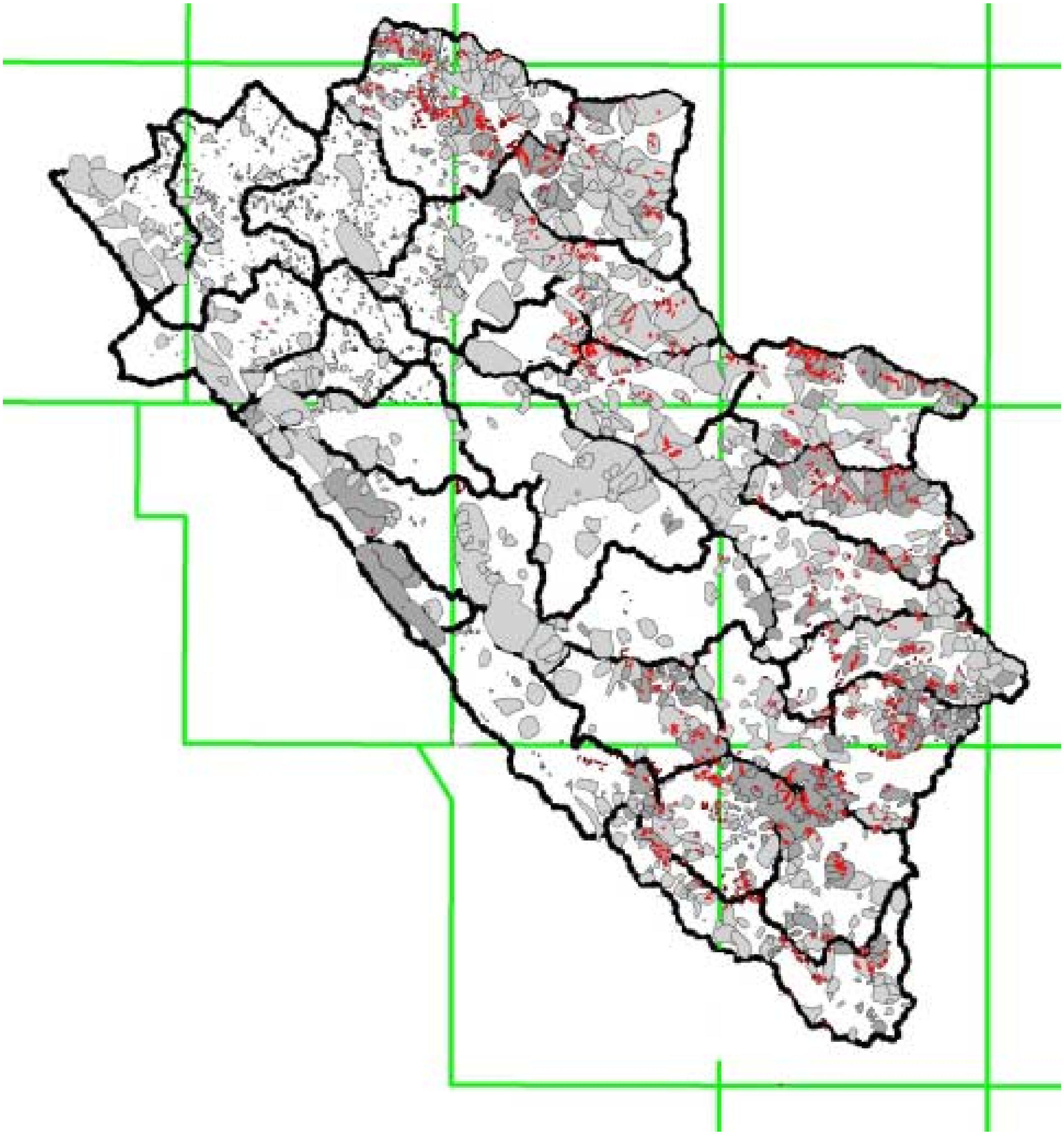


Figure 29. Gualala River watershed showing in red mapped gully features that intersect with active or dormant deep seated landslides. Approximately 50% (780 of 1524) of the mapped gullies intersect with active landslides and approximately 25% (374 of 1524) gullies intersect with dormant landslides. Overall 75% of these features are found in geologically unstable areas. Light gray polygons are dormant deep seated landslides and dark gray active deep seated. Green grid is USGS topographic 7-1/2 minute boundaries. Black dashed line are CalWater2.2 planning watershed boundaries.

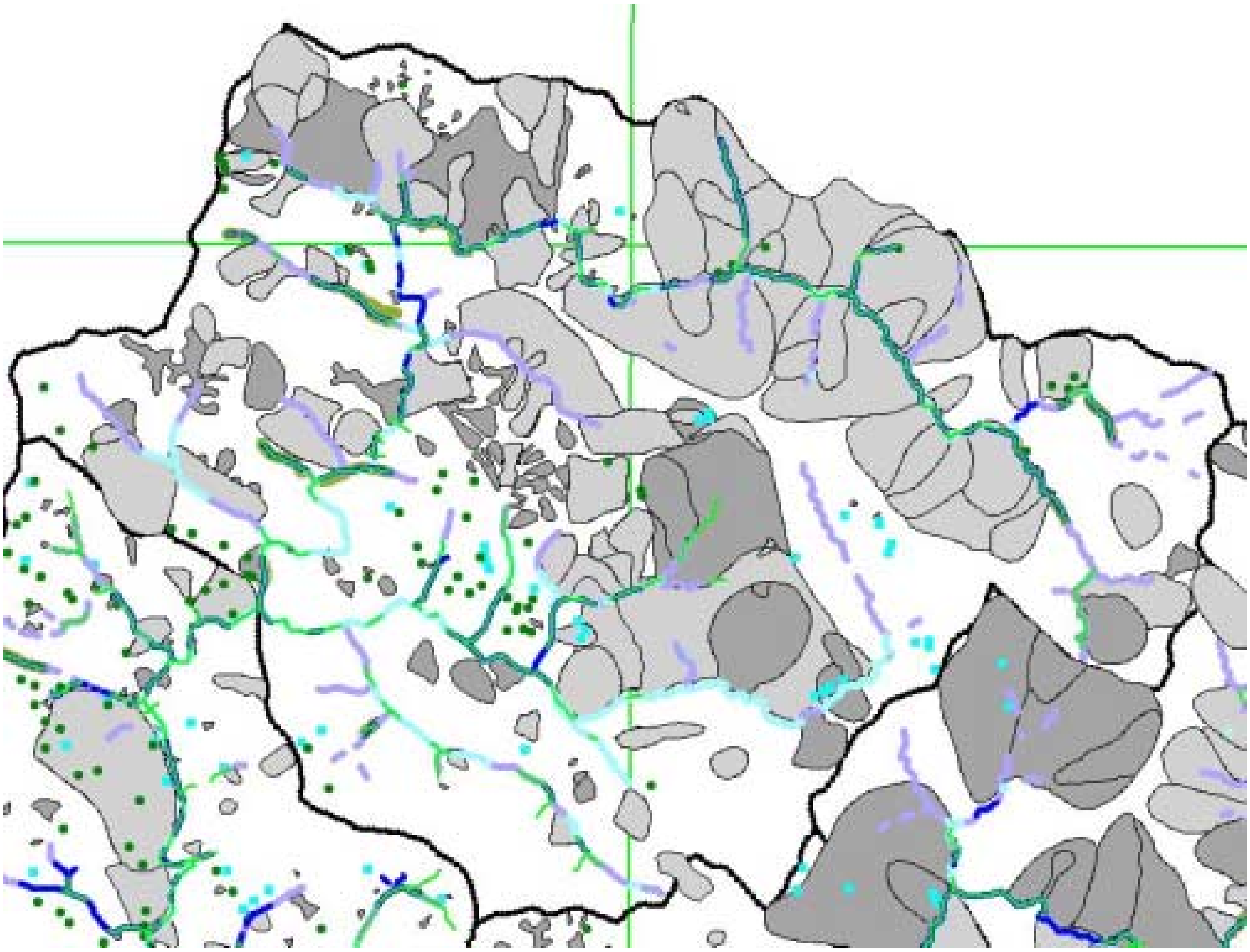


Figure 30. Close up of Billings Creek planning watershed on the North Fork of the Gualala River showing changes in mapped channel characteristics between 1984 and 2000 on top of transport and response reaches. Green lines are 1984 and dark blue lines are 2000 mapped channel features, Transport reaches are shown in violet and response reaches in light blue. Light gray polygons are dormant deep seated landslides and dark gray active deep seated. Green grid is USGS topographic 7-1/2 minute boundaries. Black dashed line are CalWater2.2 planning watershed boundaries. Dots are smaller shallow landslides colored by year identified.

Conclusions

Geologic and geomorphic conditions vary considerably across the Gualala River watershed both between and across the various rock units. For example, within the Franciscan Complex, the geomorphic contrast between NW trending Central terrane and Coastal terrane rock types, is striking in the eastern and southern portions of the basin. Superimposed on this interformational arrangement are three younger and distinctive cross-formational geomorphic subdivisions resulting in a complicated heterogeneous array of landslide features as described on pages 18-23.

The majority of the Gualala River network formed sometime after the deposition and later uplift of the Pliocene (5-1.8 million years ago) Ohlson Ranch Formation. Multiple channel offsets along the San Andreas and Tombs Creek Faults suggest coeval development. The Tombs Creek Fault is believed to be inactive since the Quaternary (10,000 –1,800,000 years ago). These geologic events bracket the time of formation of the majority of the Gualala River network to somewhere between 10,000 years and 2 million years ago.

Gualala River valleys are filled with Holocene alluvium deposited since the end of the last Ice Age (Wisconsin Glaciation), approximately 10,000 years ago. Elk Prairie near the confluence of the North Fork and the Little North Fork is an approximately 1,000 feet wide alluvial plain within the drowned North Fork valley. Subsurface information from Elk Prairie shows the North Fork valley in that area is filled with approximately 180 feet of alluvium consisting of alternating layers of blue clay, gravel, reddish brown silt. This stratigraphy is indicative of alternating low-energy brackish water and high-energy terrestrial depositional environments such as those found in an estuary and a moderate gradient stream, respectively. This implies that Holocene sea level rise was approximately in sync with uplift of the lower North Fork basin. However, at times when sea level rise exceeded uplift, blue clay was probably deposited in an estuary. Conversely, stream gravel was deposited at times when uplift exceed sea level rise. Similar processes probably account for the broad alluvial plains along the South Fork, although subsurface data has not been examined.

The plan and profile of the Gualala River and tributaries are significantly controlled by the distribution of hard versus soft rock. This distribution is related to faulting and landsliding. For example, in the Coastal Terrane of the Franciscan Complex, large relic landslides flank Gualala and Oak Ridges and control the path of the river. Another example is upper Fuller Creek, which is superimposed on and incised into relic landslide terrain. Although these and many other large landslides are dormant they remain as loci of current landsliding and anomalous in-stream sediment accumulations.

Of the “blue line” streams in the Gualala River, thirty nine percent are response reaches and 41 percent are transport reaches. However, these transport and response reaches are affected by numerous landslides. Ninety percent of anomalous accumulations of in-stream sediment were mapped in transport and response reaches based on gradient derived from a 10-meter DEM.

Active landsliding in the watershed occurs as generally small shallow failures in steep areas of the Coastal Terrane and as small to very large earthflow complexes on moderate and steep slopes of the Central, Pickett Peak, Rio Nido, and Yolla Bolly Terranes. Thirty-nine percent of the small shallow (mapped as points when greatest dimension is less than 100 feet) active landslides occur within larger active or dormant landslide. While 70 percent of anomalous accumulations of stream sediment occur adjacent to dormant and active landslide areas. An additional 20 percent of the small shallow landslides occur in areas mapped as debris slide slopes. Sixty-eight percent of mapped eroding banks also occur adjacent to dormant and active landslide areas.

The statistical relationships itemized above indicate that future channel disturbance will likely be most intense near large areas of unstable slopes and affected transport reaches will likely recover before response reaches. The relationship between recent small, shallow slides mapped as points and the surrounding deep seated, long-term landslides has not been studied in sufficient detail to allow for the resolution of what amount of instability is the result of recent land uses and what percentage is due to underlying long-term geologically driven effects. These spatial correlations between long-term geologically unstable lands both shallow and deep seated landslides, and reaches showing geomorphic characteristics that imply excess sediment deposition and erosion suggests that present day stream disturbances and sedimentation are strongly influenced by the adjacent geology and geomorphology and by the lands directly upstream. The finding that 70 percent of the mapped channel features are adjacent to deep-seated landslides or debris slide slope areas suggests that these landslides were a major source of today's channel sediment.

Mapping of landslides in forested terrain from quad scale aerial photos typical under-represents actual landslide occurrence due to masking by tree cover. The landslide potential map (published as Plate 2 of the Gualala River Watershed Assessment) includes consideration of the debris slide slopes and inner gorges as well as landslides in the estimation of landslide potential and probably accounts for many of the landslides missed by aerial photo analysis. Seventy-two percent of anomalous accumulations of stream sediment abut areas with high to very high landslide potential.

Disturbance and Recovery Trends

Temporal trends in sedimentation vary across the watershed. Comparison of aerial photos taken in 1984 with those taken in 1999/2000 show a general decrease in anomalous sediment accumulations in the transport reaches, while the response reaches showed little change. This suggests that movement of sediment in the transport reaches exceeded re-supply over this period. However, in some areas the trend was reversed.

At Valley Crossing (the confluence of the South and Wheatfield Forks), the channel has degraded since a 1942 or earlier aggradation –perhaps related to the 1906 earthquake. However, upstream on both the South and Wheatfield Forks, the loci of mass wasting and in-stream sediment storage have remained essentially the same since 1942 at which time virgin forests flanked the Wheatfield Fork. The upper North Fork, in 1936, was apparently aggraded prior to extensive land use and remains so today. Later photos may show continued aggradation based on more visible areas of gravel bars, but that may be an artifact of vegetation removal. These relationships are illustrated in Appendix A.

Between 1950 and 1970, many timbered areas of the watershed were clearcut. Tractors were operated on steep, erosion prone slopes. Erosion during the winters of those years appeared excessive compared to that of similar winters as seen in earlier photos. Regrowth of the timber stands indicates some degree of recovery throughout the watershed. However, recovery is less certain in some areas. In the oak savanna that overlie the Central Terrane of the Franciscan Complex, riparian vegetation has not re-established since logging, probably due to continued grazing and slope instability. For example, the south-facing slope, above the South Fork of Fuller Creek, marks the edge of dormant landslide terrain and continues to shed sediment at a rate apparently above pre-logging levels. Today the creek shows apparently anomalous accumulations of sediment; however, the channel is not visible in the 1942 aerial photos taken prior to logging due to dense tree canopy.

Recommendations

The potential of channel disturbance, slope instability, and relative recovery rates should be considered in land use planning and management. The Geologic and Geomorphic Features Related to Landsliding Map and the Relative Landslide Potential Map should be referenced to evaluate conditions.

Further field investigations are needed to: distinguish between impacts caused by land uses from those due to natural or background sedimentation; to establish what portion of sedimentation in the channel comes from land uses and what percentage from natural sources; and to determine the range of natural variation in channel sediment composition that should be expected when derived from various sources.

Field based monitoring can help establish transport rates of in-stream sediment. However, landslides are common throughout the watershed and the influence of local landslides on sample locations must be considered. Sediment monitoring on Pepperwood Creek in the Tombs Creek Quadrangle may be especially advantageous. The creek is unique in the watershed because it drains an unstable area of serpentinite. Serpentinite can be readily distinguished in pebble counts and channel surveys.

The landslide and fluvial mapping conducted in the preparation of this report was limited to 1984 and 1999/2000 aerial photos. Other generations of aerial photography can be used for additional mapping to better establish temporal trends. Periodic updates using newer photos should be done as conditions change.

Caution is warranted when selecting in stream sampling locations if the purpose of the sampling is to measure an “average” watershed condition. A sampling site too close to these landslides may be biased by the influx of local sediment. A local source of sediment needs a sufficient distance of transport to allow mixing with the upstream sediments to create a watershed average. Otherwise, the “average” may be heavily influenced by the perturbations in local sediment delivery.

Sediment sites were selected through multiple database queries to derive a map of areas recommended as potential restoration targets based on the data available. The map, Sediment Sites Recommended As Potential Restoration Targets for the Gualala River Watershed, is Plate 3 of the Gualala Basin Assessment Report.

Methodology

Typical tasks making up the mapping process included literature review, site reconnaissance, and mapping. The vast majority of the geologic and geomorphologic interpretations were made through the examination of multiple series of stereo-paired aerial photographs through a mirrored stereoscope. The data derived from the aerial photos was incorporated and is stored in the geographic information system (GIS). The data was transferred through either direct "heads-up" digitizing on screen, or transferred to mylar overlays and then scanned or digitized. Mapped landslides and geomorphic features were defined as indicated below. Two sets of aerial photos were reviewed for the Gualala River watershed assessment. Back and white aerial photos at a nominal scale of 1:31,500 from 1984 were reviewed for the entire watershed. Black and white aerial photos of the Mendocino County portion of the watershed that were taken in 2000 and color aerial photos of the Sonoma County portion taken in 1999 were combined into a single photo set, designated as 1999/2000. The 1999/2000 photo set is at a nominal scale of 1:20,000. Time constraints prevented the review of additional photo sets taken during different years.

Geologic and Geomorphic Base Layers in the GIS

A geologic base map, a landslides inventory map, and a relative landslide potential map were developed. The geologic base is a digital compilation of reference maps modified based on interpretations from aerial photo analysis and limited fieldwork. Topographic bases included U.S. Geological Survey 7.5' topographic maps, digital orthophotoquads (DOQ), and digital elevation models (DEM) with 10-meter contours. The landslide inventory map consists of landslides derived from reference maps, literature review, aerial photo analysis, and field studies. The relative landslide potential map was primarily derived from spatial and statistical analysis based on the presence of landslides and geomorphic features related to landsliding, landslide activity, lithology, and steepness of slope.

Field Studies for Data Verification and Collection

This was a reconnaissance level, remote sensing program. One week of field reconnaissance was conducted during initial landslide mapping and one of week of ground-truthing was conducted toward the completion of mapping. The limited field reviews were conducted to supplement and confirm aerial photograph interpretation and to improve the capture and analysis of data. The accuracy of data (i.e., maps, GIS layers) borrowed from other sources was not field-reviewed.

Geologic Map

The geologic base map (described above) was refined as needed during remote sensing. The geologic map shows the locations of major lithologic units, contacts, geologic structures, and describes the general rock types. The geologic map was compiled and adapted from published USGS geologic maps and other sources. Additional detail is provided in the Previous Work section of this report.

Landslide Assessment

CGS developed detailed information on landslide and geomorphic features. The landslide data were captured as different attributes in the GIS database. These attributes include landslide type, confidence of interpretation, relative age of the feature, thickness, whether material was delivered directly to a watercourse, and whether features such as roads, timber harvests, or stream undercutting were observed in the immediate vicinity of the landslide. The complete list of attributes are contained in the metadata for the electronic data. However, it should be noted that due to schedule constraints, not all attributes were captured for all features for the Gualala River Watershed. As such, a blank in a specific attribute field does not necessarily mean that attribute is not present or does not apply, but could be that it was not captured during the mapping efforts.

