UNMASKING THE AGENTS OF CHANGE

FLOODS, EARTHQUAKES, landslides, fires, land-use practices, and climate-influenced oceanic conditions have been major forces that have sculpted the morphology—or shape—of the Redwood Creek basin and affected its water, soil, animals, and plants. These agents of change are what keep stream channels such as Redwood Creek in a constant state of flux. And they help to maintain the habitat elements that fish need to reproduce and grow.

The concept of a "steady state" does not apply to the morphology of streams because their forms and conditions change at any place and time.[14] These agents of change are responsible for erosion of the soft geology of a watershed, which, in turn, results in characteristic levels of sedimentation. The natural sediment levels in Redwood Creek vary from year to year, but are among the highest rates of sedimentation in the world. Consequently, one must recognize that natural disturbances—agents of change—are part of the natural history of forested basins like Redwood Creek.[15]

Flooding Shapes and Reshapes the Channel

The storms that generate floods in northern California are widespread and produce moderately intense precipitation, causing discharge rates that are among the highest recorded in the United States.[16] Increases in flow result from successively greater storms. Floods occur when soil becomes waterlogged and channels overflow their banks.

The ability of floods to shape river channels is a function of the speed and volume of water in the channel as well as the quantity and character of the sediment in motion. Floods influence channel width and depth and the character of plants and other materials that form the bed and banks of the channel.[17] Stream channels may migrate laterally by erosion of one bank and deposition on the opposite bank, thus maintaining a fairly constant, but ever moving, channel profile.[18]

There are five distinct periods of flood activity in Redwood Creek: prehistoric, 1860 to 1890, 1890 to 1950, 1950 to 1975, and 1975 to present.

Streamside forests and streambanks become restructured between major floods. Note the same barn in both photos.

Photo at left courtesy of Phoebe Apperson Hearst Museum of Anthropology
Photo at right courtesy of Humboldt State University Library

Prehistoric Flooding

A legacy of prehistoric floods is evident in the Redwood Creek channel based on the study of stored sediments. The prehistoric floods, which occurred over a period of millennia up until a century and a half ago, are believed to have caused significantly greater changes than historic floods.

Scientists have approximated the prehistoric flood record by studying the sediment and dead trees stored in streambanks that were unearthed as a result of large floods. Using carbon-dating methods to determine the age of wood stored in old flood deposits, researchers have concluded that major flooding occurred regularly throughout northern California.[19] The great floods of the past, which moved dormant gravel beds, were separated by 100 years or more.[20]

1860-1890 Flooding

The time of the last major flooding of Redwood Creek can be estimated by calculating the age of trees growing along the streamside. This method is based on the fact that large floods wash away trees, and new trees become established after the ground once again becomes stabilized.[21,22] The method identified a series of major floods of unknown magnitude that occurred in Redwood Creek in the 1860s, 1880s, and 1890.[23] A 1902 photograph of Redwood Creek at the mouth of Minor Creek shows the abraded landscape from one or more of those floods.

The photograph shows dead Douglas-fir trees, bare gravel bars, and young alder trees along the stream. A wide, flat gravel bar with little evidence of defined streambanks is seen in the center—evidence of severe impacts from a large flood.[24]

Interestingly, the age and size of alder trees growing along the stream had noticeably advanced in the years since the previous flood. The alder trees appear to be 25 to 50 years old in a 1920 scene, and the creek appears to have more well-defined banks, indicating that channel sediment had been washed away and that new sediment input from upstream had diminished. It is hypothesized that by 1920, the creek was still restructuring from the effects of a circa 1861 storm.

1890 to 1950 Intermission in Flooding

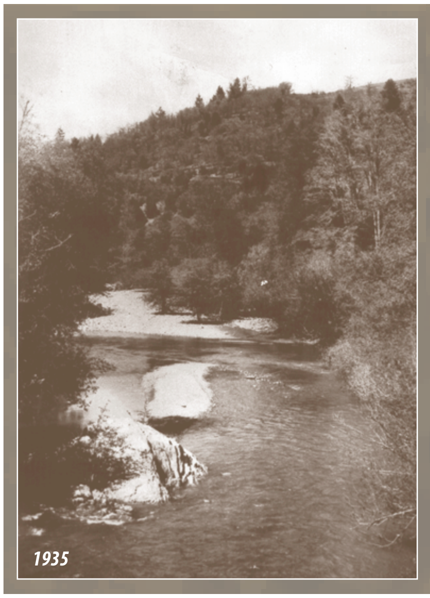
The flood record indicates that no major floods occurred from 1890 until after World War II.[25] By that time, Redwood Creek was in more advanced stages of sediment depletion, as shown in the 1935 and 1948 photos at the old Highway 299 (Chezem Road) Bridge. No major flooding had occurred in half a century, and widespread erosion from now archaic logging practices had not yet happened. The large rock in the left foreground of the 1935 photo provides an excellent benchmark for comparing the stream conditions shown in the photo time-series on pages 12-13.

