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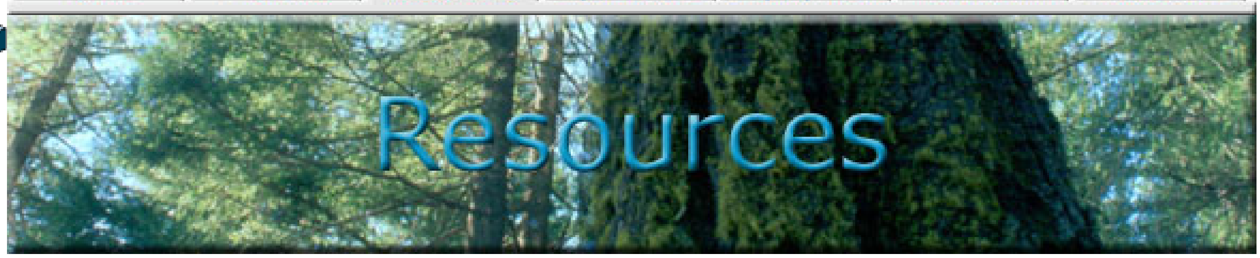

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Redwood Creek and Salmon, a recent study from Humboldt County, California

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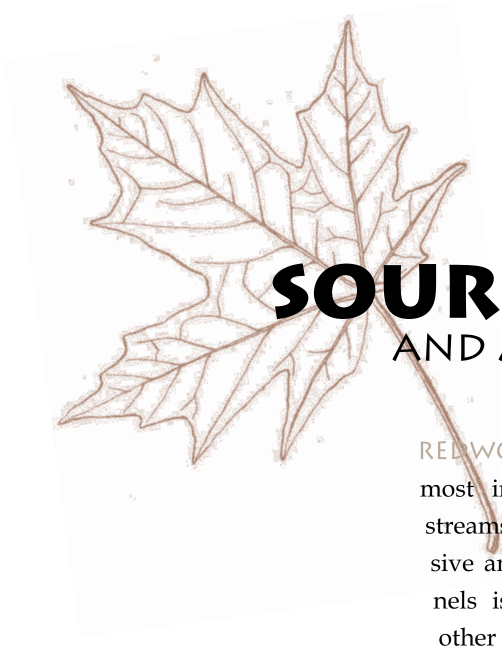


SOURCES
AND ACKNOWLEDGEMENTS

REDWOOD CREEK IS ONE OF THE most intensely studied and monitored streams of its size in the world. The extensive amount of information on its channels is generally unavailable for most other drainage basins. The cumulative story that emerges is one of water quality and the strength of the Redwood Creek salmon and steelhead trout populations, which presumably have fluctuated over time as a result of several documented factors.

U.S. Fish and Wildlife Service reports began in the late 1800s, U.S. Geological Survey reports date from the 1930s, and National Park Service surveys began in the early 1970s and continue to this day. A unique long-term monitoring program—established in 1973 by a $33 million congressional appropriation—was designed and implemented to evaluate the physical changes of the creek over time. Also, other federal and state resource agencies have sponsored studies of Redwood Creek and closely related North Coast watersheds. In addition, faculty and students of academic institutions such as Pennsylvania State, University of California at Berkeley, and Humboldt State University have conducted numerous investigations at Redwood Creek.

The authors of this document compiled information from published literature and supplemented it with local knowledge gained from historical sources, personal interviews, and photographs. This includes newspaper accounts of floods, the size of the salmon populations, and other historical events and data associated with Redwood Creek, as well as the files of historical organizations such as the Humboldt Historical Society, Humboldt County Library, and the Bancroft Library.

Subsequent to notifying the public via the local newspaper, the authors interviewed long-time residents of the Redwood Creek basin. Three different forums were held with individuals who have knowledge of the creek and its history. Approximately 200 photographs were discovered in the course of these interviews; these range from as far back as the late 1800s to the current day. A number of reaches of Redwood Creek were later rephotographed in 1999 for purposes of comparison with many of these historical photographs.

In all, this report brings together information obtained from more than 500 individual sources, including such experts as geologists, fluvial geomorphologists, hydrologists, freshwater fisheries biologists, marine biologists, oceanographers, climatologists, anthropologists, forest and range scientists, wildlife biologists, and many others. Also, we are grateful for the technical reviews of this manuscript provided by Don Chapman, Ray Rice, and Bill Platts. The collective knowledge presented here represents countless hours of work by dedicated individuals committed to conserving the natural resources of Redwood Creek.