Mapped landslides were digitized into multiple GIS layers. Landslides too small to capture at the map scale (less than the minimum mapping unit for polygons of approximately 100 feet in diameter) were captured as lines or points. Each landslide is stored in only one of the GIS layers, unless remapped due to detectable enlargement. Due to the limited photo review, data regarding the onset of active landslides were not systematically collected. Generally judgments of the recency of movement relative to the photo in which observed were recorded.

Each landslide is classified according to the materials involved and the movement type, as deduced from the associated landforms. A two-part designation is given to each slide, based on the system of Cruden and Varnes (1996). Materials are called either rock or soil, and soil is subdivided into fine-grained (earth) and coarse-grained (debris). This classification system formulated terminology that describes the materials and processes involved in a landslide, all of which could not be reliably determined from small-scale aerial photos. The terms and definitions of Cruden and Varnes (1996) were used; but were simplified to capture only the primary details of a given landslide, which could be reliably interpreted from aerial photos alone.

The following landslide types and geomorphic features were used to develop the Geologic and Geomorphic Features Related to Landsliding maps (Plate 1) of the NCWAP Gualala River Watershed Assessment. The features are described below.

Rock Slide

Rock slides consist of a mass of somewhat intact rock that in many cases may be deeply weathered and pervasively sheared. Zones of weakness such as shears or joints limit the strength of intact masses of rock. Typically these landslides move downslope on one or several shear surfaces. The shear surface(s) may be curved (as in a rotational slide) or planar (as in a translational slide). In some older classification systems, slides with curved failure surfaces are commonly referred to as slumps, while those with planar failure surfaces are called block glides.

Earth Flow

Earth flows are a mixture of fine-grained soil, consisting of surficial deposits and deeply weathered, disrupted bedrock. The material strength is low through much of the slide mass, and movement occurs on many discontinuous shear surfaces throughout the landslide mass. Although the landslide may have a main slide plane at the base, many internal slide planes disrupt the landslide mass leading to movement that resembles the flow of a viscous liquid. Earth flows commonly occur on less steep slopes than rock slides, in weak, clay-rich soils or disrupted rock units.

Debris Slide

Debris slides are composed of coarse-grained soil, commonly consisting of a loose combination of surficial deposits, rock fragments, and vegetation. Strength of the material is low, and there may be a very low strength zone at the base of the soil or within the weathered bedrock. Debris slides typically move initially as shallow intact slabs of soil and vegetation, but break up after a short distance into rock and soil falls and flows.

Debris Slide Slopes

Debris slide slopes are geomorphic features characterized by steep, occasionally well-vegetated slopes that appear to have been sculpted by numerous debris slides and debris flows. Upper reaches (source areas) of these slopes are often concave and very steep. Soil and colluvium atop bedrock may be disrupted by active debris slides and debris flows. Slopes near the angle of repose may be relatively stable except where weak bedding planes, bedrock joints, and fractures parallel the slope.

Debris Flow

A debris flow is a mass of coarse-grained soil that flows downslope as a slurry. Material involved is commonly a loose combination of surficial deposits, rock fragments, and vegetation. High pore water pressures, typically following intense rain, cause the soil and weathered rock to rapidly lose strength and flow downslope. Debris flows commonly begin as a slide of a shallow mass of soil and weathered rock. Their most distinctive landform is the scar left by the original shallow slide. In many cases debris flows leave a linear scar called a torrent track.

Rock Fall

A rock fall is where a fragment or fragments break off of an outcrop of rock and falls, tumbles or rolls downslope. Rock falls typically begin on steep slopes composed of hard rocks and result in piles of loose rubble at the base of the slope.

Disrupted Ground

This category is defined as irregular ground surface caused by complex landsliding processes resulting in features that are indistinguishable or too small to delineate individually at 1:24,000 scale, and also may include areas affected by downslope creep, expansive soils, and/or gully erosion.

Inner Gorge

An inner gorge is a geomorphic feature consisting of steep slopes adjacent to channels. The gorge typically is created by accelerated downcutting in response to regional uplift. It is defined as an area of streambank between the channel and the first break in slope.

Gullies

Gullies are distinct, narrow channels formed by erosion of soil or soft rock material by running water. Channels are larger and deeper than rills and usually carry water only during and immediately after heavy rain or following the melting of ice or snow.

Activity of Landslides

Landslides are classified based on the recency of activity as modified from Keaton and DeGraff (1996). Under NCWAP, landslides were categorized as historically active or dormant. In some cases, dormant landslides were further subdivided.

The classification system of Keaton and DeGraff (following Varnes, 1978) uses the term “active” to mean active in the past year and “dormant-historic” to active within the last 100 years. These terms were combined as “historically active” for NCWAP and the time period increased 150 years to reflect the time since European settlers arrived in the North Coast. In the North Coast, landslides that have not revegetated with mature forest or grasslands that show immature drainage are considered to be historically active (less than 150 years old). Historically active landslides under NCWAP are landslides that can be actively moving or have moved within the past 150 years, based on freshness of features related to most recent movement.

Landslides that have not moved within the last 150 years, based on geomorphic features, are classified as dormant. Some of the dormant landslides are further classified based on relative age and geomorphic features. These classifications are dormant young, dormant old, and dormant mature. Dormant young landslides are characterized by rounded scarps, the absence of cracks, and partially filled depressions or ponds. Dormant old are characterized by extensive erosion of landforms related to the landslide, including significant gullies or canyons cut into the landslide mass by streams, and rounding of original headscarp benches and hummocky topography. Dormant mature slides are recognized by the fact that the landforms have been smoothed by erosion, re-vegetation has occurred, , the main scarp is rounded, the toe area is eroded, and drainage is well established. .

In many cases in the Gualala River Watershed landslide mapping, dormant landslides were not differentiated as dormant young, dormant old, or dormant mature due to time constraints. Therefore, many dormant landslides are classified simply as dormant.

Confidence of Interpretation

Each mapped landslide is also classified as definite, probable, or questionable. Because landslides are mapped based on their landforms, the confidence of identification is dependent on the distinctness of those landforms. Landslide size also limits the confidence. Those that are too small to see clearly or those that have been altered significantly are more difficult to identify. Confidence of interpretation is classified according to the following criteria.

Definite Landslide

Nearly all of the diagnostic landslide features are present, including but not limited to headwall scarps, cracks, pronounced toes, well-defined benches, closed depressions, springs, and irregular or hummocky topography. These features are common to landslides and are indicative of mass movement of slope materials. The clarity of the landforms and their relative positions clearly indicate downslope movement.

Probable Landslide

Several of the diagnostic landslide features are observable, including but not limited to headwall scarps, rounded toes, well-defined benches, closed depressions, springs, and irregular or hummocky topography. These features are common to landslides and are indicative of mass movement of slope materials. The shapes of the landforms and their relative positions strongly suggest downslope movement, but other explanations are possible such as faulting.

Questionable Landslide

Few, generally very subdued, features commonly associated with landslides can be discerned. The area may lack distinct landslide morphology, but may exhibit disrupted terrain or other abnormal features that vaguely to strongly imply the occurrence of mass movement. Includes bulges low on the slope below upper slope concavities. However; the questionable landslide may have distinctive scarps, sag ponds, obvious benches the origin of which are questionably either seismic, mass wasting, or a combination.

Relative Landslide Potential

Once relevant relationships between geology and landsliding were recognized, a relative landslide potential map was created in GIS. The relative landslide potential map was compared with the slope maps, landslide density thematic map, and other available slope models for important variations. Any important variations were interpreted and subclassified. The relative landslide potential was defined and illustrated in five categories from 1 (most stable) to 5 (least stable). Additional modifiers, which supplement the primary definitions, were added as relevant. The assignment of the categories was an interpretative process and was based on relations drawn from the Landslide and Geomorphic Features Related to Landsliding Map, statistical analysis, and general field observations. The matrix used to develop the landslide potential map is presented below:

Table 5: Matrix for Landslide Potential Map

Landslide/Geomorphic Feature	Slope in percent				
	0 - 29	30 - 49	50 - 64	65+	
Historically active slides	5	5	5	5	
Dormant slides					
earthflow	3	4	4	4	
	Slope in percent				
	0-29	30-39	40-64	65+	
rockslide	3	3	4	4	
	Slope in percent				
	0-30	31-60	60+		
Earthflow dormant mature	2	3	4		
Rockslide dormant mature	2	3	4		
Geomorphic features					
	Slope in percent				
	0 - 29	30 - 49	50 - 64	65+	
inner gorge	5	5	5	5	
Disrupted ground	3	4	4	5	
debris slide slope	4	4	4	5	
Debris slide slope 81	3	3	3	3	
gullies	5	5	5	5	
	Slope in percent				
Others	0 - 29	30 - 49	50 - 64	65+	
High convergence areas	5	5	5	5	
Tor buffer	4	4	4	4	
	Slope in percent				
Geological subareas	0 - 14	15-29	30 - 39	40 - 64	65+
Coast	3	4	5	5	5
Qsc: Qsc1, Qscu, Qrt	1	2	4	5	5
Qal	1	2	4	5	5
Q: Qt, Qbs, Qf, Qmt, Qoal	1	2	4	5	5
Tkf: TKfs,Tkfss,Tku,Kfgs,Kfss	1	2	3	3	4
Qtor: QTor,QTorc, QTors	2	3	4	5	5
KJf: Jfmg,KJfm,KJfs	3	4	4	4	5
Tsm	3	3	4	5	5
Sp	3	4	5	5	5
Centennial	3	4	5	5	5
Triangle	2	3	4	4	5
Others:	1	2	3	3	5

KJgvs,Ka,Ksb,Ks,Tg,ch,gwy,m,sc					
	Slope in percent				
	0-14	15-29	30-49	50-64	65+
TKfss1	1	2	3	4	5
	Slope in percent				
	0-10	11-20	21-39	40-60	60+
gs	1	2	3	4	5
TKfs1	1	2	3	4	4

The landslide potential map was constructed as an individual GIS layer and produced at a scale of 1:24,000. Further explanation of the categories and their implications for land use follows:

- ***Category 1, Very Low Landslide Potential:*** Landslides and other features related to slope instability are very rare to non-existent within this area. This area includes relatively flat marine terraces, lower stream valleys, and flat-topped ridges in the Gualala River Watershed. There is the possibility that small areas with much higher landsliding potential (similar to Categories 3, 4, or 5) could be present. A limited site-specific evaluation is recommended to address slope stability issues prior to changes in existing slopes or drainage.

- ***Category 2, Low Landslide Potential:*** Gentle to moderately steep slopes underlain by relatively competent material that is considered unlikely to mobilize as landslides under natural conditions given the current understanding of regional seismicity. Landsliding in these areas is not common. This area generally includes the flat-topped ridges of the Ohlson Ranch Formation and marine terraces west of the San Andreas Fault. There is the possibility that small areas with much higher landsliding potential (similar to Categories 3, 4, or 5) could be present. A site-specific evaluation is recommended to address slope stability issues prior to changes in existing slopes or drainage.

- ***Category 3, Moderate Landslide Potential:*** Moderate to moderately steep, relatively uniform slopes that are generally underlain by competent bedrock, and may also include older dormant landslides. Some slopes within this area may be at or near their stability limits due to weaker materials, steeper slopes, or a combination of these factors. This area dominantly occurs in dormant landslides west of the San Andreas Fault and in the rocks of the Coastal Terrane west of the Tombs Creek Fault zone. Landslides in this category typically occur as small (less than an acre) debris flows, debris slides, and rockslides. In addition, there is the possibility that isolated areas within Category 3 could include features that represent higher likelihood of landsliding more similar to categories 4 and 5. A site-specific review is recommended to evaluate effects of proposed changes to existing land use with respect to slope stability.

- ***Category 4, High Landslide Potential:*** Moderately steep to steep slopes that include many dormant landslides in upslope areas and slopes upon which there is substantial evidence of down slope creep of surface materials. This area consists of large dormant earthflows dominantly occurring east of the Tombs Creek Fault zone, areas of disrupted ground on moderately steep (30-64 percent) slopes, and much of the incised and moderately steep area of the Coastal Terrane. A site-specific review is recommended to evaluate effects of proposed changes to existing land use with respect to slope stability. Additional caution is advised in these areas.

- ***Category 5, Very High Landslide Potential:*** Areas include historically active landslides (<150 years old) and inner gorges, as well as debris slide/flow source areas on steep to very steep slopes (>65 percent). Landslides typically occur as large earthflows in the Central Terrane east of the Tombs Creek Fault zone and as small (less than one acre) rock slides, debris slides, and debris flows in the Coastal Terrane. A site-specific review is recommended to evaluate effects of proposed changes to existing land use with respect to slope stability. Extreme caution is advised in these areas.

Fluvial Geomorphic Analysis

For the Gualala River Watershed, CGS evaluated, compiled, and mapped channel fluvial characteristics. Mapping was done through interpretation of aerial photographs from two time periods, 1984 and 1999/2000, and calibrated with limited field studies. CGS mapped 32 types of fluvial geomorphic attributes (Table 2-1). The purpose of the time-series analysis was to document site conditions using multiple sources of information, and to obtain information that reveals changes in channel characteristics. The fluvial data dictionary and explanatory photographs are presented in Appendix 8. Appendix B provides a photo mapping dictionary description of each mapped stream characteristic and one or more example images of mapped features.

The methodology developed by CGS for mapping fluvial geomorphic features was modified after the RAPID technique (Grant 1988) for evaluating downstream effects of forest practices on riparian zones. The basic technique of mapping channel change is the same for both methods. However, the methodology used by RAPID to measure patterns of riparian canopy disturbance was modified to include additional information on channel geomorphic characteristics that are observable on aerial photos. These features were then attributed in the GIS database for map preparation and data analysis.

CGS's fluvial geomorphic mapping identified areas of stored channel sediment or sources of sediment that could be resolved on the available aerial photographs. The attributes in Table 2-1 in bold are those that may be indicators of excess sediment in storage or sediment sources that could be considered detrimental to optimum habitats for anadromous salmonids. While most of these features are always associated with increased sediment or impaired conditions, others, such as lateral bars, may or may not represent impairment. To be conservative, if one of the features in Table 2-1 is assigned an attribute that indicates excess sediment storage or sediment sources, it is included with those characteristics considered as a potentially detrimental attribute.

While the significance of each mapped feature relative to channel habitat quality varies, the time-series mapping helps track changes and trends in channel conditions. As an example, the lateral bars were considered a detrimental feature, whereas, the point bars were not. The lateral bars were considered detrimental because they appeared more dynamic than the point bars (i.e., changing their size and position more readily than point bars). Lateral bars were often observed directly adjacent to a source of channel sediment, such as a landslide, and often remain for some time after the landslide has revegetated. The association of lateral bars and sediment sources is not unique to the Gualala River Watershed. By tracking all of the lateral bars, the changes in channel deposits can be better documented. Lateral bars that remain stable become a measure of the baseline condition. This method was applied to all of the north coast watersheds being studied by the NCWAP program.

Table 6: Database Dictionary for GIS Mapped Fluvial Geomorphic Attributes

wc - wide channel	**ag – aggrading reach**
br – braided channel	**dg – degrading reach**
rf – riffle	**in – incised reach**
po – pool	ox – oxbow meander
fl – falls	ab – abandoned channel
uf – uniform flow	am – abandoned meander
tf – turbulent flow	**cc – cutoff chute**
bw – backwater reach	**tf – tributary fan**
pb - point bar	lj - log jam
lb - lateral bar	**ig - inner gorge**
mb – mid-channel bar	**el - eroding left bank (facing downstream)**
jb - bar at junction of channels	**er - eroding right bank (facing downstream)**
tb - transverse bar	**la - active landslide deposit**
vb - vegetated bar	**lo - older landslide deposit**
vp - partially vegetated bar	**dr – displaced riparian vegetation**
bc – blocked channel	ms – man-made structure

CGS mapped the fluvial geomorphology for all watercourses in the Gualala River Watershed designated by blue lines on published U.S. Geological Survey (USGS) 1:24,000-scale topographic quadrangle maps. This information is available electronically in GIS layers and in the fluvial data dictionary.

Time-series fluvial geomorphic mapping conducted for the project provided data to allow for evaluation of changes in channel morphology between 1984 and 1999/2000. Other fluvial parameters mapped by CGS at this reconnaissance scale include channel slope calculated from a 10-meter DEM(provided by Fire and Resource Assessment Program [FRAP]) and channel type, using the Rosgen classification system (Rosgen, 1996). Blue line stream hydrography was coded for stream slope based on percent values calculated by ArcInfo 8.1 software. The six stream slope categories were plotted to match stream class breaks of the Rosgen classification system (Rosgen, 1998). Table 7 lists the Rosgen classes associated with each the ranges of slope gradient.

Table 7: Rosgen Classes and stream gradients.

Stream Gradient Ranges	**Rosgen Classes**
0 – 0.1%	**Gc, F, Bc, E, Cc-, Dc-, DA**
0.1 – 1%	**Gc, F, Bc, C, E, DA**
1 – 2%	**Gc, F, Bc, E, C, D**
2 – 4%	**G, Fb, B, Eb, Cb, Db**
4 – 10%	**A, Ba**
> 10%	**A+**

Six groups of fluvial features were mapped, *stream features* (polygons, line, points), *gullies* (lines), *alluvial contacts* (polygons), *channel classification* (lines), *watershed characteristics* (points), *channel data sources* (points), and *delivering landslides* (points). Because of the ArcView shape file requirements, features were mapped either as a polygon, line or point. Three shape files for stream features were produced for each photo set. The project mapping scale was set at the 7-1/2 minute, 1:24,000 scale, even though the GIS would allow for a larger scale. Standards were used by CGS staff for both the fluvial and landslide mapping to distinguish when to map a feature as a polygon, line or point. Polygons were mapped when the feature has a diameter of 100 feet or greater and an area of 1/5 acre (8,700 square feet or 750 square meters). Line features were at least 150 feet long (45 meters). Feature smaller than these criteria were mapped as points.

The primary characteristic field was used in the NCWAP Watershed EMDS modeling effort to determine whether the feature indicated channel instability or excess sediment storage. This EMDS requirement resulted in an exception to the rule of placing the most dominant feature in the primary characteristic field whenever the project geologist felt that the mapped feature should or should not be counted in EMDS as a stream feature that was detrimental to habitat of anadromous salmonids. For example, when a large point bar had a small active landslide feeding it, the active landslide characteristic was entered into the primary field if it was felt to still be providing sediment to the channel.

Limitations

Limited aerial photo coverage does not bracket temporal distribution of important watershed events, which may not be evident in photos taken years after the fact.

This project consisted of a reconnaissance level review of two sets of aerial photographs. The photos were taken in 1984 and 1999/2000. Mapping was conducted at a scale of 1:24,000 and covered the entire watershed. At this scale, the detection of features smaller than 100 feet in greatest dimension is poor.

Detailed site level mapping of landslides and sediment delivery were conducted by outside parties in various portions of the watershed; however, time and staffing constraints prevent evaluation of that data.