1950-1975 Flooding

Starting in January 1953, a series of major storms and floods dramatically affected the Redwood Creek basin after

Turbulent waters periodically reshape the landscape as shown at Orick and near the mouth of Minor Creek.

Top photo courtesy of Humboldt County Public Works Department
Bottom photo courtesy of Charles R. Barnum III


1935


1948

Overhanging vegetation and the variety of sediment sizes reflect an intermission in flooding.

Photo at left courtesy of the Andy Pon family
Photo at right courtesy of CalTrans

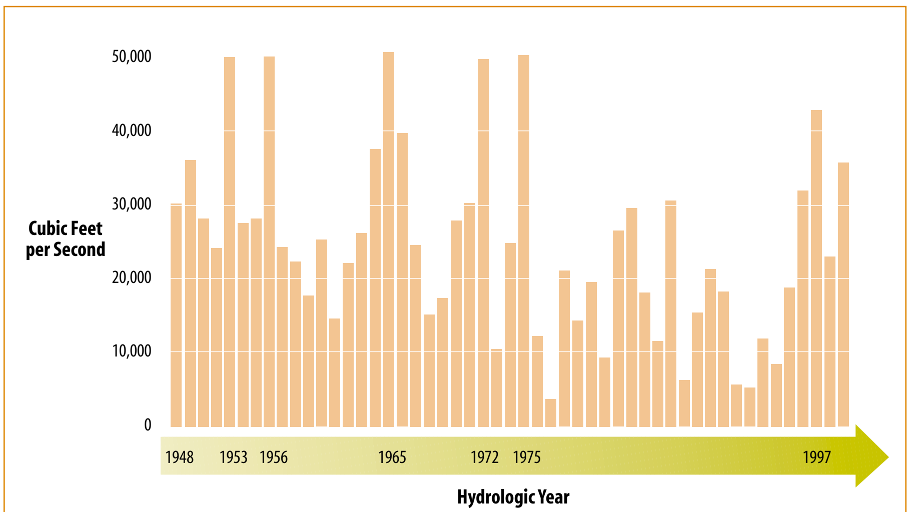
decades of below normal rainfall and no major flooding.[26,27] The January 1953 flood was followed by a flood in December 1955, the benchmark flood of December 1964, two floods in 1972, and one in 1975—coincidentally the advent of modern forest practices rules. Each flood corresponds to the significant peak flows shown in the hydrologic chart, and represents storms with 15- to 50-year recurrence intervals.[28]

Unlike previous periods, the impacts of these floods during this period are well documented by photographs and flow measurements. The town of Orick, near the mouth of Redwood Creek, was submerged during the 1964 flood, and the water was turbulent during the January 1972 flood.

Perhaps the effects of the floods were best captured by the photo time-series at the old Highway 299 (Chezem Road) Bridge over Redwood Creek, photos at the 1926 Bridge across Minor Creek near its mouth, and photos at the Don O'Kane Bridge.

Earthquakes Shake Up Soils

Redwood Creek flows along the course of an earthquake fault in an area that is among the most seismically active areas in California.[32] On December 21, 1954, the epicenter of



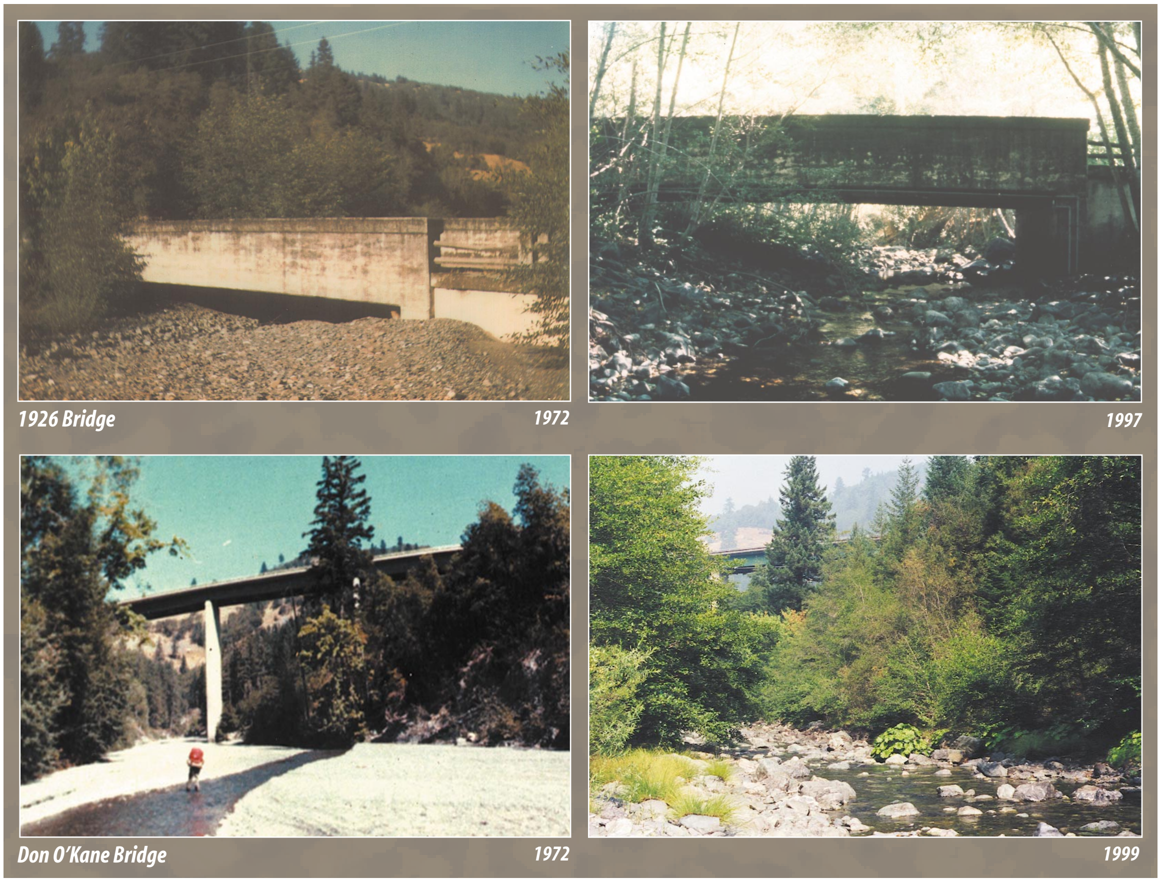
Prior to 1997, the last significant peak flow of Redwood Creek occurred in 1975.