CONTENTS

FOREWORD

THE AUTHORS OF THIS COMPENDIUM are members of the Redwood Creek Landowners Association. The Association is comprised of ten private landowners ranging from small to large who own and manage tracts in the Redwood Creek drainage basin. Its collective land ownership encompasses more than 80 percent of the privately owned portion of the basin. Some members have managed land in the basin for half a century or longer. Thus, the Redwood Creek landscape and its uses are of vital concern to the authors.

The Association's members represent a mix of land uses, including ranching and forestry activities. The primary land-use concerns of the Association center around timber operations in the Redwood Creek basin where: (1) the creek is listed under the Clean Water Act Section 303(d) as impaired based on sediment; and (2) populations of anadromous salmonids are listed as threatened under the federal Endangered Species Act.

Our resource stewardship is best when we can analyze and synthesize all of the available information pertinent to land management. This document brings together an extensive library of information not previously available in one place: a library of about 12,000 pages of reports and materials. With this document, the Redwood Creek story is perhaps more complete now than ever before. And the story points to a need to re-examine salmonid ecology as it relates to the creek's habitats, sediment conditions, and compatible land uses.

This document examines the agents of ecological change—floods, earthquakes, landslides, fires, land uses, and the influence of the ocean—and the consequences of these changes on the physical environment and aquatic resources within the Redwood Creek basin. An understanding of the current status of the basin and expectations for the future are subsequently presented. The authors make the conclusion, based on the scientific evidence at hand, that it is time to rethink past speculations about sediment impairment of salmonid productivity in Redwood Creek. On the basis of the evidence, the authors further hope that this document about the Redwood Creek basin will provide a springboard for improved fact-finding, resource analysis, and decision-making in the months and years to come.

WHAT IS THE STORY OF REDWOOD CREEK?

Sedimentation and salmonids

THE JOURNEY THAT LED TO THE creation, and later the expansion, of Redwood National Park has had lasting effects on environmental policy and land uses in the basin as well as forest practice regulations in California. More than 30 years after formation of the Park, Redwood Creek, the major waterway flowing through the Park to the ocean, continues to be a focal point of interest. The water quality of the creek, the creek's anadromous salmon and trout populations, tall trees, and the use of the surrounding forest continue to be subjects of concern to many.

In 1992, the U.S. Environmental Protection Agency (EPA) declared, under Section 303(d) of the federal Clean Water Act, that Redwood Creek water quality was impaired due to sedimentation. The evidence for listing has been less than ironclad, and a public debate has since ensued. Central to the discussion is the fact that Redwood Creek is prone to storm-induced erosional events and the watershed has natural geologic instability.

Along with the concern about water quality are related concerns about protection of fish listed as threatened under the federal Endangered Species Act, including the compatibility of modern forest practices with fish protection and long-term landscape sustainability. In 1997, the National Marine Fisheries Service listed coho salmon as threatened throughout its range in California—including Redwood Creek. In 1999, chinook salmon were listed as threatened, and in 2000, steelhead were listed.

The listing of Redwood Creek as water-quality impaired and the continuing dialog on controlling diffuse (nonpoint) sediment sources and protecting specially-designated fish has prompted a re-examination of the body of information available on the subject. Perhaps a better understanding of the issues will influence future regulatory treatment of Redwood Creek when the water quality and Section 303(d) status is reconsidered; this is the impetus for *A Study in Change: Redwood Creek and Salmon*.

The Questions

- What effects do agents of change have on sediment loading?
- What is the relationship between the strength of salmonid populations and stream sedimentation?
- How has our understanding of Redwood Creek's natural history deepened through observation and study?