Existing geologic mapping of the Rockpile Creek subbasin is limited to the CDMG 1:250,000 scale regional map. The presence and location of geologic features in this area were inferred from surrounding areas where more detailed mapping was available.

Due to access, time, budget, and staffing constraints; field checking of interpretations was extremely limited.

Landslide mapping from 1:24,000 scale aerial photos typically under-represents the abundance of small landslides due masking by forest cover and the lack of resolution. Similarly, channel characteristics are under represented because of masking by forest cover, and submergence by surface flows. Gullies are also under represented because they are typically only observed if they are in grass lands or sparsely vegetated areas, and must be deep enough to cast a shadow.

Spatial and temporal associations developed from comparisons of geologic, landslide and stream channel geomorphic characteristics mapping do not imply or otherwise demonstrate the physical causes of the mapped features, their importance to site specific projects or studies, or the biological response or effects of the mapped features.

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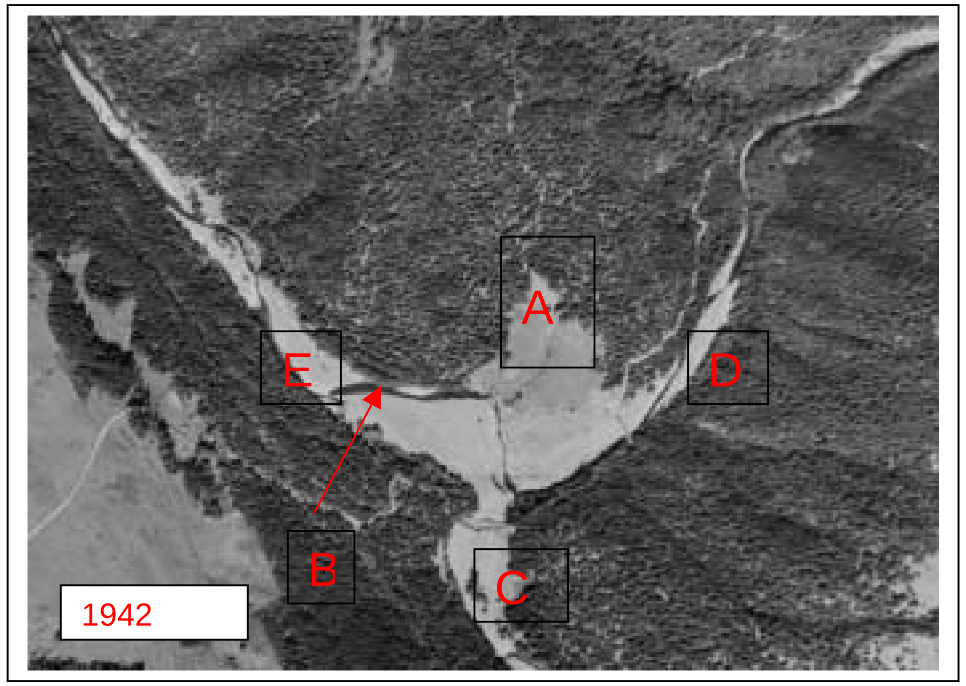
APPENDICES

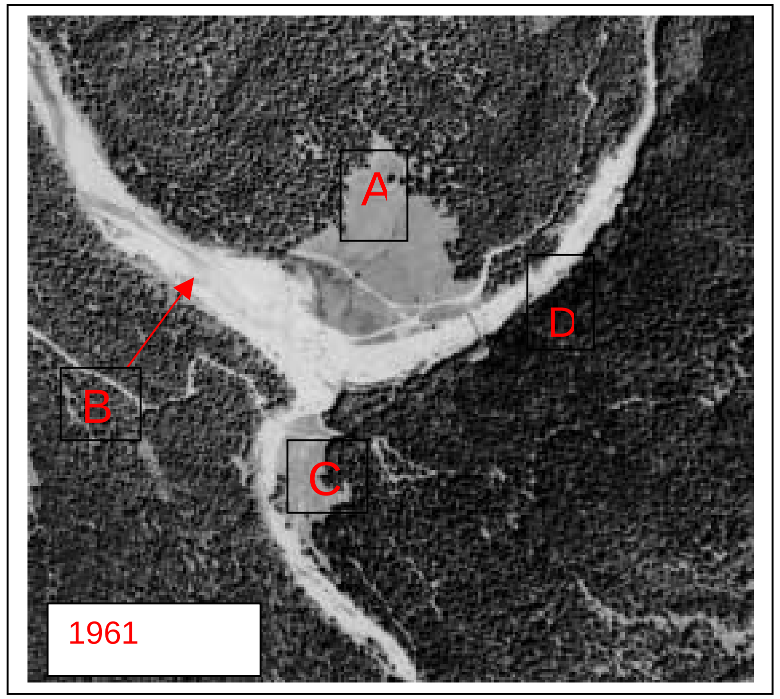
APPENDIX A

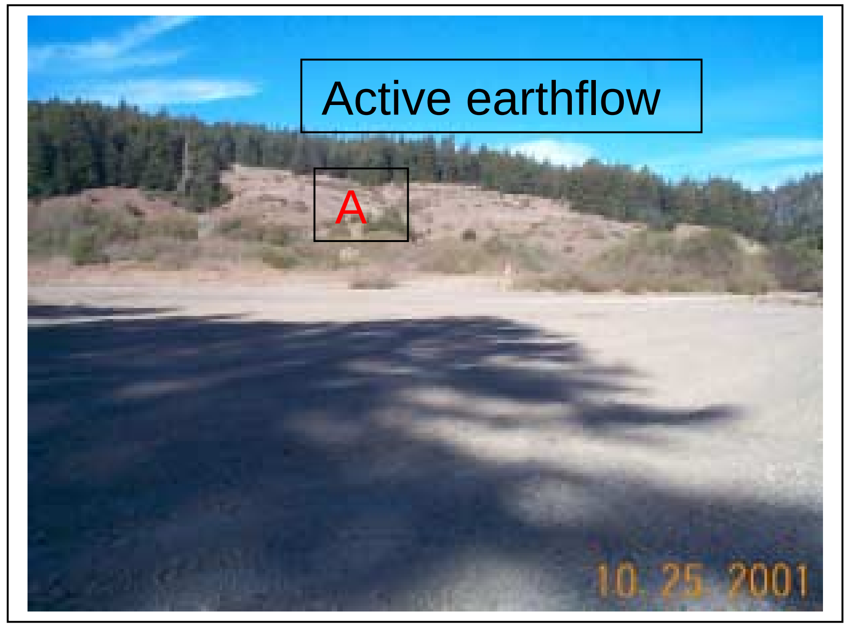
Selected Time Series Aerial Photos for Change Detection

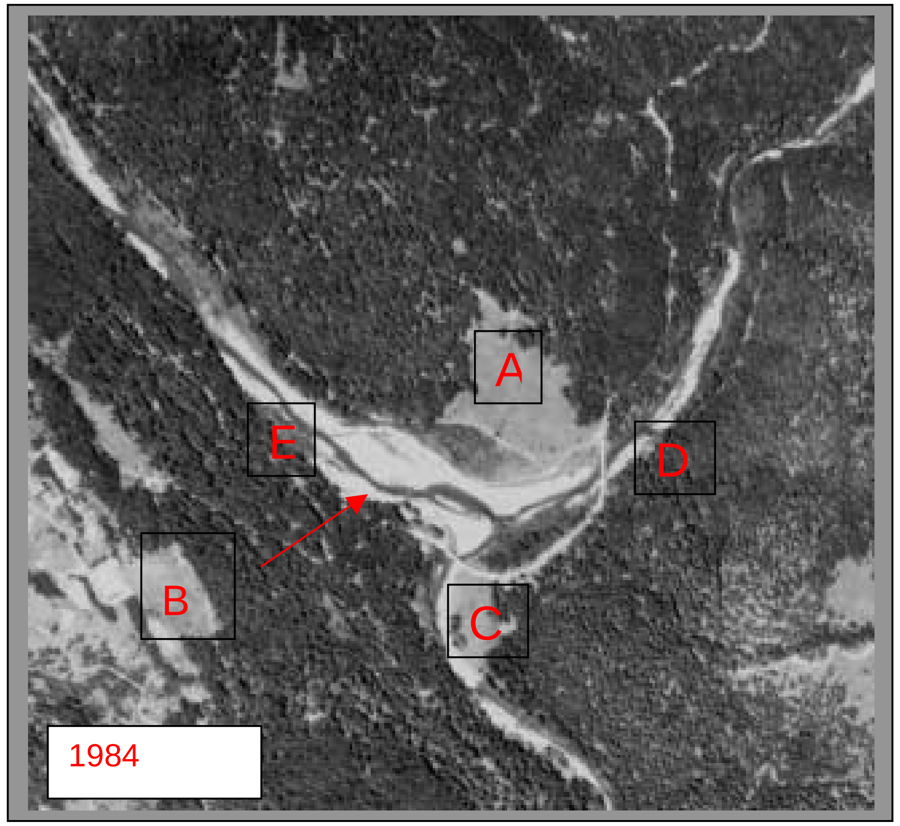
THE CONFLUENCE OF THE WHEATFIELD AND SOUTH FORKS OF THE GUALALA RIVER THROUGH TIME

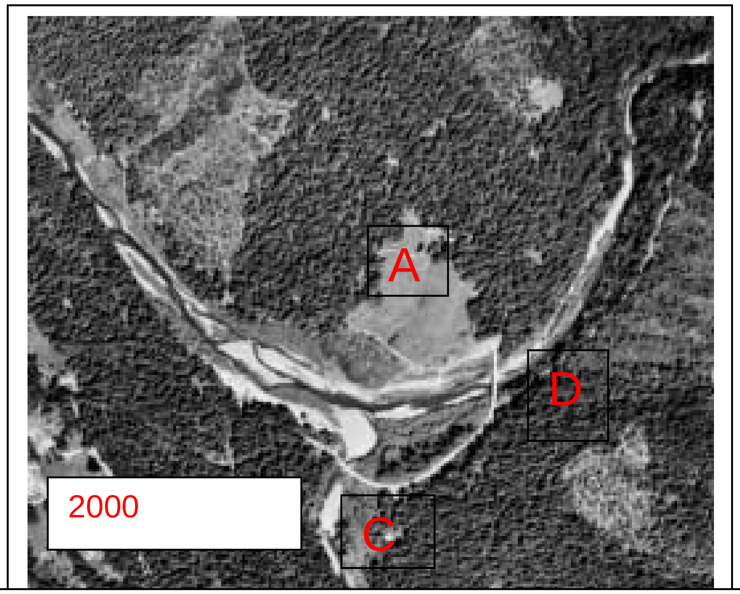
Progressive downcutting, sediment stabilization, and transport

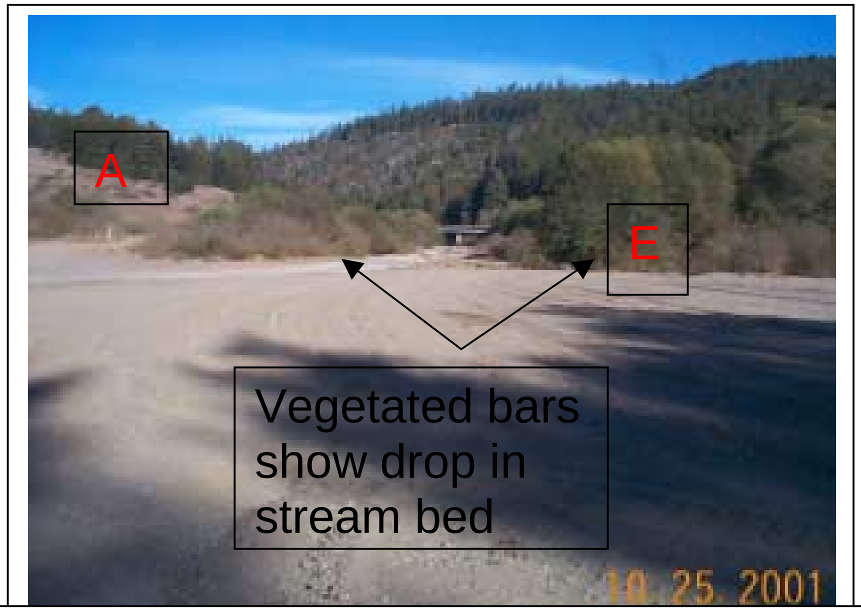








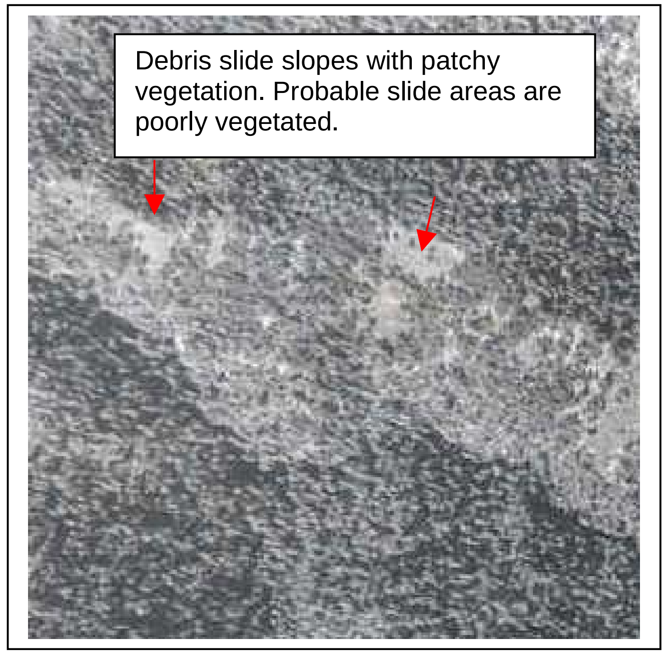




Feature A: Active earthflow
Feature B: Main Channel migrates away from toe of earthflow
Features C, D, and E: Bars active in 1942, abandoned by 1984, and vegetated by 2000

Upper Fuller Creek watershed in 1942 and 1993

1942

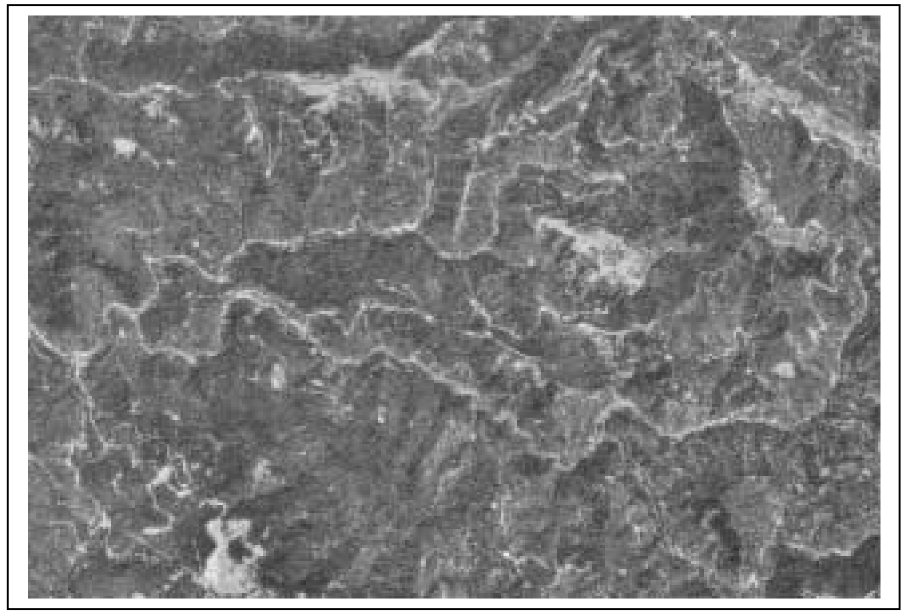


Debris slide slopes with patchy vegetation. Probable slide areas are poorly vegetated.

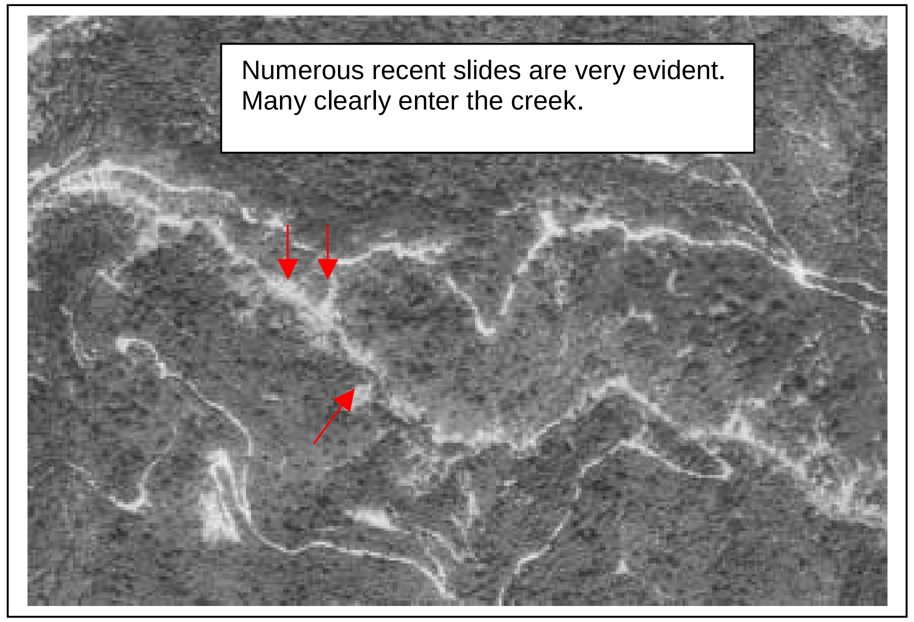
Lower South Fork

Upper South Fork

Comparison shows a persistent elevation in landslide activity. According to CDF photoanalysis, landsliding increased shortly after tractor logging on these steep slopes.