Source: R. Klein. 1999. Redwood National Park.

FLOODING: IN A NUTSHELL

It is widely agreed that the streambed changes that occurred during the floods of the mid-20th century were slight when compared to those that occurred prehistorically. While the December 1964 and other recent floods brought major changes to Redwood Creek, they did not move the stable, buried gravel bars deposited by prehistoric floods.[29]

Redwood National Park scientists have concluded that the flooding period from 1950 to 1975 was similar to the flooding period from 1860 to 1890.[30] But others contend that the changes that occurred during the 1860-1890 floods were less pronounced than the 1950-1975 floods, in particular, the 1955 and 1964 floods that took place during the onset of the heavy logging era.[31] Their belief is based on perceptions of changes in the number of landslides, and the size and condition of residual streamside alders and streambed gravels shown in the airphoto record. However, no studies have been found that definitively characterize the late 19th century flooding effects as more or less than those associated with the 1954 or 1964 floods.



Impressive changes in streambed gravel composition, sediment elevation, and vegetation condition are captured in these repeat photographs.

one of the most intense, ground-shaking earthquakes ever recorded in Humboldt County was centered in the Redwood Creek basin.[33] Local residents felt significant ground shaking during this quake.[34]

Though the 1954 Earthquake was significant, it was only the most recent of what appears to be a series of earthquakes stretching back much further in time. Geologists working in Humboldt County have found physical evidence that testifies to great, ancient earthquakes, greater than any earthquake felt by European settlers.[35] These great earthquakes were ten times greater than the 1954 Earthquake.

Large earthquakes have an impact on the morphology and sedimentation of Redwood Creek.[36,37] In seismically active areas of northern California, earthquakes have contributed 25 percent of the total sediment yield of streams.[38]

Earthquakes set into motion a number of different mechanisms that, in turn, deliver sediment to streams.[39] One mechanism is earthquake-triggered rock slides that deposit sediment directly into streams. Another involves the loosening of soil by tree shaking, ground shaking, and the uplifting and settling of the soil mantle near bedrock hollows and ridge tops.[40,41] Loosened soils are later eroded by intense rainfall. These sediment delivery processes operate on a relatively short (1 to 10 years) time scale following the actual earthquake.

There are also longer lasting effects of earthquakes on sediment loads that result from continued tectonic uplifting that, in turn, cause long-term readjustment of slope angles in areas with earthflows and gooey soils.[42] The tectonic uplift rate of the Redwood Creek basin is 3 feet per 1,000 years.[43] As uplift occurs and the slope angles steepen, more sediment falls into the creek.

Landslides Deliver Slugs of Sediment in Pulses

Mass soil movement from earthflows, debris slides, and streambank failures are major sources of sediment to stream channels of the basin, even where land use is minimal.[44,45,46,47,48] Along with erosion caused by surface water, mass soil movement is the principal means by which sediment enters stream channels; this movement governs many aspects of aquatic and riparian habitat formation.[49,50,51,52]

Bowl-shaped basins, convex-upward hillslopes, and benched slopes throughout the basin suggest that mass movement has been responsible for much of the landscape form, even in areas where discrete landslide features are absent.[53] One report puts the number of active landslides in the Redwood Creek basin at 551, covering 10-16 percent of the total basin area.[54,55] An additional 15 percent of the basin is covered by inactive landslides.