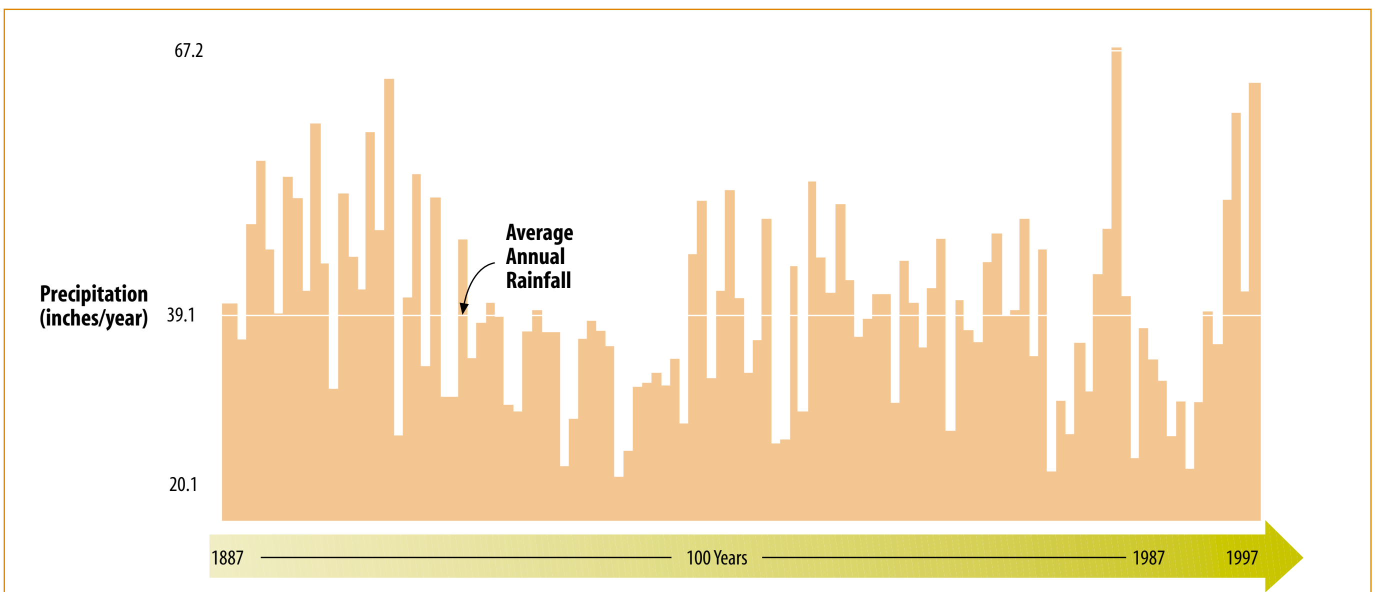
Lush vegetation and abundant fish habitat characterize much of Redwood Creek.

Photo courtesy of Barnum Timber Company

In Search of Understanding

Our story explores the stream sedimentation processes and strength of the Redwood Creek salmonid populations, which have fluctuated over time. Over the years, archaic or partial data and unsupported opinion have influenced many perceptions concerning Redwood Creek; these misconceptions have, unfortunately, continued up to the present day. To provide a new perspective and a scientific basis for re-examining existing policy, the authors of this document have gathered every piece of known data, reviewed all published reports, spoken to available historical eye witnesses, and gathered as many photographs as possible that might shed light on the subject. Our purpose in writing this story is to document that process and facilitate access to information for resource planning and management by stakeholders, policy makers, and other interested parties.

New information on the relationships between natural and man-made ecological changes in producing and maintaining healthy salmon habitat is reviewed, and recent understandings of the effects of changing ocean conditions on adult salmon populations in the context of Redwood Creek provides the basis for this story. In addition, we take another look at historic and current juvenile salmonid surveys to infer the effects that



Annual rainfall at Eureka fluctuates greatly about the average.

Source: Pacific Lumber Company. 1999.

The tributaries of Redwood Creek flow toward Orick and the ocean.

floods, land uses, and other agents of change have had on the salmon populations.

Redwood Creek: A Bird's Eye View

The physical conditions and aquatic habitats of Redwood Creek have varied significantly over recorded history; there is a legacy of extreme natural events and conditions that occurred far in the past, prior to the 20th century. These patterns of natural variability and ecological cycles have made Redwood Creek what it is today.

Redwood Creek is a free-flowing stream that initially winds its way through working forests that provide market-based commodities and natural amenities. It then flows through Redwood National Park on a course to the sea. It rises in the coastal range of Humboldt County up to an elevation of 5,300 feet and runs 80 miles in a northwesterly direction, entering the Pacific Ocean near the town of Orick along California's north coast. The total drainage area of the Redwood Creek basin—technically a sub-basin—covers approximately 180,000 acres or 285 square miles.

A visitor today sees what appears to be a pristine, wild stream. The banks are full of lush vegetation and water flows over cobbles, boulders, and large rocks. Tributaries flow under a canopy of full shade in the summer months.[1] Smaller tributaries have steep gradients where water flows over and around larger cobbles and mossy boulders, moving fine sediment and smaller-sized spawning gravels rapidly downstream.[2]

The vegetation that grows in the Redwood Creek basin is a product of profuse rainfall, which ranges in annual amount from 32 to 98 inches and falls mostly during the winter and spring.[3] Redwood and Douglas-fir forests, tan oak forests, true-oak woodlands, and grass prairies cover the landscape. The famous Tall Trees Grove of Redwood National Park contains redwoods that are among the tallest trees in the world.