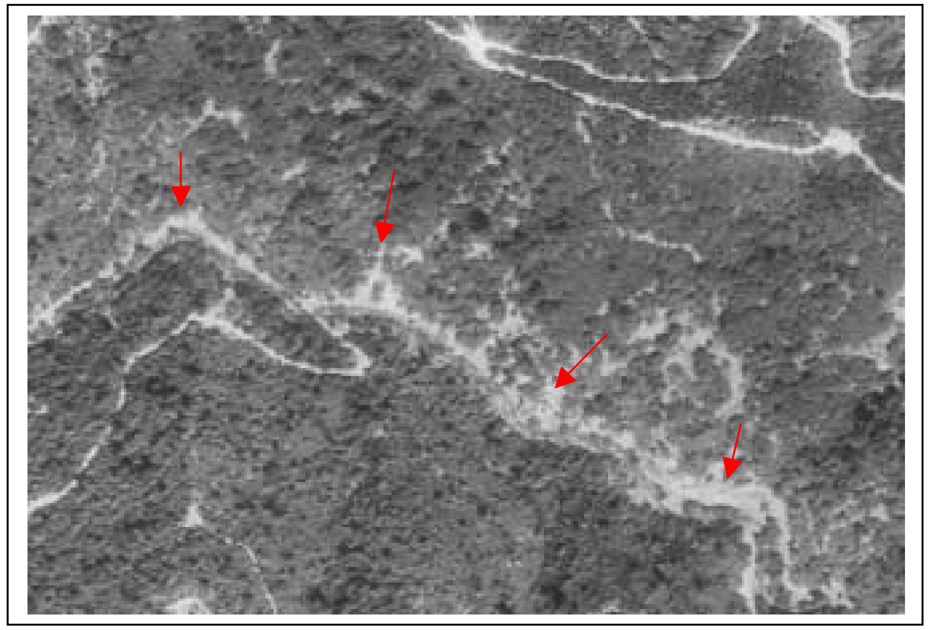


1993

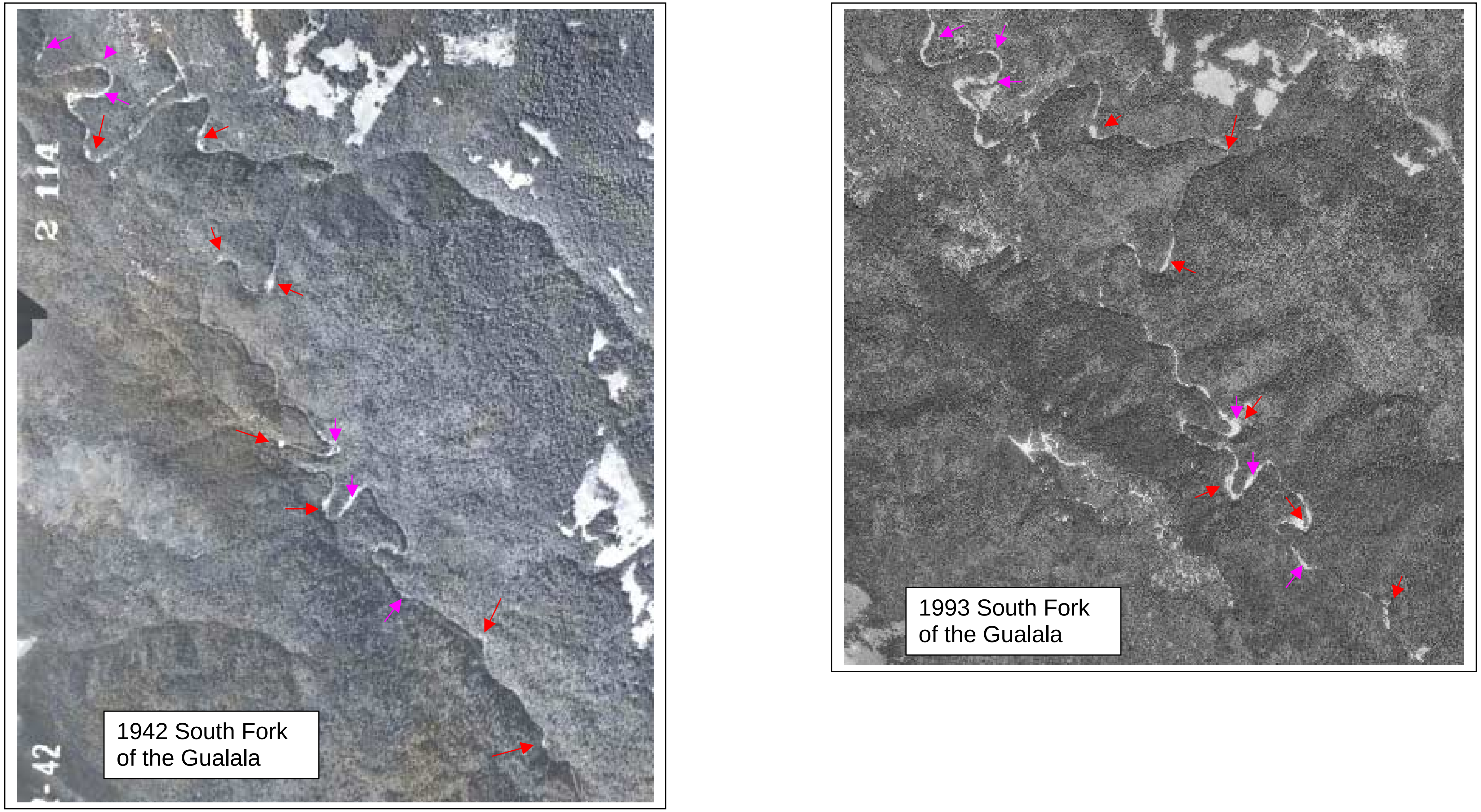


Numerous recent slides are very evident. Many clearly enter the creek.

Lower South Fork



Upper South Fork



Persistent sediment storage (purple arrows) and sediment source areas (red arrows).

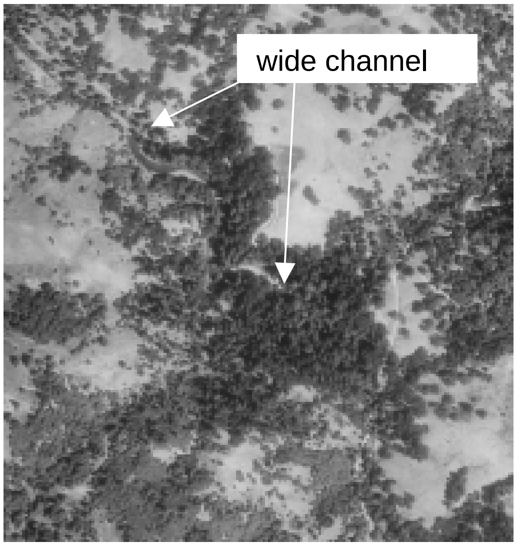
APPENDIX B

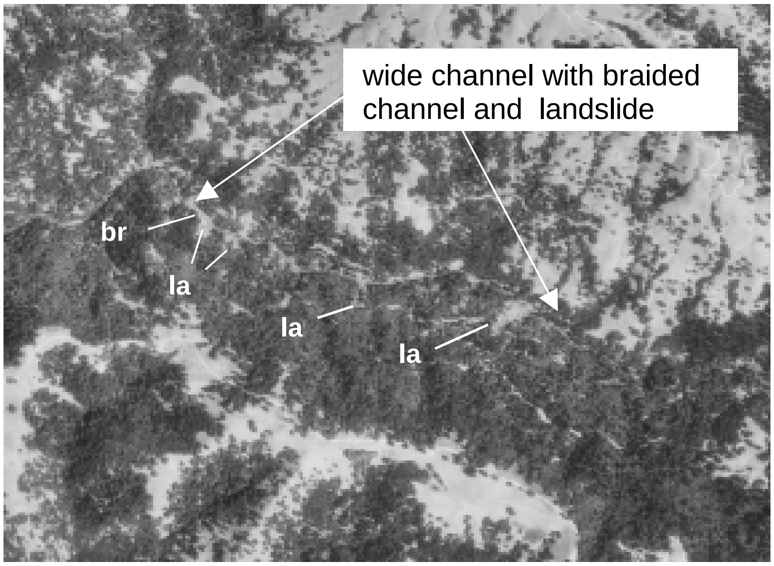
Stream Characteristics Photo Mapping Dictionary

Stream Characteristics Photo Mapping Dictionary

This stream characteristics aerial photo mapping dictionary is provide to document the general appearance of stream and stream channel influencing features that are mapped by the California Geological Survey's NCWAP staff for the fluvial geomorphic component. These images are only an example of each characteristic, but are generally representative. Most of the images in this document were take from the USGS digital orthorphoto quadrangles (DOQ's). Some copyrighted images are used with permission and taken from aerial photos provided by WAC Corporation (www.waccorp.com). The channel characteristics are generally only visible when the channel canopy cover is sufficiently open to allow observation. Thus, fluvial geomorphic feature mapped by these characteristics should be consider reconnaissance. Information observed on the aerial photos is used for GIS data base attributing. Attributes and the association of attributes are to considered only as spatially associated geomorphic observations. Spatial association of mapped geomorphic features should not be interpreted as evidence of cause-and-effect. Other geologic information that cannot be observed or interpreted from aerial photos may be relevant or causal to the mapped stream channel characteristic. Determination of cause-and-effect of these features mapped by aerial photo interpretation requires that site specific investigations be done to confirm or modify remotely sensed interpretations.

Wide channel (wc)– characteristic is mapped when width of channel sediment is anomalous to the surround channels of similar order. Thus, this mapped characteristic varies across the watershed based on local geologic and geomorphic conditions and vegetation density and types. Typically, additional attributes are included to describe channel characteristics associated with the increase in channel width. The *wc* attribute is also used whenever the resolution of the image prevented clear identification of ground features, but the anomalous lack or disturbance of channel riparian vegetation suggest a potential for greater than optimum sediment deposition. The *wc* condition is often found at or near the same sections of channel in photos of different years and is often mapped adjacent to a landslide. This characteristic is considered detrimental to optimum habitat for anadromous salmonids.





Braided channel (br) – characteristic is mapped when channel is a multi-threaded, interlaced streams within the active channel. A braided channel is commonly associated with an aggraded reach. This characteristic is considered detrimental to optimum habitat for anadromous salmonids because of excess sediment.

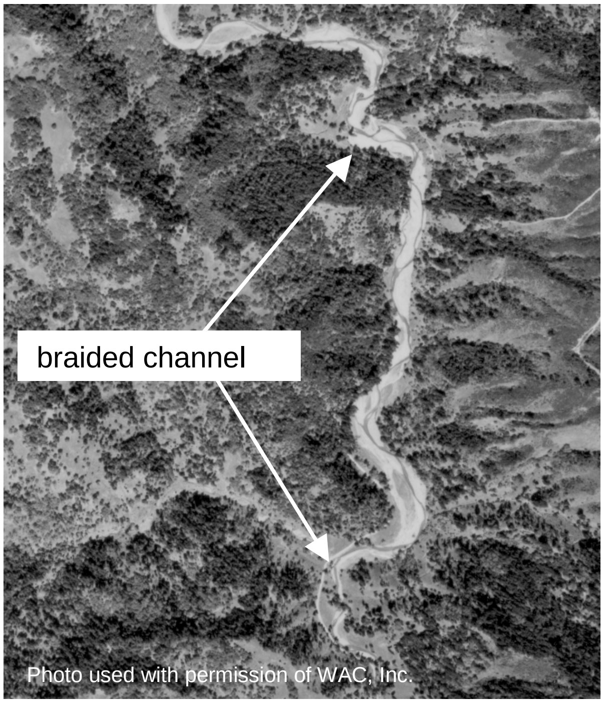


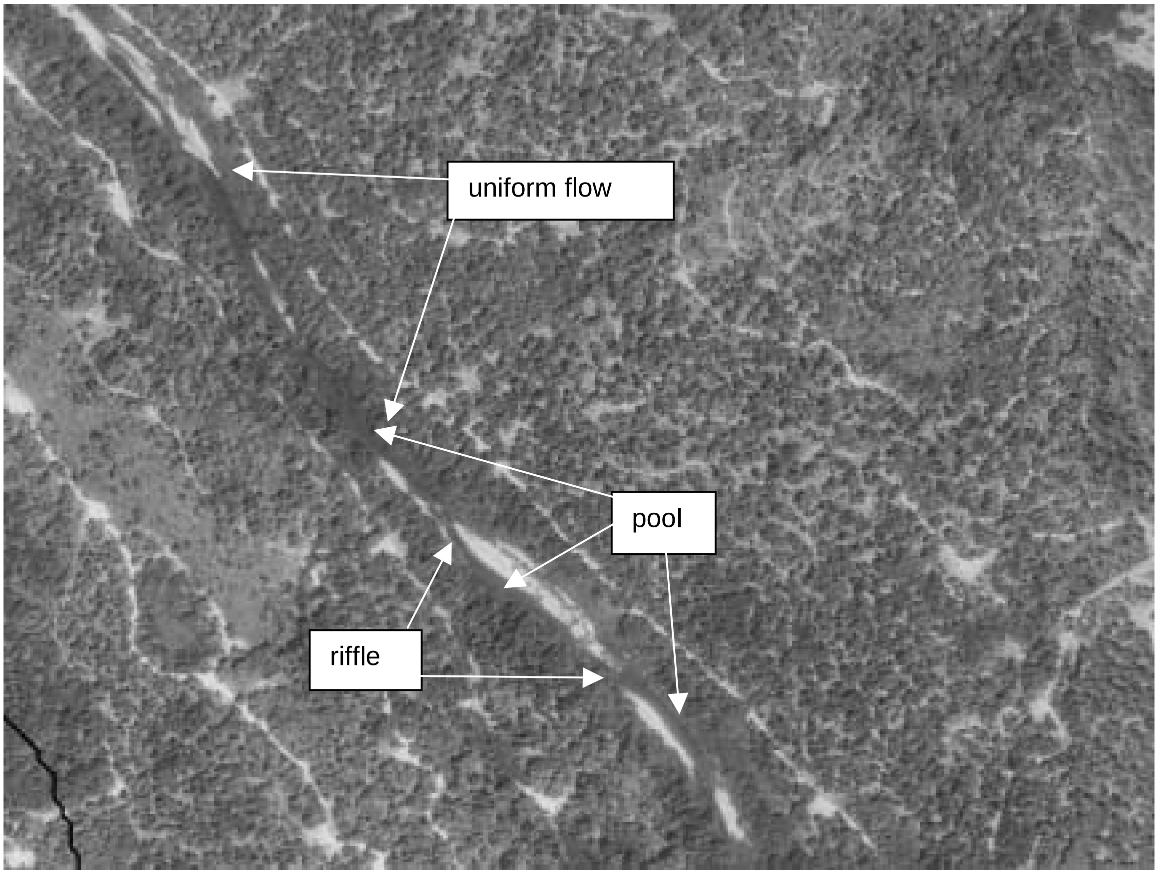
Photo used with permission of WAC, Inc.

Falls (fl) – characteristic is generally not visible on reconnaissance aerial photos and therefore seldom mapped from photos at a scale of 1:12,000 or smaller. This characteristic is generally a point feature and would be mapped in a site specific field study. This characteristic is considered detrimental to optimum habitat for anadromous salmonids becase of the restriction on fish passage.

Riffle (rf) – characteristic is generally not mapped at the 1:24,000 reconnaissance scale because of small size and great number. This attribute is included in the database for completeness to facilitate mapping at a larger scale, and for mapping specific reaches. This feature is mapped between pools with no distinction made for runs or glides. This characteristic is best mapped as a point feature. This characteristic is not considered detrimental to optimum habitat for anadromous salmonids.

Pool (po) – characteristic is generally not mapped at the 1:24,000 reconnaissance scale because of small size and great number. This attribute is included in the database for completeness to facilitate mapping at a larger scale, and for mapping specific reaches. This feature is mapped at the outside of meanders or channel bends. This characteristic is best mapped as a point feature. This characteristic is not considered detrimental to optimum habitat for anadromous salmonids.

Uniform flow (uf) – characteristic is generally not mapped at the 1:24,000 reconnaissance scale since most channel flow appears calms at that scale. This characteristic is used for reach specific studies and provided for completeness as a contrast to turbulent flow characteristic which may be mapped at a reconnaissance scale, if extensive. This characteristic is not considered detrimental to optimum habitat for anadromous salmonids.


uniform flow
pool
riffle

Turbulent flow (tf) – characteristic is mapped whenever the channel water shows signs of excessive whitewater, suggesting that large obstacles occur within the active channel. This feature usually is a secondary attribute. This characteristic may or may not be detrimental to optimum habitat for anadromous salmonids

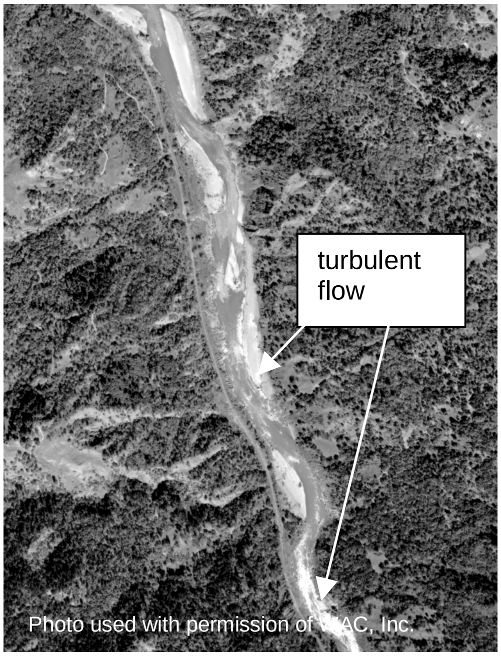


Photo used with permission of WAC, Inc.

Backwater (bw) – characteristic is mapped when sediment deposits built up at the mouth of a tributary channel as it joins with a larger river or due to channel constriction or blockage, such as a delivering landslide. Deposition generally caused by a slowing and blocking of storm flows as they try to merge. Deposits often cause low flows to go partially or completely subsurface. This characteristic may or may not be detrimental to optimum habitat for anadromous salmonids because of the impacts on fish passage at low flows.

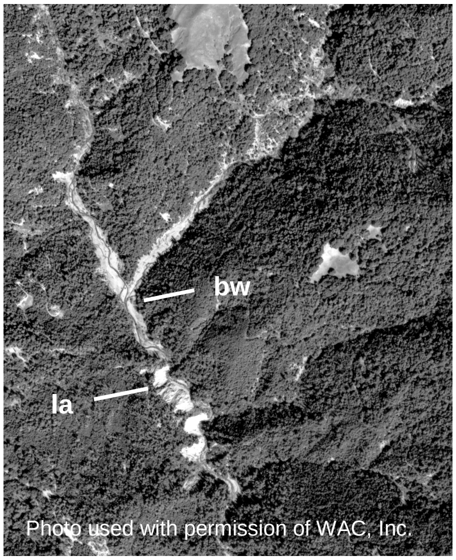
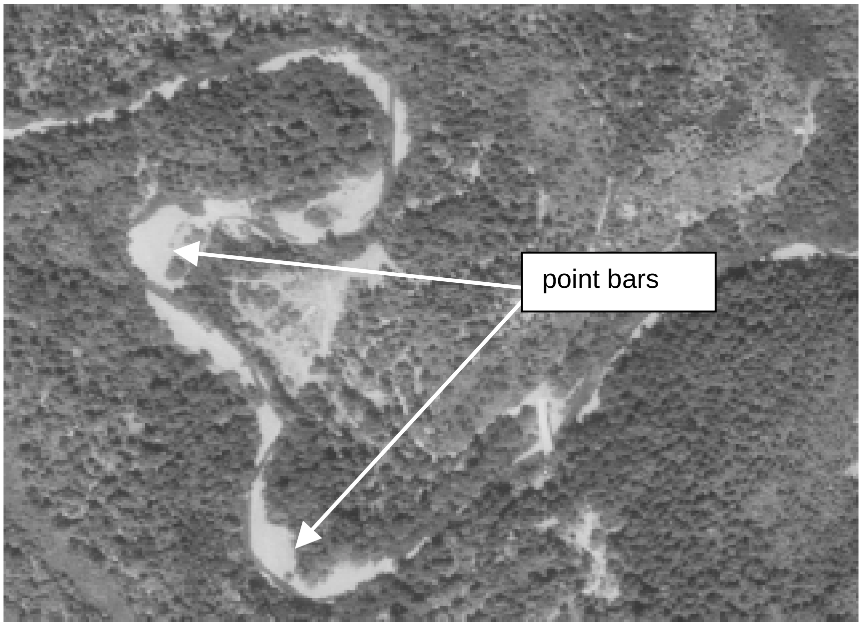


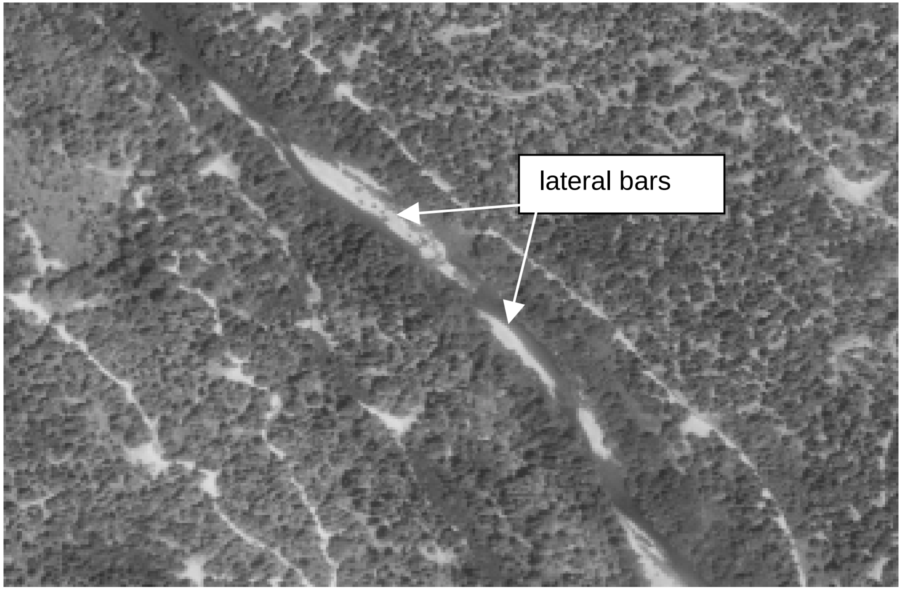
Photo used with permission of WAC, Inc.