Landslides and debris flows have an extremely low probability of occurrence at any particular site or point in time, but over a broad landscape, their patterns and frequency are more predictable. One can identify areas most likely to fail by examining the basin's rock formations. Bedrock with finer grain and more intense shearing is most susceptible to landslides and debris flows.[56]

The probability that a landslide or debris flow occurs in Redwood Creek increases in the downstream direction of the channel due to an increase in the number of potential landslide source areas and increased probability of large storms with larger drainage areas. About half of the 1964 landslides existed prior to 1964; they initially slid during the intense storms associated with the floods of 1953 and 1955, which predisposed them to slide again.[57,58]

But what "goes in" eventually must "come out." The majority of sediment delivered to Redwood Creek by landslides exited its tributaries and the upper reaches of the main stem of Redwood Creek within a decade of the 1964 storm.[59]

Fire-Scarred Landscapes Facilitate Soil Erosion

Historically, wildfires ignited by lightning or humans (mostly Native Americans) have caused changes in the sediment balance of Redwood Creek.[60] For tens of thousands of years, Redwood Creek was subjected to changes caused by fire every 1 to 12 years based on cultural evidence and plant indicators.[61,62,63] Native Americans maintained prairies for game management and prepared areas for food and tobacco production through controlled burning.[64]

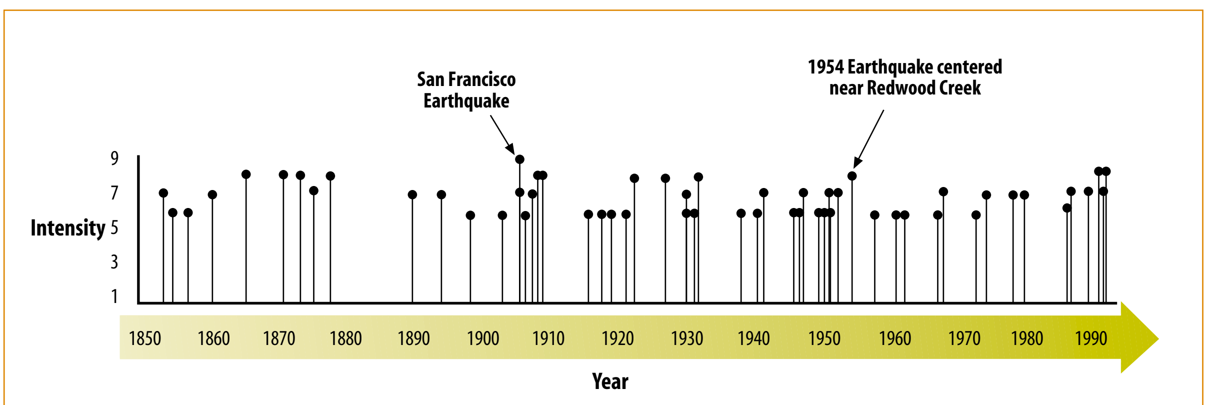
Severe fires can accelerate soil erosion processes.[65,66] Fire-induced accelerated sedimentation is usually greatest during the first year following a fire, and remains elevated for the next 4 to 6 years.[67] Increased sedimentation can also occur from removal of ground litter and vegetation cover as well as increased water repellency or reduced soil strength. Wildfires that occurred prior to European settlement probably played an important role in triggering

THE REDWOOD CREEK ESTUARY:

Early photographs of the Redwood Creek estuary at the mouth of the creek show a valley forested with spruce trees. Tree age studies of remnant groves near the estuary suggest that the trees became established following the floods of 1861-62 and 1890.

Early European settlers converted the floodplain forests to agriculture, establishing dikes as early as 1927. Following the floods of 1953, 1955, and 1964 that took human lives and devastated property, modern flood levees were established along the stream throughout the estuary to protect the town of Orick.

As a result of the levees, 50 percent of the original estuary area has been lost by filling or become isolated from the bay, cutting off access to rearing habitat for juvenile salmonids and smolts.[77] These rearing areas are believed to be important final growth areas for salmon and steelhead smolts before they enter the sea.[78]



Larger earthquakes occur frequently in Humboldt and Del Norte Counties.

Source: L. Dengler, G. Carver, and R. McPherson. 1992. California Geology 45:40-53.

Old logging practices along streams have been replaced with low-impact methods.

Photo courtesy of Ted Hatzimanolis

Photo courtesy of Barnum Timber Company

landslides.[68] Where wildfires occurred, the soil of fire-damaged terrain accounted for over 60 percent of the total sediment production.[69]

In some instances where large wood in stream channels burned, severe increases in transported sediment in streams have been documented. This has been the case even in the absence of overland flow or debris torrents. Where this occurred, channels became unstable and large quantities of sediments that had been stored behind accumulations of large wood were released.

Since European settlement, and particularly since World War II, fire suppression and exclusion policies have significantly reduced the frequency and intensity of fires in the Redwood Creek basin.[70,71] This reduced fire frequency—at least for the time being—removed this potentially significant cause of soil surface erosion.

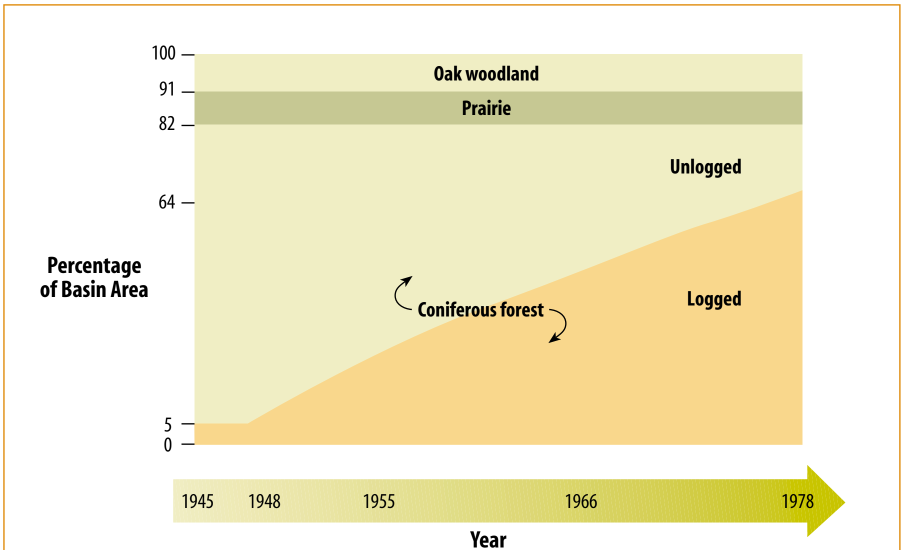
New, Smarter Land-Use Practices Minimize Erosion

By definition, "land use" implies the use of land by people, and, historically, this use has contributed to increased erosion of soils and sedimentation of Redwood Creek. This was as true of the Native American tribes who lived along Redwood Creek for thousands of years—the Yurok, Chilula and Whilkut—as it was of the Europeans who began to settle near Redwood Creek in the middle 1800s.[72,73,74] Modern-day residents who live near Redwood Creek have, for example, cultivated and allowed livestock to graze open areas, harvested timber, and built roads. The practice of diking pastures, particularly around the estuary, for flood protection has likely disconnected floodplains from the stream system. Infrastructure "improvements" at Orick along State Highway 101 and elsewhere also contributed to an altered natural ecology.[75]

All of these activities have had an effect on the creek; many of them are measurable.[76] The human-caused disturbances generally differ from natural disturbances in that they are on a much smaller scale, but are more frequent.

Currently, the most widespread land use in the Redwood Creek basin is logging, which increased rapidly from 1948 to 1954 when approximately 15 percent of the basin was logged.[79]

During the next decade, from 1955



Fifty-nine percent of the coniferous forest of the Redwood Creek basin was harvested between 1948 and 1978.

Source: D.W. Best. 1995. U.S. Geological Survey Professional Paper 1454.

to 1966, an additional 20 percent of the basin was logged.[80] Many of the older logging practices changed the streamside conditions of Redwood Creek in ways that resembled the effects of major historical flooding events. For example, in the 1972 scene, streamside trees were cut and the streambed was used for roads and landings.

Also, government mandated the removal of large tree stems, root wads, and debris dams from streams during the logging operations of the 1950s to 1980s. This practice may have had the greatest negative impact on streambeds and fish habitat.[81,82]

Notwithstanding relatively heavy timber harvesting during these earlier periods, researchers studying Redwood Creek have concluded that **for the period 1973 to 1980, the aquatic habitat and water quality were excellent**.[83] Where fine sediments in pristine northern California streambeds range from 8 to 26 percent by volume, two Redwood Creek tributaries that were logged within a 15-year period contained only 24 to 25 percent fine sediment; that is, they were within the range reported for pristine areas.[84,85]

Forest practice rules, harvesting technologies, and the character of trees being harvested are much different today. Increased reliance on overhead systems of winch-driven cables to transport logs has reduced erosion.[86,87] Also, harvesting second-growth trees with tractors has resulted in less ground disruption than historical harvesting of old-growth redwoods.[88] A recent best-estimate of the amount of soil entering northern California streams from forestland logged under the modern forest practices rules amounts to less than 5 percent of the natural sediment yield.[89,90,91,92]

Today's logging methods, such as cable yarding, conveyance with helicopters, improved road construction and maintenance, and retention of streamside trees, have much lighter impacts on the basin than older logging practices.[93,94]

How Much Sediment Do Roads Deliver?

For many years, man rather than nature was suspected to be the greatest source of suspended sediment loading of Redwood Creek.[95] In the 1970s, geologists sought to determine how much of the erosion in the Redwood Creek basin was caused by human activities. After much study, they determined that most sources produced minor or inconclusive amounts, but it became clear that the largest amount of human-caused erosion was at the point where roads crossed small streams.[96,97,98] Roads tend to erode when intense rains loosen soils, and improper road construction can divert the flow of a stream causing the stream to establish a new channel or gully.[99,100] Gullies, in turn, have the potential to damage roads and erode precious topsoil from hillsides.