Flow backwaters (bw) as channel is constricted by toe of active landslide (la) causing sediments to deposit upstream of constriction.

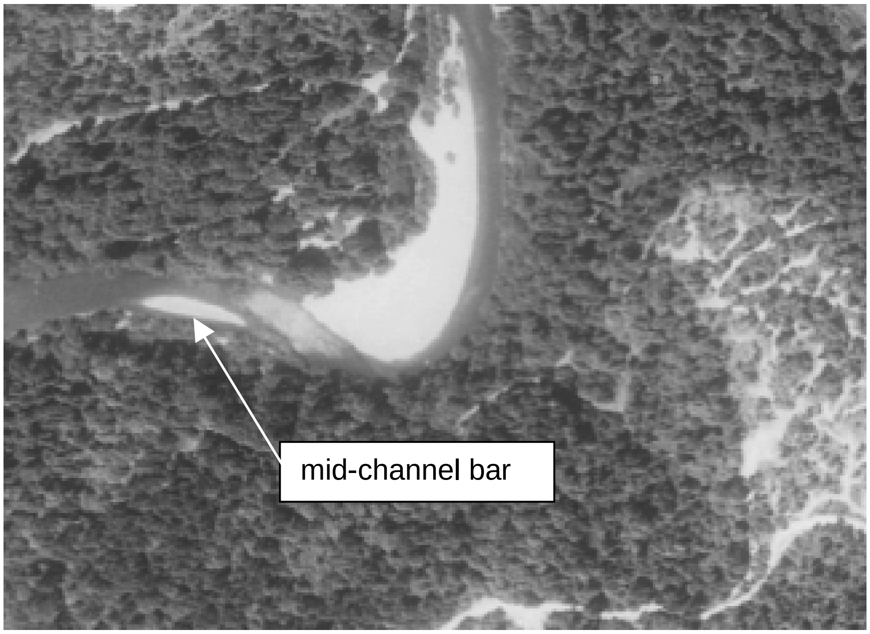
Point bar (pb)– characteristic is mapped at the inside of a channel meander. This feature is distinguished for the lateral bar by its crescent plan form and location. For the purposes of CGS's NCWAP project, the point bar is not considered detrimental to optimum habitat for anadromous salmonids.



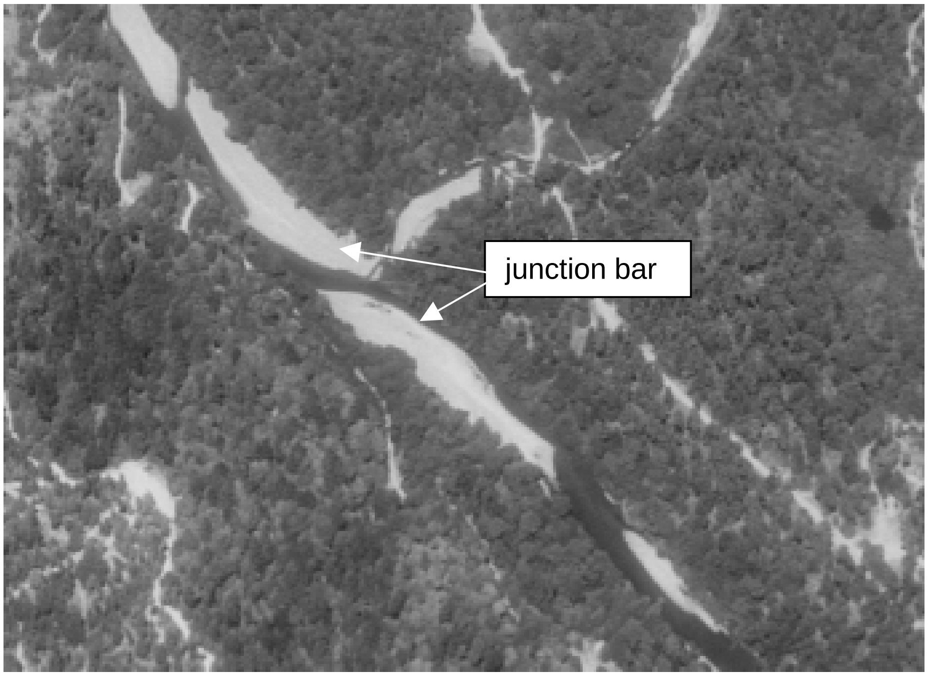
Lateral bars (lb) – characteristic mapped when sediment deposits are aligned sub-parallel with the channel boundary and not on sharp radius meanders. Groups of lateral bars may alternate back and forth from across the active channel forming large radius meanders. Lateral bars are often found where banks are eroding at the toes of a landslide that delivers sediment to the stream. For the purposes of CGS's NCWAP project, this characteristic is generally considered detrimental to optimum habitat for anadromous salmonids because its presence is often due deposition of to excess sediment and often changes locations or becomes a different feature, i.e., mid-channel bar.



Mid-channel (mb) – characteristic is mapped when elongated bars are found in the center of channel and water is flowing on both sides. This feature differs from transverse bars in its general shape. This characteristic is considered detrimental to optimum habitat for anadromous salmonids because these bars generally indicate excess sediment.

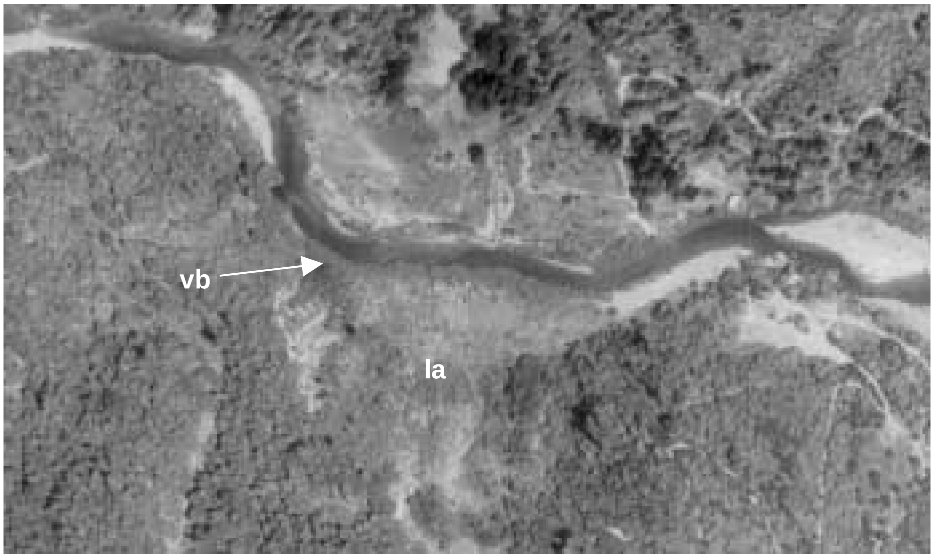


Bar at junction of channels (jb) – characteristic is mapped when a bar develops at the mouth of tributary stream. This bar may be within main or tributary channel. This characteristic is considered detrimental to optimum habitat for anadromous salmonids because these bars generally indicate excess sediment and they can block fish passage at low flows.



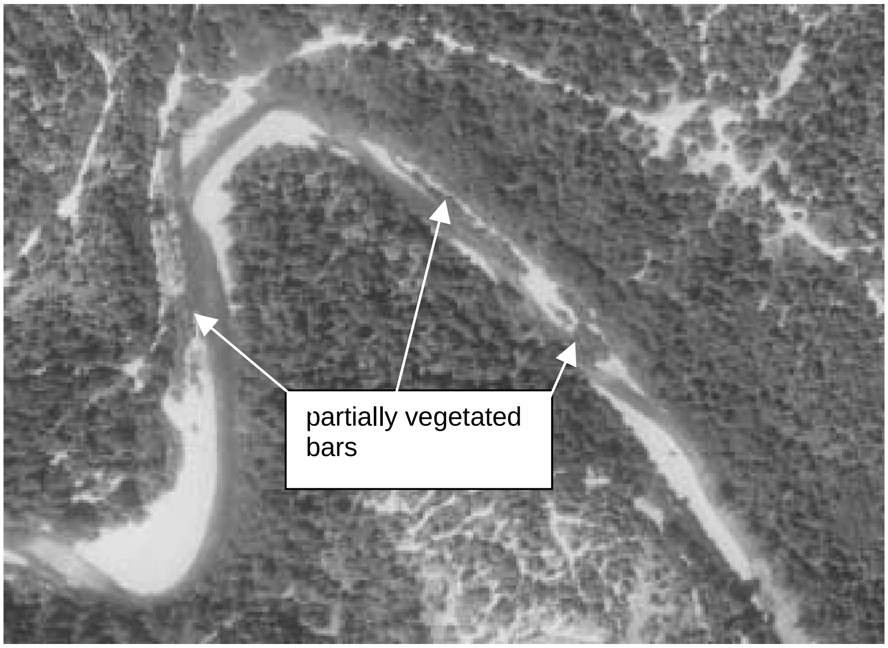
Transverse bars (tb) – characteristic is mapped when a series of bars develop across channel at an angle diagonal to the active channel. This characteristic is considered detrimental to optimum habitat for anadromous salmonids because these bars generally indicate excess sediment.

Vegetated bar (vb) – characteristic is mapped when an active channel bar is well vegetated, generally greater than 75 percent of visible bar area. This characteristic is not considered detrimental to optimum habitat for anadromous salmonids because these bars generally indicates stable sediment and provide cover.

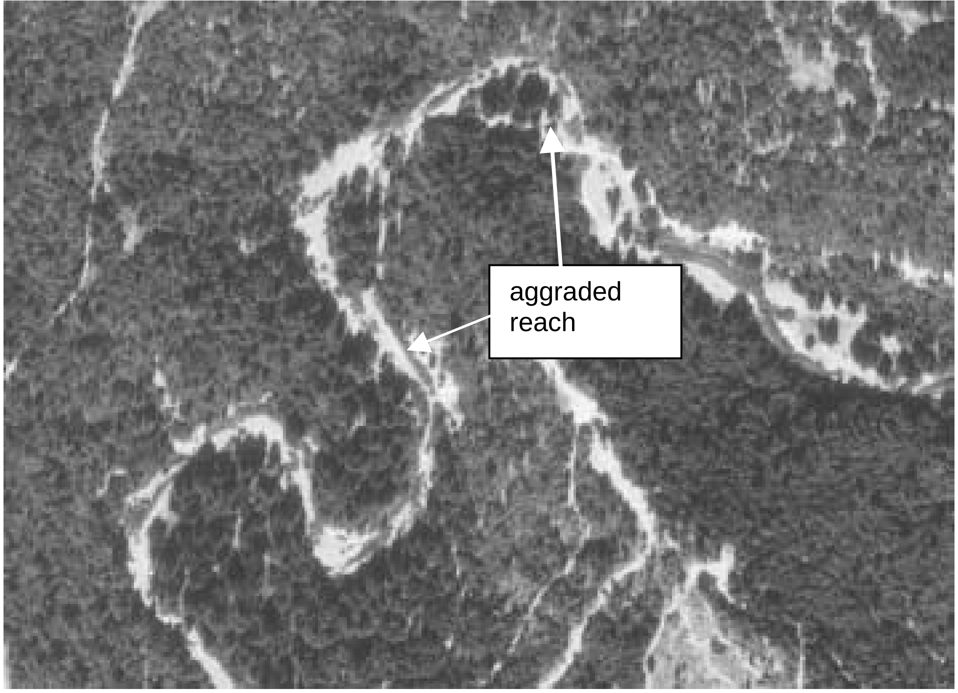


Vegetated lateral bar at toe of landslide

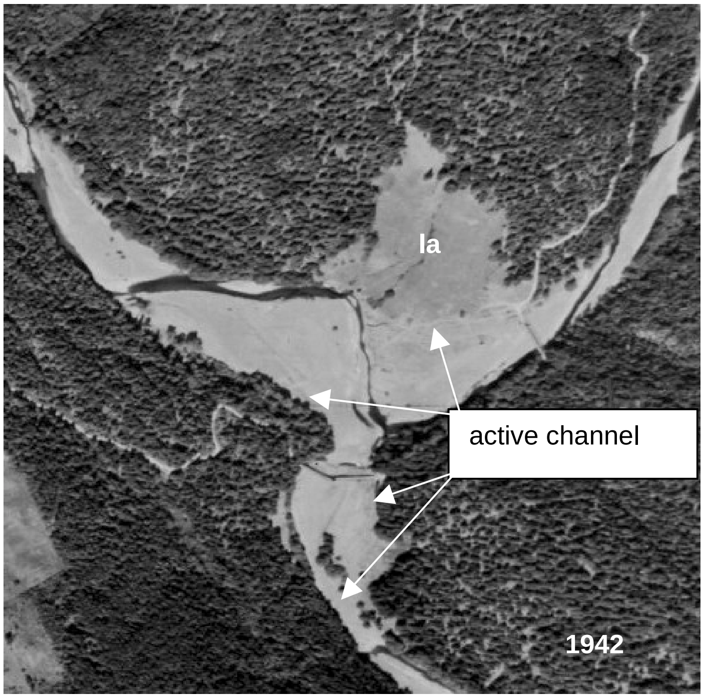
Partially vegetated bar (vp) – characteristic is mapped when a bar is vegetated at less than 75 percent. This characteristic is not considered detrimental to optimum habitat for anadromous salmonids because these bars generally indicates a more stable sediment deposits and can provide partial cover.



Aggrading (ag) – characteristic is mapped when channel deposits appear excessively wide and deep, often indicated by channel flow going subsurface in aggraded reach or an anomalous widening of active channel sediment. This characteristic is considered detrimental to optimum habitat for anadromous salmonids because aggredation generally indicate excess sediment and can impact fish passage.



Degrading (dg) - characteristic is generally not visible on reconnaissance aerial photos and therefore difficult to recognize from photos at a scale of 1:24,000 without a photo time series and field inspection. This characteristic is distinguish from incised channels in its lateral extent and is much greater in the change in channel width. This characteristic may or may not be detrimental to optimum habitat for anadromous salmonids.



Upper photo shows channel in 1942 meandering north into toe of landslide. Lower shows channel in 2000 with vegetation established on bars south of bridge and along toe of landslide. Field observations show channel downcut several feet isolating vegetated bars.

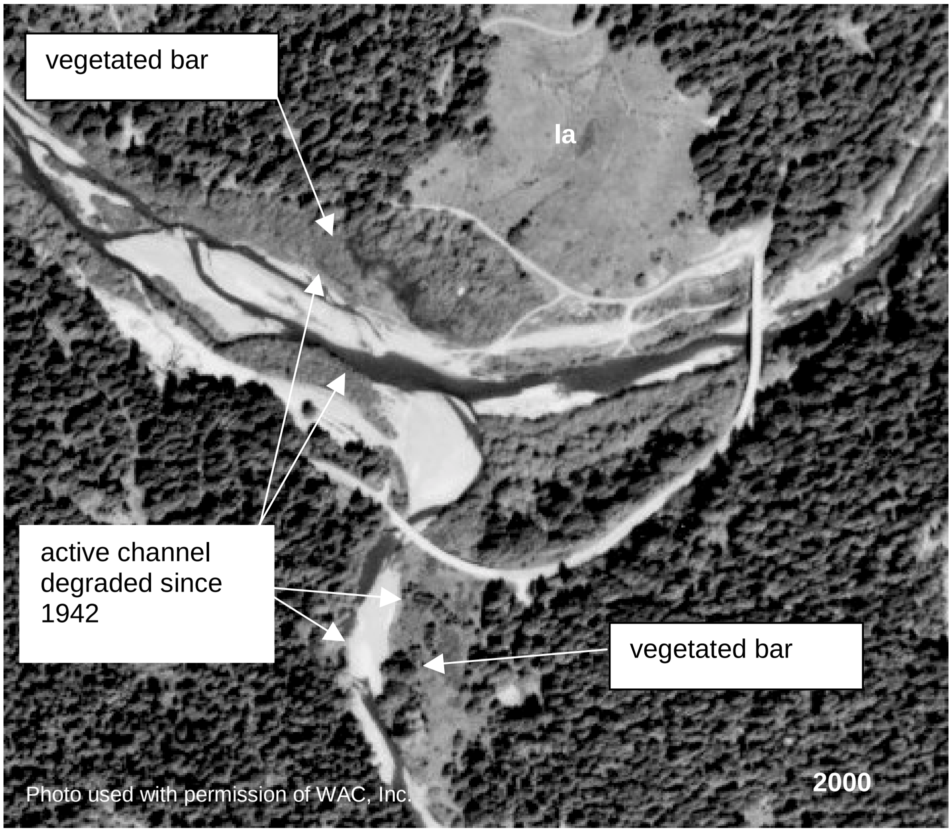
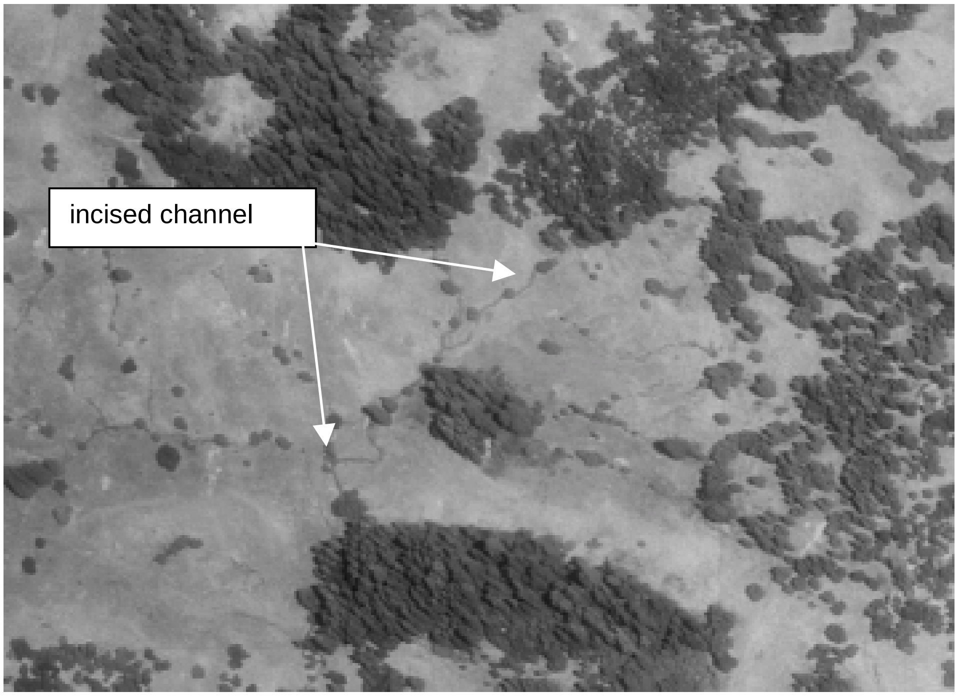
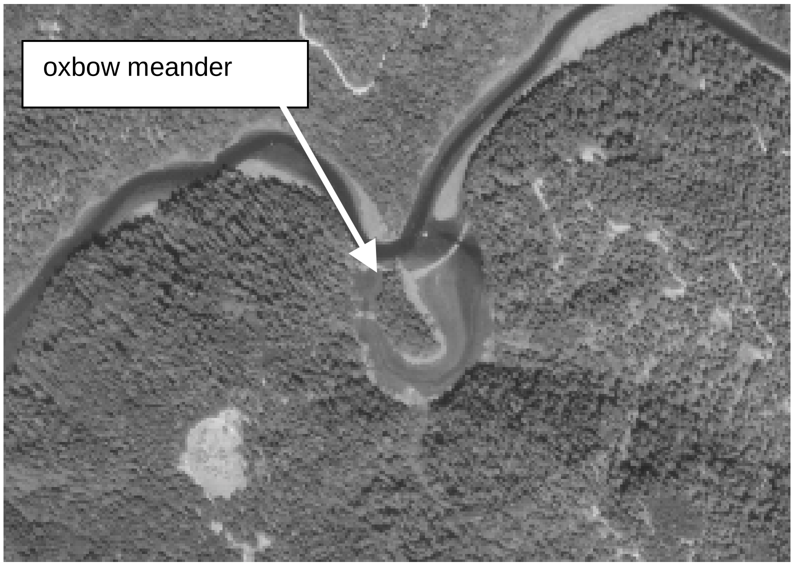


Photo used with permission of WAC, Inc.

INCISED (IN) – CHARACTERISTIC IS MAPPED WHEN ONE OR BOTH BANKS OF A CHANNEL HAVE ERODED VERTICALLY SUCH THAT THE ACTIVE CHANNEL IS ENTRENCHED. BECAUSE OF THE RECONNAISSANCE SCALE OF AERIAL PHOTOS, HEIGHT OF THE VERTICAL BANK MUST BE SUFFICIENT AND THE SUN ANGLE APPROPRIATE TO CAST A OBSERVABLE SHADOW. THIS CHARACTERISTIC MAY OR MAY NOT BE DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.



OXBOW MEANDER (OX) – CHARACTERISTIC IS MAPPED WHEN THE CHANNEL MEANDER IS CUT OFF ACROSS THE NARROW PIECE OF LAND THAT SEPARATES THE TWO SECTION OF THE BEND AND THE ABANDONED CHANNEL PARTIALLY FILLS IN LEAVING AN ISOLATED CHANNEL OR POND. THIS FEATURE IS GENERALLY FOUND IN FLATTER GRADIENT REACHES, SUCH AS A MEADOW OR ESTUARY. THIS CHARACTERISTIC MAY OR MAY NOT BE DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.



ABANDONED CHANNEL (AB) – CHARACTERISTIC IS MAPPED WHEN A MAJOR CHANNEL IS TODAY ABANDONED. TYPICALLY VEGETATED MARKS OLD CHANNEL. THIS CHARACTERISTIC MAY OR MAY NOT BE DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.

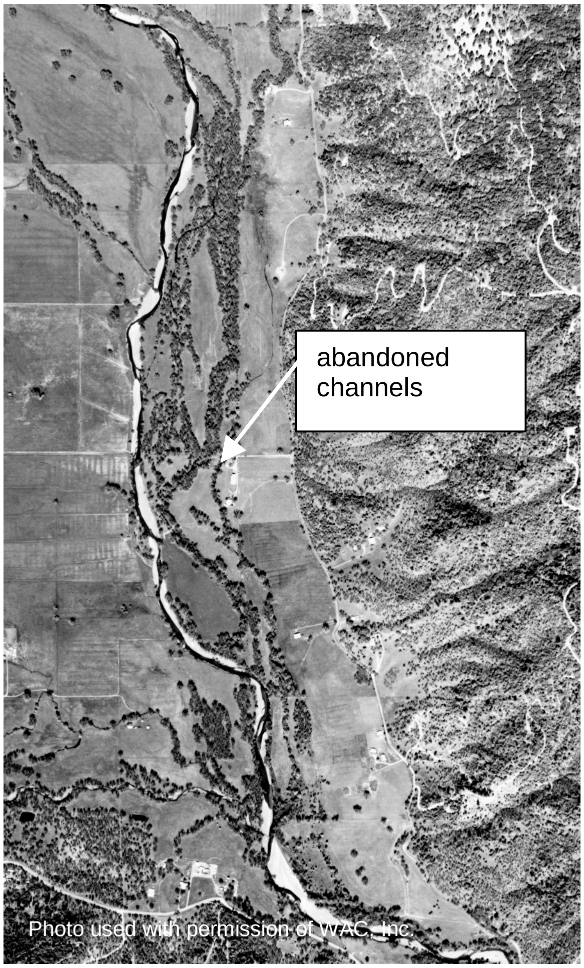


Photo used with permission of WAC, Inc.

ABANDONED MEANDER (AM) – CHARACTERISTIC IS MAPPED WHEN A MEANDER HAS BEEN CUT-OFF OR ISOLATED FROM THE ACTIVE CHANNEL. ABANDONED MEANDERS ARE LESS CIRCULAR THAN OXBOW MEANDERS. ABANDONED CHANNEL IS TYPICALLY MARKED VEGETATION WHOSE DENSITY IS AN INDICATION OF LONGEVITY. THIS CHARACTERISTIC MAY OR MAY NOT BE DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.

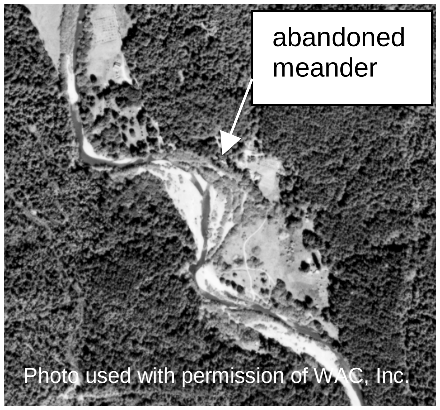
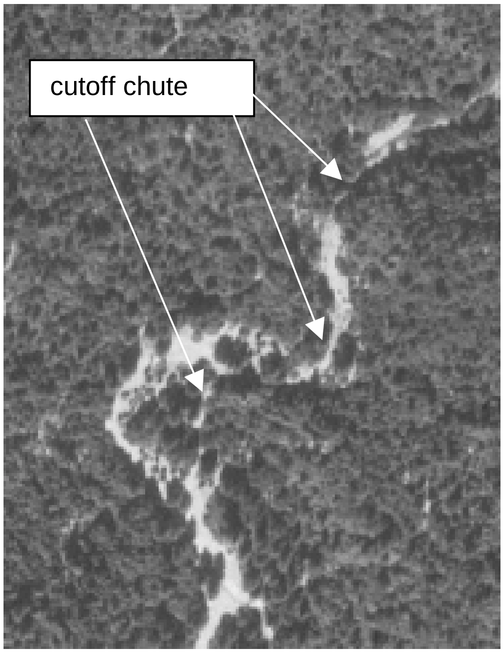


Photo used with permission of WAC, Inc.

CUTOFF CHUTE (CC) – CHARACTERISTIC IS MAPPED WHEN THE CHANNEL CUTS ACROSS A MEANDER BEND AND ESTABLISHES A NEW CHANNEL. CUTOFF CHANNEL MAY ONLY FLOW DURING HIGHER STAGES, BUT CUTOFF CHANNEL INDICATES INSTABILITY OF MEANDER. THIS CHARACTERISTIC MAY OR MAY NOT BE DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.



TRIBUTARY FAN (TR) – CHARACTERISTIC IS MAPPED WHEN A TRIBUTARY CHANNEL CREATES A SEDIMENT FAN AS IT JOIN A LARGER CHANNEL. TRIBUTARY FAN IS DISTINGUISHED FROM JUNCTION BAR BY GREATER VOLUME OF MATERIAL DEPOSITED, COMMON INCISION OF ACTIVE CHANNEL AND ISOLATION OF PARTS OF THE FAN FROM NORMAL FLOWS. THIS CHARACTERISTIC MAY OR MAY NOT BE DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.

LOG JAM (LJ) – CHARACTERISTIC IS MAPPED WHEN LOGS AND VEGETATION ARE OBSERVED BLOCKING THE ACTIVE CHANNEL. TYPICALLY FOUND AT BASE OF LANDSLIDES THAT DELIVER SEDIMENT TO THE CHANNEL FROM WOODED TERRAIN. THIS CHARACTERISTIC MAY OR MAY NOT BE DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.

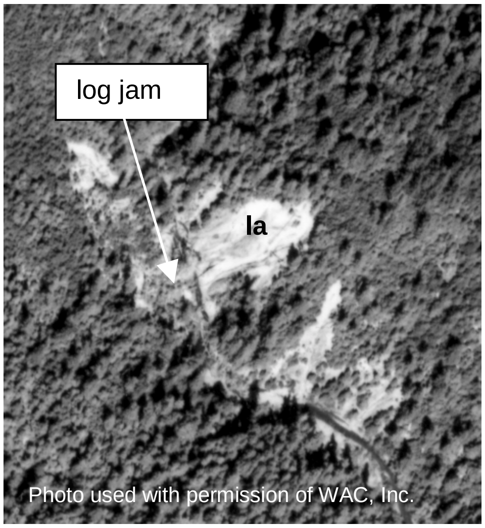
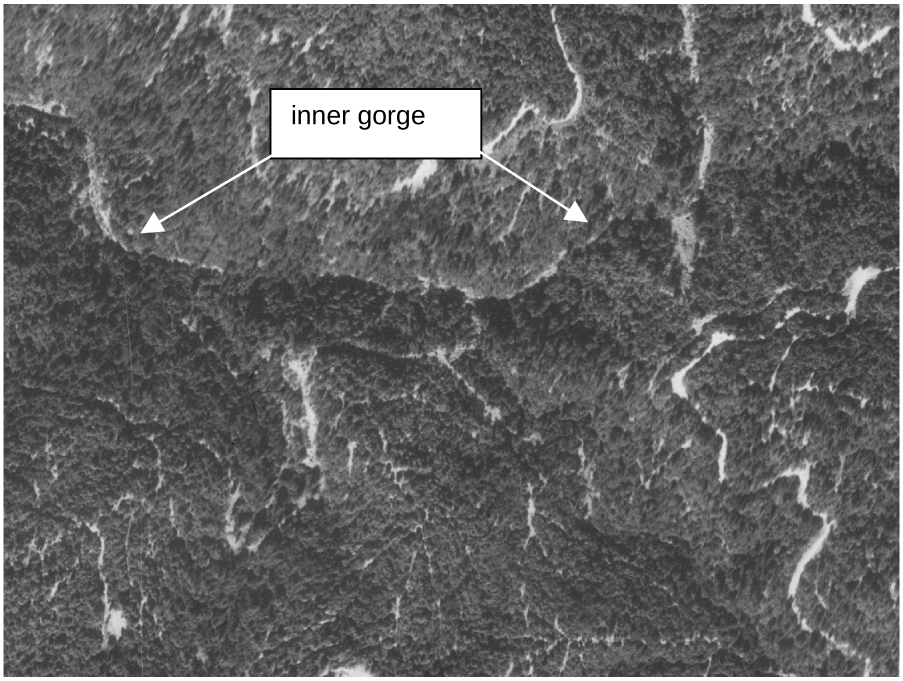
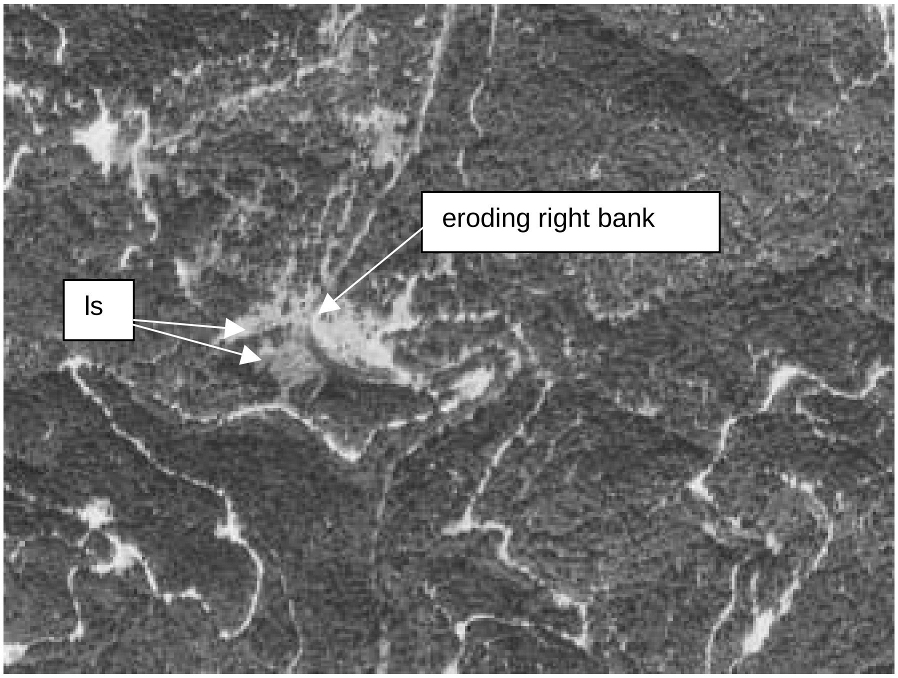


Photo used with permission of WAC, Inc.

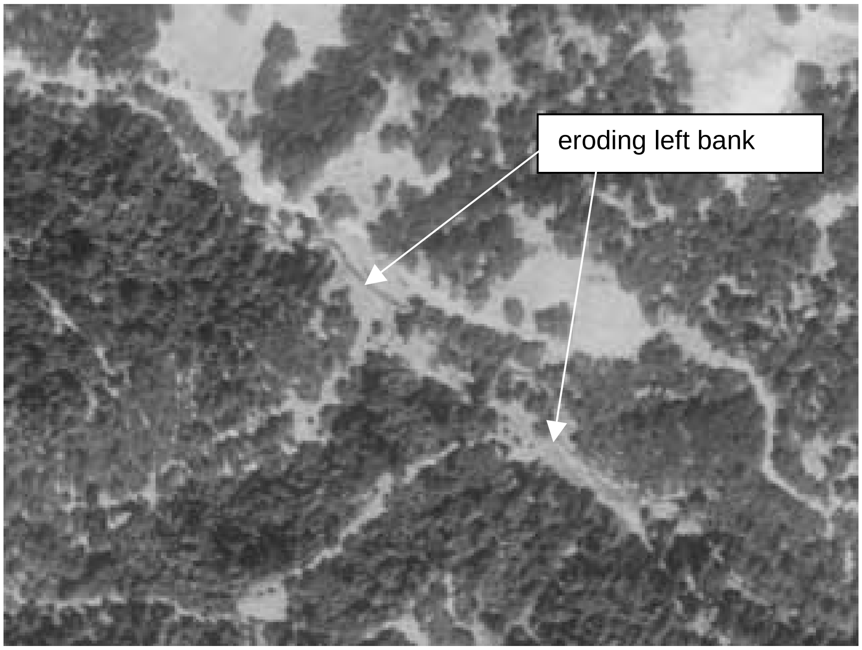
INNER GORGE (IG) – CHARACTERISTIC IS MAPPED WHERE STEEP SLOPES RISE FROM THE CHANNEL AND THEN FLATTEN ALONG A NEAR LINEAR BREAK IN SLOPE. SHALLOW LANDSLIDES ARE OFTEN FOUND IN THE INNER GORGE SLOPE. THIS FEATURE IS TAKEN FROM THE LANDSLIDE MAPPING AND TRANSFERRED TO THE FLUVIAL LAYERS. THIS CHARACTERISTIC IS CONSIDERED DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS BECAUSE OVERSTEEPENED SLOPE TYPICALLY HAS A HIGH RATE OF SEDIMENT DELIVERY TO THE ACTIVE CHANNEL.



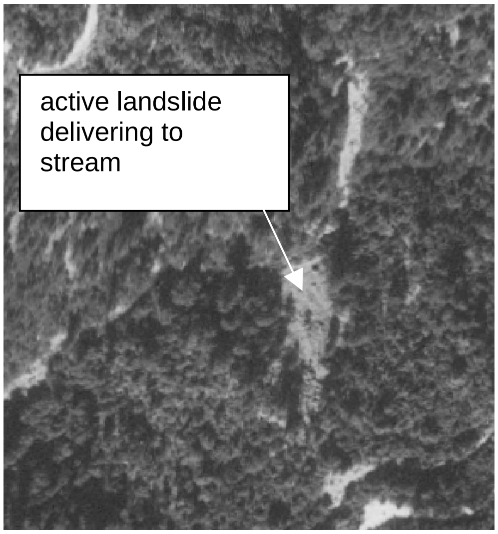
ERODING RIGHT BANK (ER) – CHARACTERISTIC IS MAPPED WHEN RIGHT BANK OF CHANNEL, WHEN VIEWED FACING DOWNSTREAM, IS ACTIVELY ERODING. BANK EROSION IS COMMONLY FOUND AT TOE OF DELIVERING LANDSLIDE AND OUTSIDE BANK OF A MEANDER. THIS CHARACTERISTIC IS CONSIDERED DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.