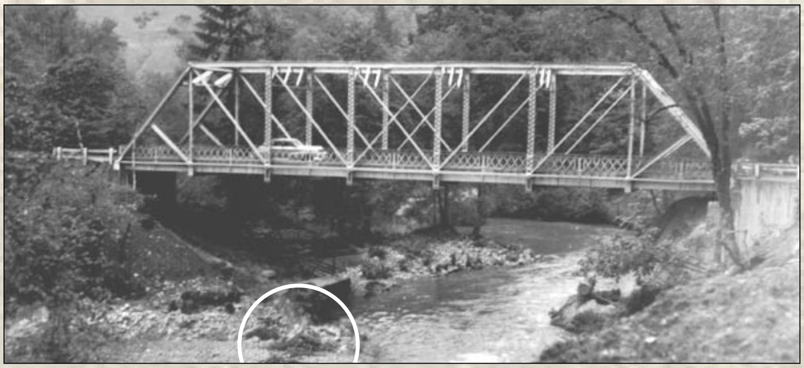
When land managers realized that simple improvements in road-building techniques could effectively minimize erosion, they began to adopt the new techniques.[101,102,103] These refined techniques were shown to be effective through a Critical Sites Erosion Study, which examined 179,000 acres of land in northern California that was logged using conscientious, improved erosion control practices.[104] Erosion from roads on private forest lands where modern road-building techniques are practiced has been reduced by 97 percent when compared to unattended roads destroyed by storms in the 1950s, 1960s, and 1970s.[105]

Well-attended roads produce much less sediment than rehabilitated or unmaintained roads.

Time period	Unattended	Rehabilitated	Attended
		cubic yards/mile	
1997	1,326[113]	725[111]	13[114]
1995-97	--	--	206[112]
1980-1997	--	1,353[115]	372[112]

LAND USE: IN A NUTSHELL

Unlike the early settlers of the region, we now understand how sediment delivery occurs and how new, improved land-use practices such as building stable roads can assist in controlling erosion. Numerous studies have concluded that streams draining timber-harvested areas with roads temporarily contain higher amounts of fine sediment after logging when compared to "control" streams. However, timber harvesting does not appear to have had lasting adverse effects on sediment levels. Timber harvesting practices generate less than 5 percent of background sediment yield, and modern road-building practices have reduced road-related erosion to about 3 percent of the amount produced by older, unattended roads. This has reduced to mere speculation the possibility that modern-day land uses are producing discernable effects on sedimentation of Redwood Creek, and these effects are small when compared with past land-use impacts and natural disturbances.



- Variety of streambed sediment sizes, including coarse rocks
- Low sediment elevation
- Middle-aged trees overhanging banks

- High water 2 weeks after the 1964 flood
- High sediment elevation
- Damaged riparian vegetation

1890 Flood

1948

1953 Flood

1955 Flood

1965

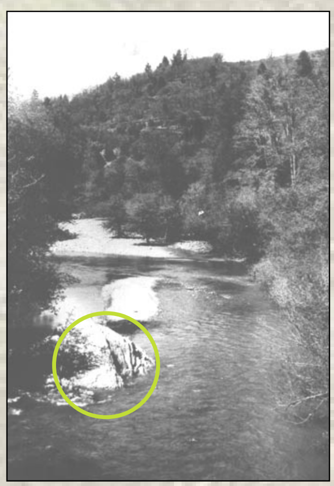
1902

1935

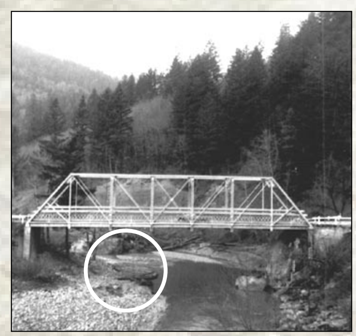
1962

1964 Flood

- Small and medium size streambed gravels left from 1890 flood
- Moderate sediment elevation; original covered bridge required a lateral brace
- Young riparian vegetation



- Variety of streambed sediment sizes, including coarse rocks
- Low sediment elevation
- Middle-aged trees overhanging banks



- Small gravels following the 1955 flood
- Moderate sediment elevation
- No vegetation in channel

- Small and medium size streambed gravels, dramatic changes from the 1964 flood
- High, about 7 feet higher than it was in 1935
- No vegetation in channel; damaged riparian vegetation

- Large streambed gravel sizes; conditions are like 1948
- Low sediment elevation
- Young riparian vegetation is present mid-channel and on the gravel bar

1970 — 1972 Floods — 1972 — 1975 Flood — 1999

- Small streambed gravels
- High sediment elevation
- No overhanging streamside tree canopy or vegetation in channel

Changes in stream channel conditions over time are captured in photographs.