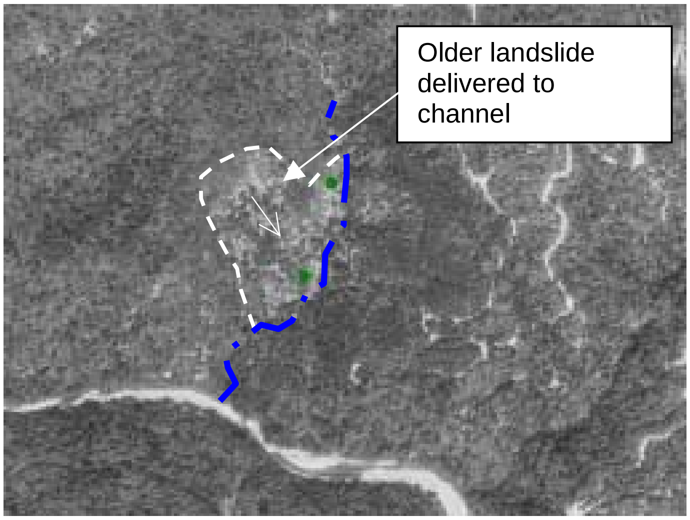
ERODING LEFT BANK (EL) – CHARACTERISTIC IS MAPPED WHEN LEFT BANK OF CHANNEL, WHEN VIEWED FACING DOWNSTREAM, IS ACTIVELY ERODING. BANK EROSION COMMONLY FOUND AT TOE OF DELIVERING LANDSLIDE AND OUTSIDE BANK OF A MEANDER. THIS CHARACTERISTIC IS CONSIDERED DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.



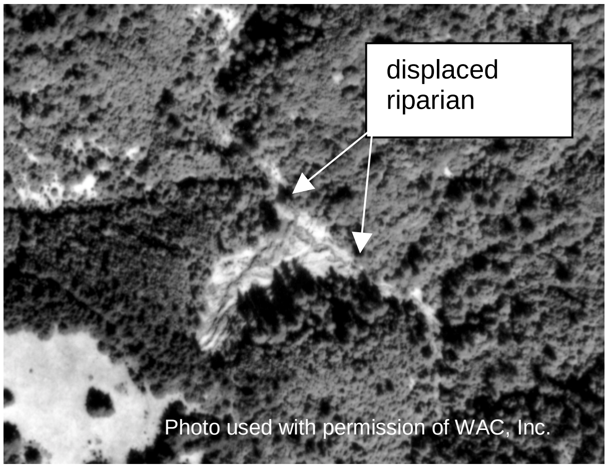
ACTIVE LANDSLIDE DEPOSIT (LA) – CHARACTERISTIC MAPPED IS TYPICALLY A SMALL, POORLY VEGETATED, SHALLOW LANDSLIDE THAT APPEARS TO DELIVER SEDIMENT TO THE CHANNEL. THESE FEATURES ARE MAPPED AND PROVIDED TO THE LANDSLIDE MAPPING STAFF FOR THEIR REVIEW AND ENTRY INTO THE LANDSLIDE MAPPING LAYERS. THESE SLIDES ARE MAPPED BY FLUVIAL MAPPING STAFF BECAUSE THEIR CLOSER SCRUTINY OF NEAR CHANNEL SLOPES AIDS IN FINDING THE SMALLER “POINT” LANDSLIDES AND PROVIDES A QUALITY CONTROL CHECK TO THE DELIVERING SHALLOW LANDSLIDE DATABASE. THIS CHARACTERISTIC IS CONSIDERED DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.



OLDER LANDSLIDE DEPOSIT (LO) – CHARACTERISTIC MAPPED IS TYPICALLY A SMALL, MODERATELY- TO WELL-VEGETATED, SHALLOW LANDSLIDE THAT APPEARS TO HAVE DELIVERED SEDIMENT TO THE CHANNEL. THESE FEATURES ARE MAPPED AND PROVIDED TO THE LANDSLIDE MAPPING STAFF FOR THEIR REVIEW AND ENTRY INTO THE LANDSLIDE MAPPING LAYERS. THESE SLIDES ARE MAPPED BY FLUVIAL MAPPING STAFF BECAUSE THEIR CLOSER SCRUTINY OF NEAR CHANNEL SLOPES AIDS IN FINDING THE SMALLER "POINT" LANDSLIDES AND PROVIDES A QUALITY CONTROL CHECK TO THE DELIVERING SHALLOW LANDSLIDE DATABASE. THIS CHARACTERISTIC IS CONSIDERED DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.



DISPLACED RIPARIAN (DR) – CHARACTERISTIC IS MAPPED WHEN SEDIMENT, TYPICALLY FROM A LANDSLIDE, DISRUPTS OR DISPLACES CHANNEL RIPARIAN. TYPICALLY THIS ATTRIBUTE IS NOTED WITH OTHER CHANNEL CHARACTERISTICS, SUCH AS ACTIVE LANDSLIDE DEPOSIT, BLOCKED CHANNEL OR WIDE CHANNEL. THIS CHARACTERISTIC IS CONSIDERED DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS.



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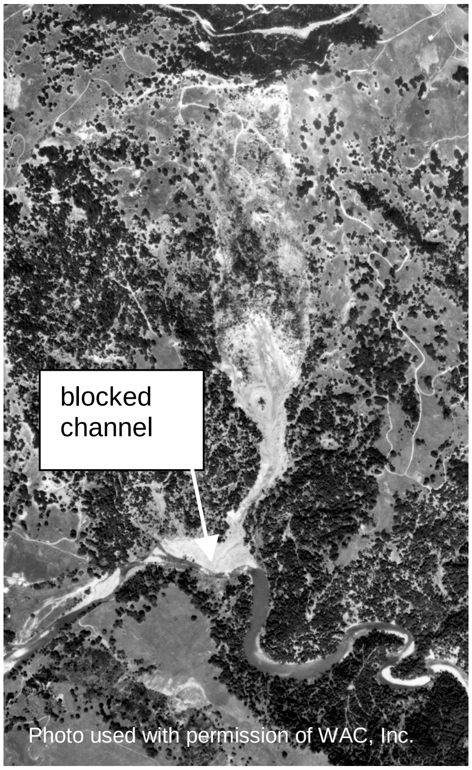
BLOCKED CHANNEL (BC) – CHARACTERISTIC IS MAPPED WHEN LANDSLIDE DELIVERS SUFFICIENT SEDIMENT TO THE CHANNEL TO BACK UP OR SIGNIFICANTLY DIVERT THE FLOW OF WATER. CHANNEL FLOW TYPICALLY DISAPPEARS OR BECOME SIGNIFICANTLY REDUCED OVER THE BLOCKED REACH. CHANNEL OFTEN INCISE TO RE-ESTABLISH AN ACTIVE CHANNEL. THIS CHARACTERISTIC IS CONSIDERED DETRIMENTAL TO OPTIMUM HABITAT FOR ANADROMOUS SALMONIDS BECAUSE IT BLOCKS FISH PASSAGE AND DIRECT DELIVERY OF SEDIMENT TO THE CHANNEL.



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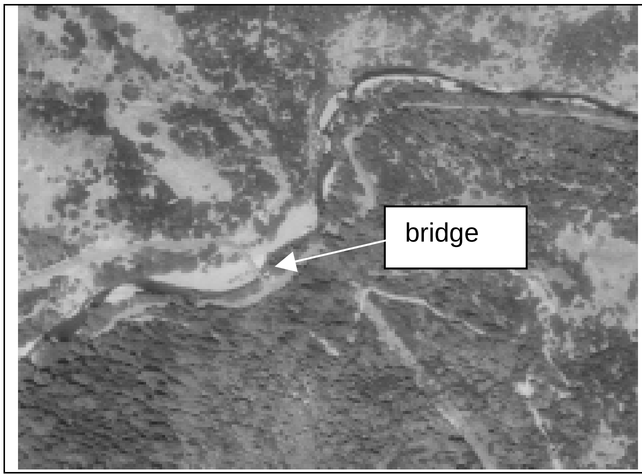
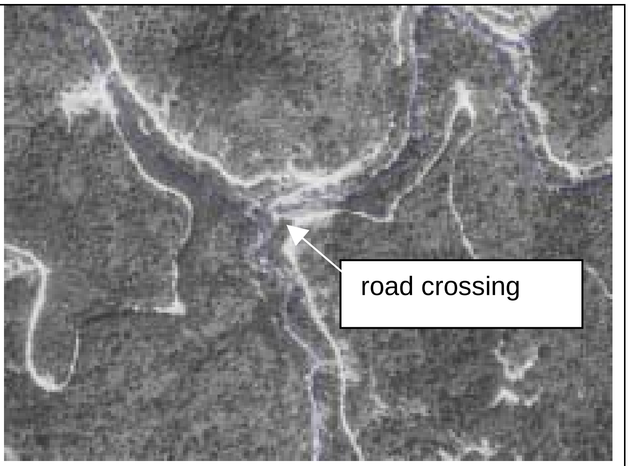
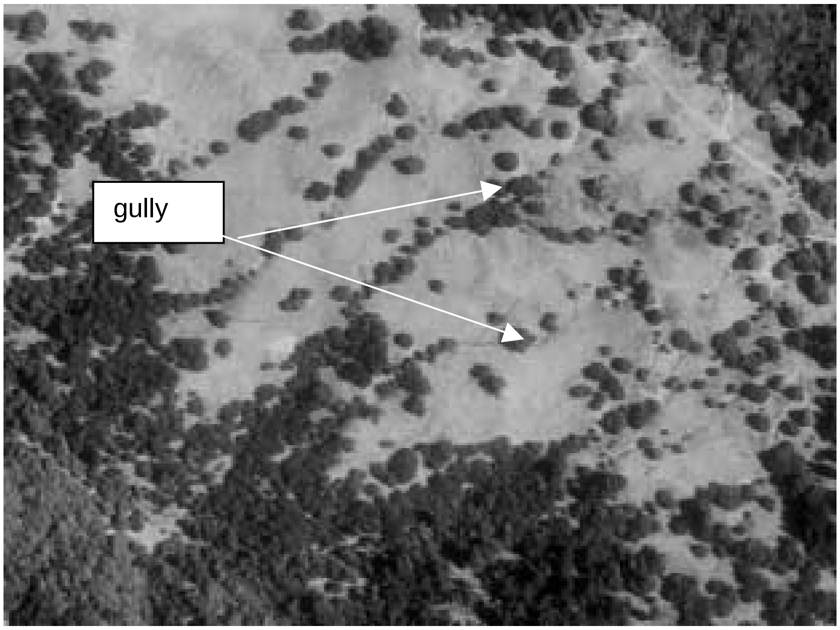
MAN-MADE STRUCTURE (MS) – CHARACTERISTIC IS MAPPED WHEN A MAN-MADE STRUCTURE IS INFLUENCING STREAM FLOWS AND/OR STREAM SEDIMENTATION. TYPICALLY THIS FEATURE IS IDENTIFIED WHEN SEDIMENT DEPOSITS ARE NOTICED NEAR A BRIDGE, CULVERT OR ROAD CROSSING SUGGESTING THAT THE STRUCTURE INFLUENCES CHANNEL HYDRAULICS.





GULLY – CHARACTERISTIC MUST BE SEEN ON AERIAL PHOTO AND THEREFORE CAN ONLY MAPPED IN PARTIALLY VEGETATED OR GRASSLAND AREAS. FEATURE IS SUFFICIENTLY LONG AND DEEP THAT IT CASTS A DISCERNABLE SHADOW. A GULLY OFTEN IS FOUND IN PROXIMITY TO A SHALLOW LANDSLIDE OR ROAD. FEATURE IS MAPPED AS A LINE AND PLACED ON A SEPARATE LAYER FROM OTHER FLUVIAL CHARACTERISTICS BECAUSE IT IS OUTSIDE OF THE 1:24,000 BLUE LINE DRAINAGE NETWORK. A GULLY WOULD BE ATTRIBUTED AS ENTRENCHED IF IT WERE PART OF THE 1:24,000 STREAM NETWORK.



APPENDIX C

The significance of new CGS landslide data

The significance of new CGS landslide data

Geologic mapping presented in this report can be used to update the natural sediment source budget for the Gualala River Watershed. The previous sediment budget conducted for the Gualala River Watershed (NCRWQCB, 2001) calculated natural sediment from two sources, small landslides not associated with any anthropogenic activity and stream bank erosion of mostly earthflows within the central belt of the Franciscan terrain. Although CGS's studies documented in this report found a significantly greater number of small landslides depicted as points on the geologic map than previously identified, CGS did not assign a cause to these landslides. Thus, a recalculation of the volumes of natural versus anthropogenic caused small landslides has not been done. However, a GIS analysis was done on the occurrence of small landslides found that most (58%) of the CGS smaller landslides lie within larger deep-seated landslides or geomorphic terrains created by landsliding, i.e. debris slide slopes or disrupted ground. This strong spatial correlation between the smaller landslides mapped as points and underlying larger deep-seated landslides and landslide geomorphic terrain suggest that additional study is needed in order to assign the actual cause of the landsliding to either natural or anthropogenic activities or some combination of both.

Recent geologic mapping by CGS described in the main body of this report found substantially greater areas of deep-seated landsliding in Gualala River Watershed in both the central and coastal belts of the Franciscan than was assumed in the stream bank erosion methodology done previously for the Gualala River Watershed sediment budget (NCRWQCB, 2001). CGS found that approximately 34 percent of the 298 square mile Gualala River Watershed is underlain by deep-seated landslides, e.g., earthflows or rock slides. Approximately 9 percent of these landslides are historically active, earthflows 8.3% and rock slides 0.5%. The remaining deep-seated landslides are either dormant earthflows (8%) or dormant rock slides (16.8%). For the purposes of estimating natural sediment, terrains other than the deep-seated landslides were combined with other unmapped more stable areas even though CGS mapped much of the area as geomorphically unstable terrains, i.e., debris slide slopes or disrupted ground. Both a low and high estimate of natural sediment load was developed in order to evaluate the importance of the variations in rate of landslide movement.

Deep-seated landslides are distinguished from shallow landslides by their larger and less elongated area, slower relatively movement, and a depth to the basal failure surface that is generally well below the soil layer. Deep-seated landslides are also less susceptible to single precipitation events triggering large to catastrophic increases in rate of movement. Rate of movement in deep-seated landsides typically fluctuate seasonally as well as responding to longer of wet and dry climate cycles. Nevertheless, deep-seated landslides can respond to heavy precipitation with localize shallow failures along with gully development or enlargement. In fact, much of the sediment shed from deep-seated landslides, i.e., earthflows, is derived from shallow failures and concurrent surface erosion within these larger unstable terrains (Kelsey, 1977, 1978). For this natural sediment budget present here, the landslides included in the deep-seated class are the earthflow and rock slide polygons of CGS's Gualala River Watershed NCWAP geologic and geomorphic maps presented as a plates to the main CGS report.

As part of the watershed assessment, a higher resolution stream drainage network was developed from a 10-meter DEM using RiverTools (Research Systems, v. 2.4, 2001) and the D-Infinity algorithm of Tarboton (1997) and setting the zero-order basin area at 1 hectare (2.4 acres). This area is consistent with areas of zero-order drainage studied in Caspar Creek watershed (Keppeler and Brown, 1998) and falls within the range suggested by Dietrich and Montgomery (1992). A review of Gualala River Watershed imagery and the 7-1/2 minute topography found the 1-hectare source area a reasonable estimate of the minimum area needed to generate a channel based on channel development visible on aerial photos. Streams developed from the 10-meter DEM produce a drainage network much denser than the 7-1/2 minute USGS topographic maps. Total length of 10-meter DEM drainage was approximately 6,900 kilometers (km) compared to the USGS 7-1/2 minute blue-line stream length of approximately 1,188 km. As a comparison, the 10-meter DEM 4tth order streams were typically the 1st order of the USGS blue-line stream network. While the 10-meter DEM stream network is denser than found on topographic maps, it is still essentially derived from the 7-1/2 minute topography. In this study the topographic maps had a 40-foot contour interval. Thus, the DEM cannot develop more drainage detail than was there originally in the topographic maps. The use of the DEM allows for more rapid identification, plotting and tabulation of the drainage network expressed in the topographic contour crenulations. Studies have shown that finer details drainage networks can be developed when a higher resolution DEM is used, such as those obtain using Lidar (Dietrich and others, 2001). If a higher resolution DEM was available, it would likely show a greater difference in drainage density between deep-seated landslide terrains and other more stable lands than currently measured with the 7-1/2 minute topography and the resultant 10-meter DEM.

An estimate of natural sediment load in the Gualala River Watershed from the large, deep-seated landslides and creep of soils on the other more stable terrains was made using information on the landslide type, landslide area, stream density, stream length and stream order developed by CGS as part of their geologic and geomorphic mapping (see main body of this

CGS report). Data on soil thickness, rates of landslide movement and soil creep were taken from literature reporting on northern coastal California landslides (Kelsey, 1977; Keppeler and Brown, 1998; Harden and others, 1978; Nolan and Janda, 1995; Swanston and others, 1995; Tom Spittler, personal communication, 2002). Variations in the sediment thickness was assumed based on field studies that found landslides often have differential movement both vertical and horizontal (Kelsey, 1977; Harden and other 1978; Nolan and Janda, 1995). The calculation of sediment load from large, deep-seated landslides used the ArcView GIS to tabulate the lengths of the stream network derived from a 10-meter DEM that fall on each type of landslide terrain. Intersected stream were classified by landslide type, either earthflow or rock slide. Both historically active and dormant landslides were used. The total length of streams were then broken into classes by Strahler stream order. Sediment delivery was adjusted to account for the availability of sediment to impact the channel each year (Kelsey, 1987). The lower order streams with their higher average gradient (25% – 30%) were assumed to have most of their delivered sediment available annually for transport (Pitlick, 1995). Whereas, the higher order channels were assumed to need a higher flood stage, lower frequency flows, to mobilize the sediment delivered to the edge of the channel. Although sediment load was not tied directly to precipitation rate, some sediment production from fluvial processes acting on landslide terrains is implicit in the results of this is sediment budget because of the use of a higher resolution drainage network and the assumption that lower order drainages rapidly transport deposited sediment. Sediment delivered to the lower order channels may come from a variety of processes including down slope creep, gully erosion, as well as fluvial erosion. The strong correlation of CGS mapped gullies with landslide terrains and the alignment of these gullies with low order channels supports the assumption of rapid transport of sediment from low order channels and suggests that these channels are a long-term geomorphic feature.