- Streambed Gravel Composition
- Sediment Elevation
- Vegetation Condition

Large Rocks for Streambed Elevation Reference

- White circle: 1902, 1948, 1962
- Green circle: 1935, 1970, 1999

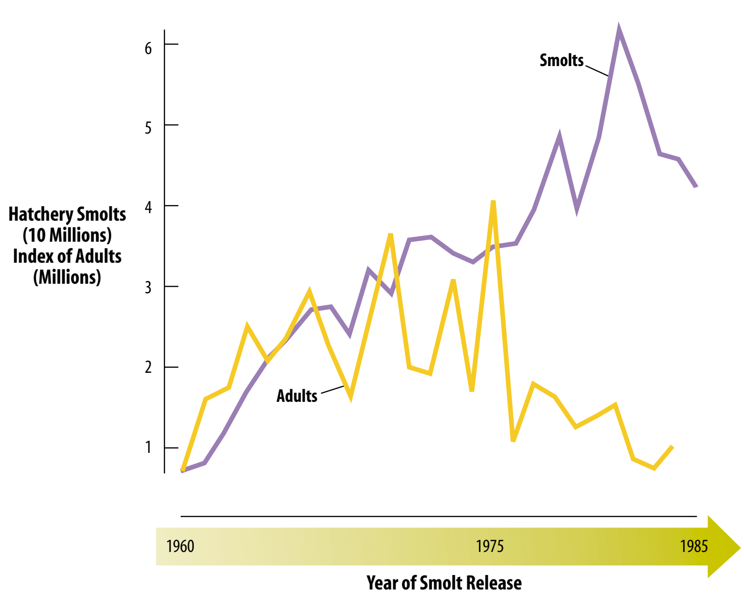
Another estimate that can be developed puts the amount of potential erosion from today's roads at less than 8 percent of what actually occurred from unattended roads during the 1972 and 1975 floods.[106,107,108] This suggests that erosion risk on private lands has been reduced by improved road building and maintenance techniques.

However, not all road-related problems have occurred on private land. Redwood National Park inherited lands with unattended roads and numerous stream crossings that have a high potential to create gullies. Because these roads were built without awareness of the potential risk to release sediment, Redwood National Park undertook an ambitious effort to remove unneeded roads and rehabilitate actively used roads to bring them up to modern erosion-control standards.[109]

Road upgrade and maintenance projects in Redwood National Park are reducing sediment inputs to Redwood Creek. Currently, rehabilitated roads in the Park generate about one-half of the sediment produced by unattended roads.[110,111]

Upstream of Redwood National Park, erosion from private attended roads is even less than the erosion from rehabilitated roads in the Park; these roads generate only one-fourth of the amount produced by the rehabilitated roads in Redwood National Park.[112]

Putting road-related erosion into perspective: it is estimated that between 11 and 15 cubic yards per acre of total potential erosion is associated with roads in the headwaters of Redwood Creek.[116,117,118] If all of the potential erosion were to occur at once and at the same rate over each of Redwood Creek basin's 180,000 acres—although unlikely—it would generate less sediment than the amount of erosion generated by flooding in a single year.[119] Moreover, a great flood would also trigger massive natural erosion from slides and debris flows that would effectively minimize the effects of road-related sediment washed into the creek. However, this road erosion scenario is unlikely because many roads in the Redwood Creek basin have already been rehabilitated and many acres contain no roads.[120]



The divergence between numbers of hatchery coho salmon smolts released along the West Coast and estimated abundance of hatchery and wild adults produced in the following year is dramatic.

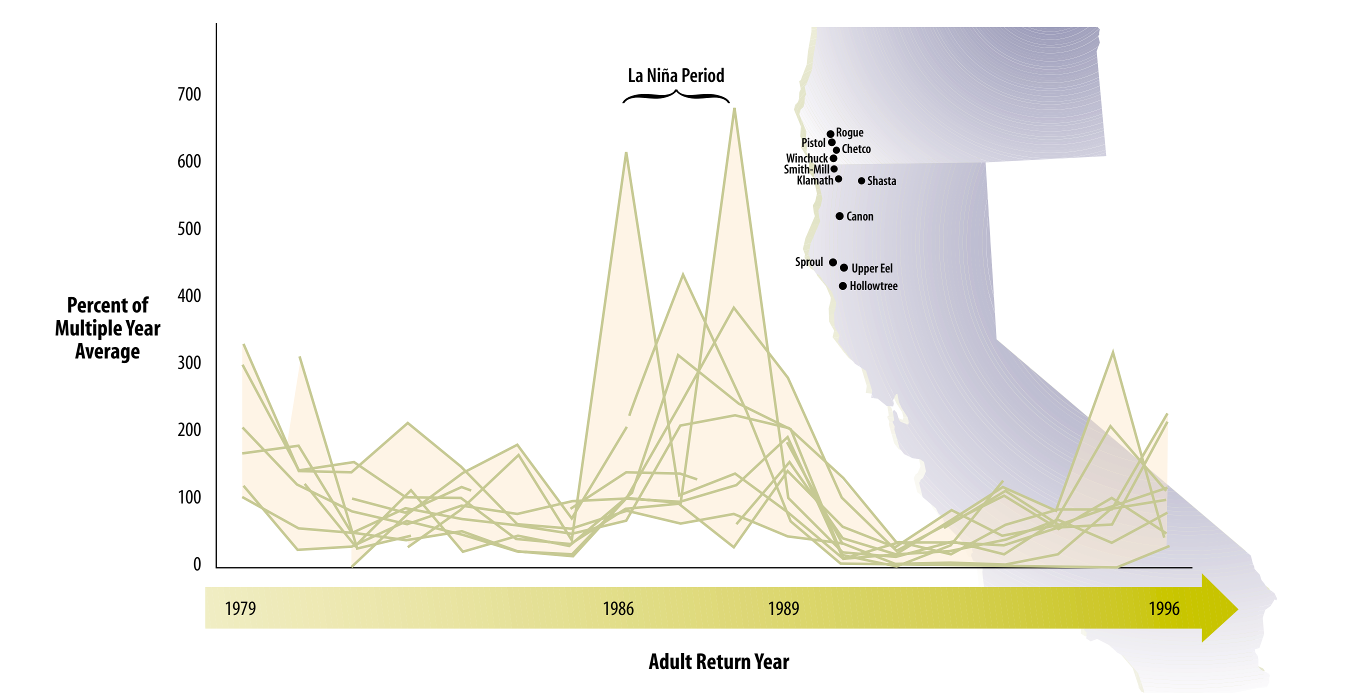
Source: D.L. Bottom. 1999. Northwest Power Planning Council.