Rates for landslide movement were taken from literature and varied by landslide type (Harden and others, 1978; Kelsey, 1977, 1978, 1987; Nolan and Janda, 1995; Swanston and others, 1995). The rate of landslide movement used for this estimate are taken from studies conducted in Redwood Creek (Harden and others, 1978; Swanston and others, 1995). Analysis of the movement rates for 36 transects on landslides studied by Harden and others (1978) found a mean annual movement of approximately 131 mm/yr. Recent landslide mapping of Redwood Creek Watershed by CGS staff found that the activity of the three sites monitored by Swanston and others (1995), sites 6, 7 and 8, and used in the previous Gualala River Watershed sediment budget (NCRWQCB, 2001) actually range from active to dormant. The that reason the lower sediment source budget reported here separated rather than averaged the creep rates reported by Swanston and others (1995). For the low estimate of natural sediment, a landslide delivery rate of 130 mm/yr was used for historically active earthflows based on Harden and others (1978) and the landslide rate of Swanston and others (1995) for the CGS historically active landslide. A 10 mm/yr delivery rate was assumed for the dormant earthflows based on Swanston and others (1995) rates ranging from 8 to 17 mm/yr for CGS mapped dormant landslides. For the high estimate of natural sediment, a landslide delivery rate of 300 mm/yr was used for historically active earthflows because this value was at the low end of earthflow rates reported for the coast ranges of northern California by Kelsey (1987). A 20 mm/yr delivery rate was used for the higher estimate dormant earthflows based on maintaining the same active-to-dormant ratio as used in the lower estimate. Delivery rates for rock slides were set based on literature (Swanston and others, 1995; Kelsey, 1987) and professional judgment. Historically active rock slides were assigned delivery rates of 25 and 50 mm/yr for the low and high estimates, respectively. Dormant rock slides were assigned delivery rates of 5 and 10 mm/yr for the low and high estimates, respectively. Soil creep for other terrain was assigned the same 1.6 mm/yr rate used in the previous sediment budget (NCRWQCB,2001). The same soil density of 1.48 tons per cubic yard used in the previous sediment budget (NCRWQCB, 2001) was assumed for this report. Table C-1 summarizes the natural sediment source budget done for this report.

The difference in lower and higher estimates of natural sediment load reflects the variability of movement rates and soil thickness. All other model parameters were held constant. The results of these natural sediment source calculations found a watershed wide annual average background sediment load of approximately 1,000 to 3,100 tons/mi$^{\wedge 2}$/yr from large, deep-seated landslides, both earthflows and rock slides combined with slower soil creep on more stable terrain. Most of the sediment delivered from large, deep-seated landslides, 85 to 90 percent, was derived from those mapped as historically active. This was due in part to the high percentage of large, deep-seated historically active earthflows, 94 percent, while the remaining 6 percent were rock slides. The remaining mass of background sediment was primarily delivered from the larger area of dormant deep-seated landslides. This range of natural sediment load is consistent with those found in other sediment load studies on the northern coast of California including reservoir sedimentation studies (see discussion below). In addition, a three fold variability in sediment load rate is not inconsistent with field studies that measure sediment delivery over time (Kelsey, 1977, 1987; Nolan and Janda, 1995). These studies found that an order-of-magnitude difference in sediment delivery rate from active landslides was common and due in part to variation in annual precipitation. While not specifically linked to precipitation rate, the variation between the lower and higher natural sediment estimates done for this report does incorporate impacts from increased rainfall through increase in rates of movement. Given the uncertainty in the long-term rate of movement of large, deep-seated landslides, large variations in annual sediment delivery should be anticipated.

Table C-1
Gualala River Watershed
Natural Sediment Source Budget from
Deep-Seated Landslides and Soil Creep

Lower Estimate	Percent Area	Annual Delivered Sediment, m^3	Annual Unit Sediment Load, Mg/km^2	Annual Unit Sediment Load, tons/mi^2
Historic Active Earthflows	8.3	134,507	306	874
Historic Active Rock Slides	0.5	1,691	4	11
Dormant Earthflows	8.0	6,924	16	45
Dormant Rock Slides	16.8	6,930	16	45
Other Terrains	66.4	2,886	7	19
Total area = 298 mi^2 Sum		152,938	349	994
Higher Estimate				
Historic Active Earthflows	8.3	408,034	928	2,651
Historic Active Rock Slides	0.5	6,361	15	41
Dormant Earthflows	8.0	23,335	53	152
Dormant Rock Slides	16.8	23,707	54	154
Other Terrains	66.4	3,256	7	21
Total area = 298 mi^2 Sum		464,687	1,060	3,019

Significance of published rates and yields

Studies of natural landslide movement and sediment production have been done in several areas of the northern California coast. The most extensive of these studies that are the most applicable to the geologic units of Gualala River watershed were done in Redwood Creek and the Van Duzen River watersheds. From Kelsey’s (1978, 1980) extensive study of landslides in the Van Duzen River watershed an average movement of 3.1 meters/year (3,100 mm/yr) was found for earthflows within the Franciscan central belt mélange terrain with a ranged from 2.4 to 4.0 meters/year (2,400 to 4,000 mm/yr). For block glides, Kelsey (1987) reported a typical range of movement between 0.5 to 1.0 m/yr (500 – 1,000 mm/yr). Kelsey also reported an annual sediment yield from earthflows in the Van Duzen Watershed of 24,900 metric tons/sq. km-yr, or 71,214 tons/sq. mi-yr (1 metric ton/sq.km = 2.86 US tons/sq.mi-yr). Kelsey noted that gully erosion from earthflows produced 26,300 metric tons/sq. km-yr, approximately equal to the load discharged by landslide mass movement. In contrast, Nolan and Janda (1995) reported that gully erosion was approximately 10 percent of the sediment load from two earthflows in Redwood Creek Watershed. Kelsey (1980) concludes that the active earthflows in Van Duzen River watershed are an order of magnitude greater than elsewhere in similar Franciscan terrain.

Several studies have been done on landslide movement and sediment yield rates in Redwood Creek (Harden and others, 1978, 1995; Nolan and Janda, 1995; Madej, 1999; and Swanston and others, 1995). Nolan and Janda (1995) reported on the movement of two landslides in Redwood Creek watershed that had rates as high as 15.3 meters/yr (15,300 mm/yr) and annual sediment yields that ranged from 730 Mg/sq. km (2,000 US tons/sq.mi.-yr) to 25,100 Mg /sq. km (71,800 US tons/sq.mi–yr) (1 Mg = 1 metric ton). This data indicates that sediment yield can be highly variable and a range of one and a half orders of magnitude is not unexpected. Nolan and Janda state that these sediment yields are from 1.6 to 18.3 times the basin wide average. They also note that fluvial processes in gullies on the earthflows delivered up to 80 percent of the sediment during years of low colluvial discharge. More than 90 percent of the total sediment delivered between the study years of 1979 to 1982 was delivered to adjacent streams by mass-movement processes.

Harden and others (1995) reported on landslides mass movement in Redwood Creek watershed noting that the average movement rates on four earthflows they studied between 1974 and 1982 (Harden and others, 1978) ranged from 0 to 2.5 m/yr (2,500 mm/yr). Madej (1999) conducted a sediment budget for Redwood Creek watershed as part of an overall watershed assessment. Madej notes earthflows contribute relatively little sediment to Redwood Creek because of the small overall area; very active earthflows are approximately 2% of the watershed. However, Madej does provides an analysis of the loading rate of 400 metric tons per year for a small, 25-acre earthflow on Minor Creek, and then uses this load rate to calculate a total annual load for the remaining Redwood Creek watershed. Nolan and Janda (1995) also describe total sediment discharge from a Minor Creek earthflow between 1978 and 1982 as averaging approximately 12,000 Mg/sq.km-yr.

Napolitano (1996) studied the sediment transport and storage of the 3.8 km^2 (1.5 mi^2) North Fork Casper Creek watershed estimated a sediment yield from 1980 to 1988 just prior to a period of second-growth logging at approximately 69 Mg / sq.km-yr (197 US tons/sq.mi.-yr) and 262 Mg /sq.km-yr (749 US tons/sq.mi.-yr) for the wet years of 1963 to 1976. An estimate of the area and type of landsliding was done for the North Fork Caspar Creek area based on recent geologic and landslide mapped done by CGS (Short and Spittler, 2002). These areas and landslide types were then used to for comparison with the Gualala River Watershed natural sediment budget done for this report. An estimate of sediment delivery using the Gualala River Watershed low and high unit area sediment loads calculated an annual sediment load ranging from 25 to 69 Mg /sq.km-yr for the low and high estimate, respectively.

By way of comparison, the previous sediment budget for Gualala River Watershed (NCRWQCB, 2001) estimated that 200 US tons/sq.mi.-yr of sediment was delivered from earthflows that covered approximately 2.5 percent of the watershed. If the newer CGS estimate of 8.3 percent historically active earthflow is used instead and the previous load rate is scaled upward to reflect the increased area, then a sediment delivery rate of approximately 665 US tons/sq.mi.-yr from earthflow is calculated. This sediment load rate does not include the increased areas of historically active rock slides or dormant landslide terrains.

Besides direct measurement of landslide movement and sediment yield, there are other methods available to estimate long-term natural sedimentation rates for Franciscan terrains including studies of reservoir sedimentation, instream sediment load measurements and semi-equilibrium with tectonic uplift rates.

Ritter and Brown (1971) studied turbidity and suspended-sediment transport in the Russian River basin which included the Dry Creek watershed that lies directly east of the Gualala River Watershed. The Dry Creek Watershed is similar to the Gualala River Watershed in that it is underlain by Franciscan terrains, has similar land uses of timber and agriculture, and a climate similar to the eastern portion of Gualala River Watershed. For the years 1965 to 1968 studied by Ritter and Brown, an average suspended-sediment load of 5,700 tons/sq.mi.-yr was measured, with a range from approximately 1,150 to 14,000 tons/sq.mi.-yr, the highest being in the very wet 1965 water year. Sediment studies on Dry Creek continued between 1965 and 1985 by the USGS in association with the Warm Springs Dam. Figure 1 charts the measured suspended-sediment discharge from USGS gage station 11465200 with a drainage area of approximately 162 square miles (http://co.water.usgs.gov/sediment/). This figure shows, prior to the dam, that suspended-sediment yields typically ranged from 200,000 to 600,000 metric tons per year, or 1,350 to 4,000 US tons/sq.mi.-yr. Using this data, Brown and Jackson (1974) calculated average annual basin-wide elevation loss at 1.15 mm per year. Again, this is load rate is within the range calculated by direct studies of landslide movement and estimated by the product of landslide creep and load rates and landslide area.

Another source of mass removal is dissolution of mineral from weathering bedrock and soils and transport out of the basin by surface waters. If it is assumed that the runoff measured on the South Fork Gualala River gage (USGS #11467500)with a drainage area of 161 square miles is representative of the entire basin, then that unit runoff can be multiplied by the entire watershed area of 298 square miles producing an average annual runoff of approximately 558,000 acre-feet (see DWR's Hydrology report appendix for runoff data). The quality of the surface waters in the North Fork Gualala have been reported as part of the North Gualala Water Company's monitoring program and shows that quality of surface waters is generally 100 milligrams/liter (mg/L) total dissolved solids (Luhdorff and Scalmanini, 1998). If it is assumed that this water quality is representative of the South Fork Gualala River, then an average total annual dissolved solids load can be estimated. Since 1 mg/L is approximately 2.72 pounds/acre-foot, the 558,000 acre-feet of surface waters discharges annually from the Gualala River Watershed approximately 152 million pounds of dissolved minerals, or approximately 255 tons/sq.mi.-yr.

Kelsey (1987) presented as summary of recent geomorphic processes on the north coast of California. He notes that tectonic uplift rates in the northern California coast range from 1.0 to 4.0 meters per 1,000 years (m/ka) with regional averages that likely are on the order of 0.6 to 1.5 m/ka. Merritts and Vincent (1989) studied the geomorphic responses to uplift rate in the Mendocino triple junction region. They reported uplifts rates of approximately 0.3 mm/yr at Fort Bragg, 4mm/yr about 20-40 km south of Cape Mendocino, and 2.8 mm/yr at the triple junction at Cape Mendocino. Richardson (2000) reported that the marine terraces along the coast west of the Gualala River Watershed have uplift rates that increase northward from Fort Ross to Sea Ranch of 0.24 to 0.58 m/ka, respectively. If it is assumed that regional erosion rates are approximately half tectonic uplift rates, then the long-term rate of natural erosion can be estimated from the long-term regional erosion rate. For the Gualala River Watershed that results in an regional erosion rate that ranges from approximately 700 to 1,450 US tons/sq.mi.-yr (1.0 m/ka uplift = 1 mm/yr ≈ 5,000 US tons/sq.mi.-yr erosion), or an average of approximately 1,075 US tons/sq.mi.-yr.

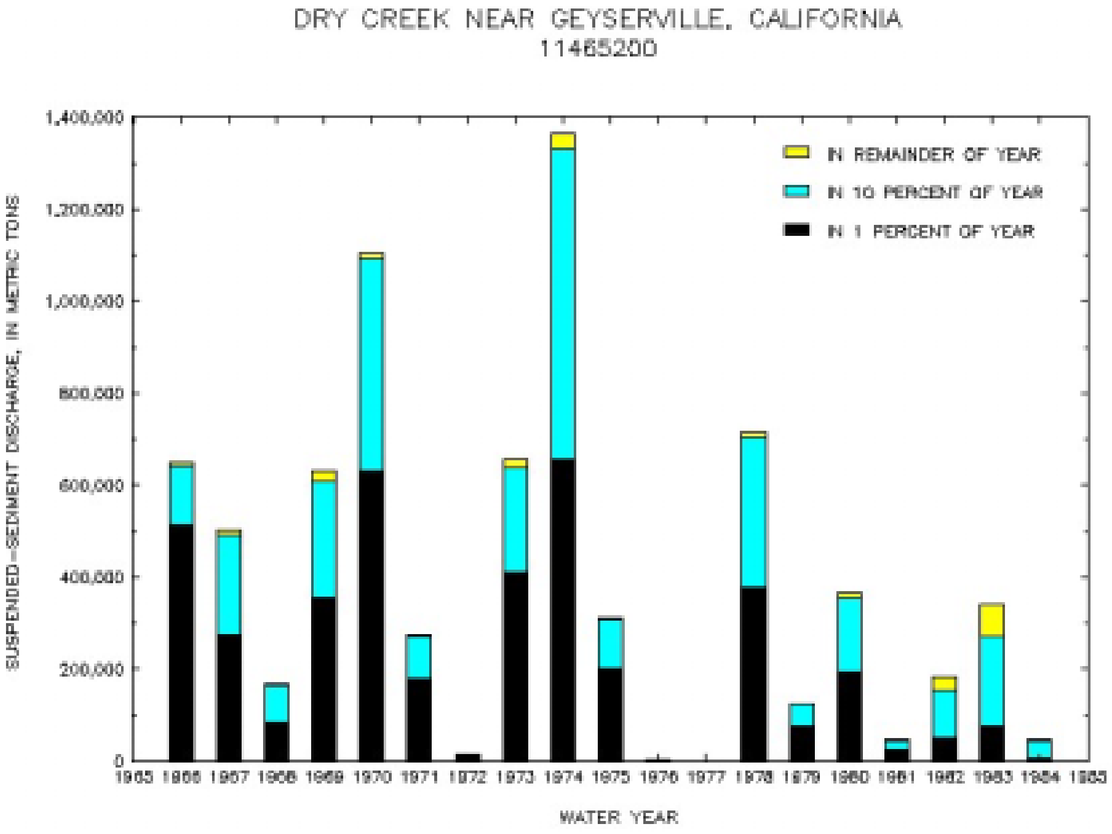


Figure 1. Histogram of suspended-sediment discharge at USGS gage 11465200, Dry Creek from 1966 to 1984. Web source:http//co.water.usgs.gov/sediment/.

The discussion given above for regional estimates of natural watershed erosion makes it apparent that deep-seated landslides, both active and dormant, and gullying within these unstable terrains are major sources of natural sediment. This conclusion appears to agree with the finding of CGS's fluvial geomorphic mapping in the Gualala River watershed. CGS found good spatial correlation between lands mapped as geologically unstable, both shallow and deep-seated landslides, and reaches showing fluvial geomorphic characteristics that imply excess sediment deposition and channel erosion. In the Gualala River Watershed approximately 70 percent of anomalous accumulations of stream sediment occur adjacent to dormant and active landslide areas. Sixty-two percent of mapped eroding banks also occur adjacent to dormant and historically active landslide areas. This suggests that present day stream disturbances and sedimentation are strongly influenced by the adjacent geology and geomorphology, and by the lands directly upstream.

Estimates of natural annual sediment yield for watersheds in coastal northern California underlain by central belt Franciscan terrain and mélange with deep-seated landsliding range from approximate 1,000 tons/sq.mi-yr (Gualala River watershed) to possibly as high as 70,000 tons/sq.mi.-yr (middle and upper Van Duzen River watersheds). The watershed rate of natural sediment delivery to the channels is strongly influenced by the percentage of lands underlain by historically active deep-seated landslides. If unit sediment loads measured elsewhere in coastal northern California are typically, watersheds underlain by 10 to 40 percent deep-seated historically active landslides in the central belt Franciscan terrain and mélange will likely have long-term natural sediment yields ranging from approximately 1,000 to 3,000 tons/sq.mi.-yr. The percentage of lands underlain by other types of landslides, such as debris slides, and geomorphic terrains created by landsliding, such as debris slide slopes will add to this natural background sediment load.

VARIABLE	VALUES	REFERENCE
Tectonic uplift rate	0.24-0.58 mm/yr	Richardson, 2000
Measured movement rates of earthflows in Van Duzen basin	2,400-4,000 mm/yr. Average: 3,100 mm/ yr	Kelsey, 1978 and 1980
Annual sediment yield from Van Duzen earthflow movement	71,214 US tons/ sq. mi/yr	Kelsey, 1978,1980, 1987
Annual sediment yield from gullies on earthflows in Van Duzen	75,218 US tons/sq/yr	Kelsey, 1978,1980, 1987
Measured movement rate of two landslides in Redwood Creek	Up to 15,300 mm/yr.	Nolan and Janda, 1995
Annual sediment yield of two landslides in Redwood Creek	From 1979-1982, 2,000- 71,800 US tons/ sq. mi/yr	Nolan and Janda, 1995
Measured suspended sediment yield of Russian River above Guerneville	From 1965-1968, 4,370 tons/ sq. mile/yr from 1,340 sq. mi. drainage area	Ritter and Brown, 1971
Measured suspended sediment yield of Dry Creek tributary to Russian River	From 1965-1968, 5,770 tons/ sq. mi/yr from 128 sq. mi. drainage area ranging from 1,150 to 14,100 tons/ sq. mi./yr.	Ritter and Brown, 1971
Measured annual sediment yield on Dry Creek for water year 1980 with annual water yield = 61,955 cubic feet	Suspended sediment: 313 tons/ sq. mi/yr Bedload sediment: 80 tons/ sq. mi/yr Total sediment yield: 392 tons/sq. mi/yr	USGS Gage 11465200 records
Measured annual sediment yield on Pena Creek for water year 1980 with annual water yield = 8,366 cubic feet	Suspended sediment: 532 tons/sq. mi/yr Bedload sediment: 106 tons/sq. mi/yr Total sediment: 640 tons/ sq. mi/yr	USGS Gage 11465150 records
Total suspended annual sediment yield for water year 1970 on Dry Creek with annual water yield =111,342 cubic feet	Suspended sediment : 1,866 tons/sq. mi/yr	USGS Gage 11465200 records
Measure movement rates of earthflows from 1974-1982	0-2,500 mm/yr.	Harden and others, 1995 Harden and others, 1978
Measured creep rate of earthflows in Redwood Creek	3-130 mm/yr.	Swanston and others, 1995
Measured rate of movement of an active earthflow	488 mm/yr.	Madej, 1999 and references therein
Calculated yield from an active earthflow in Redwood Creek	29,280 US tons/sq. mi/yr.	Madej, 1999

Table C-2: Variables and values considered in estimation of sediment yield.

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