The Ocean as an Agent of Change

Why are we so concerned about sedimentation? Because it is essential to freshwater salmonid habitats! But assessment of Redwood Creek's salmonid populations must focus on factors other than the physical processes of the freshwater creek. It must also touch on the physical conditions of the ocean as they affect the strength of anadromous salmon and trout populations. Salmon spend up to 95 percent of their lifetime in the ocean, so ocean conditions are a predominant factor governing the production of West Coast salmon.[121]

More productive ocean conditions for California salmon are created when the ocean depths "upwell" as a result of favorable winds associated with a strong North Pacific high pressure system and its associated increase in rain in northern California, Oregon, and Washington.[122,123] Upwelling is the rise of deeper, nutrient-rich water to the surface of the ocean along the coasts. By bringing up nutrients, upwelling improves food sources for young salmon, which aid survival.[124] Conversely, when upwelling is poor, as generally was the case between 1977 and 1994, salmon survival is low.[125,126,127,128]

Another potential cause-and-effect relationship between salmon mortality and upwelling may have to do with changes in water temperature. The surface temperature of the ocean drops when upwelling occurs. Some believe that 90 percent of the variation in the coho salmon ocean mortality rate can be explained by the surface temperature at the time when juvenile fish first enter the ocean, and during



The cycles of spawning salmonid populations among geographically distant rivers are in rough synchrony.

Source: Steiner Environmental Consulting. 1998. Final Report: Potter Valley Monitoring Project.

their second year in the ocean.[129,130,131]

Shifting climate regimes have an impact on ocean temperature and upwelling. Climate regimes shift about every 20-30 years between cool, wet, windy weather with increased coastal upwelling and high salmon survival and warm, dry periods with limited coastal upwelling and low salmon survival.[132]

A dramatic climate regime shift to warm, dry conditions last occurred along the West Coast in 1977.[133,134,135,136] The unfavorable ocean conditions at that time may explain the increased mortality of hatchery-reared salmon.[137,138] The release of hatchery-raised coho increased sharply through the 1960s and 1970s and leveled off in the 1980s.[139] These releases appeared to result in substantially increased coho salmon harvests up until about 1977, when harvests began to drop and ocean conditions began to decline.[140]

Within the 20- to 30-year climate cycles, ocean conditions can temporarily reverse or become accentuated by short-term El Niños and La Niñas.[141,142] El Niños are warm, dry weather events and La Niñas are cool, wet, windy weather events. El Niño years have been associated with disastrous salmon fishery failures; La Niñas have been associated with a superabundance of salmon. One such La Niña period occurred in 1986-1988. Ocean survival of both coho and chinook young was high during this period when California experienced its all-time high chinook salmon harvest and local spawning runs thrived.

The influence of unfavorable ocean conditions on salmon smolts was dramatically demonstrated by the nearby Eel River chinook salmon population. In 1988, the number of chinook smolts entering the ocean was high, but adult runs faced near-total collapse during the following years, indicating poor growth and survival in the ocean.[143,144]

Ocean Conditions: In a Nutshell

Salmonids spend the majority of their lives at sea and the physical conditions of the ocean have a significant impact on salmonid health and their ability to survive at sea. Cycles of higher salmonid abundance occur during cycles of favorable ocean conditions.[145,146,147] The annual rainfall pattern, which is correlated with the quality of ocean conditions for salmon and the amounts of salmon caught each year by commercial ocean fishers, suggests the years when ocean conditions were either favorable or unfavorable to salmon. For example, annual rainfall was relatively low and ocean conditions were very poor from 1977 through at least 1994 when the abundance of West Coast salmon was very low.