The Redwood Creek basin is formed mostly of sheared and fractured bedrock: sandstone deposits that were scraped off an ancient sea bed and lifted up 2 million years ago by the North American Tectonic Plate.[4,5] The sandstone deposits are muddy sediments that once formed inland mountains, but eventually eroded into the sea. The hillslopes of Redwood Creek are composed of sediment that eroded from these ancient mountains standing along the western edge of North America in the final days of the age of the dinosaurs.[6] For example, the Tall Trees Grove grows on a streamside terrace formed by the accumulation of 4,000 years of silt.[7]

Redwood National Park, created in 1968, originally covered only 28,000 acres, encompassing land near the mouth of Redwood Creek.[8] On March 27, 1978, a 48,000-acre extension—representing nearly 30 percent of the Redwood Creek basin—was added to Redwood National Park.[9] The new buffer was designed to protect the resources of Redwood National Park from human activities. This expansion assumed that the private land uses occurring upstream of the new buffer would continue into the future and that the park would be sufficiently large to absorb or resist the political, scientific, and environmental uncertainties associated with the dynamic natural environment.[10]

Land management in such a dynamic environment requires dynamic human responses to new information. In the spirit of adapting to new technology and scientific information, landowners upstream of Redwood National Park have signed a Memorandum of Understanding with the Service.[11] This entails other federal, state, and county agencies; several timber companies; and many private landowners working cooperatively with Park staff to develop and implement state-of-the-art land management practices in a constantly changing political and natural environment.[12,13]

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

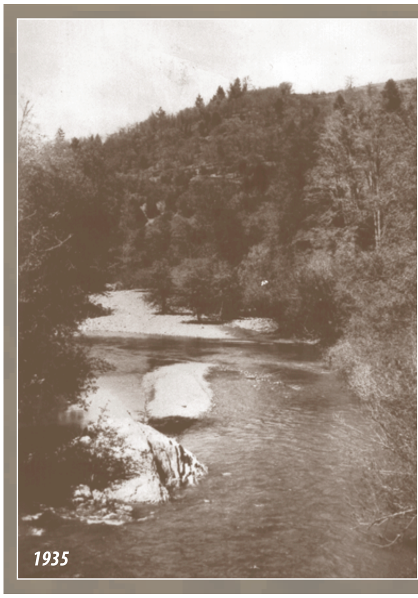
The flood record indicates that no major floods occurred from 1890 until after World War II.[25] By that time, Redwood Creek was in more advanced stages of sediment depletion, as shown in the 1935 and 1948 photos at the old Highway 299 (Chezem Road) Bridge. No major flooding had occurred in half a century, 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.

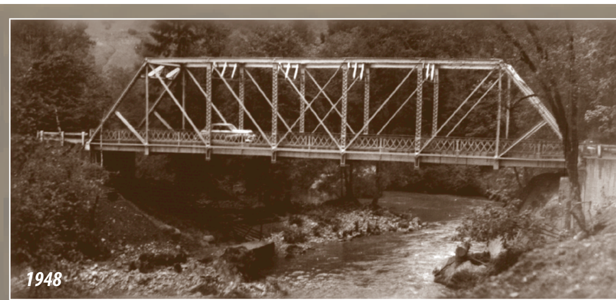
1950-1975 Flooding

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





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

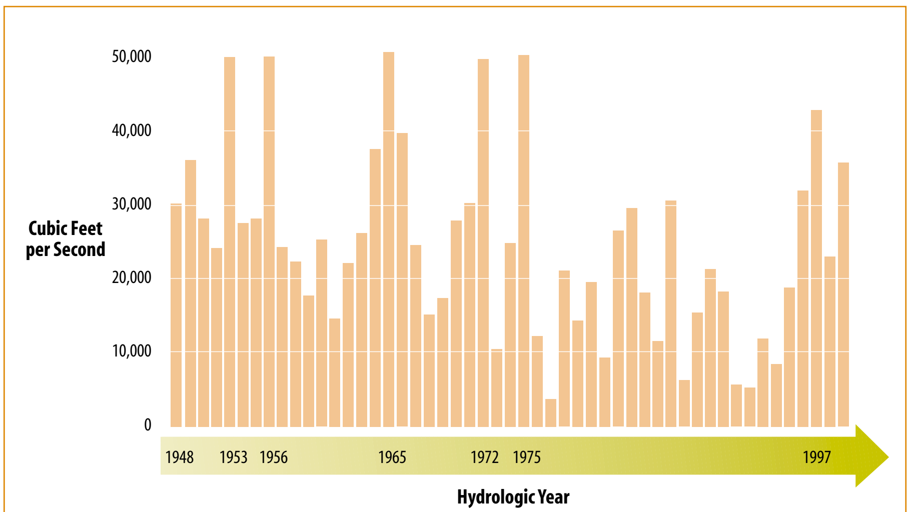
decades of below normal rainfall and no major flooding.[26,27] The January 1953 flood was followed by a flood in December 1955, the benchmark flood of December 1964, two floods in 1972, and one in 1975—coincidentally the advent of modern forest practices rules. Each flood corresponds to the significant 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



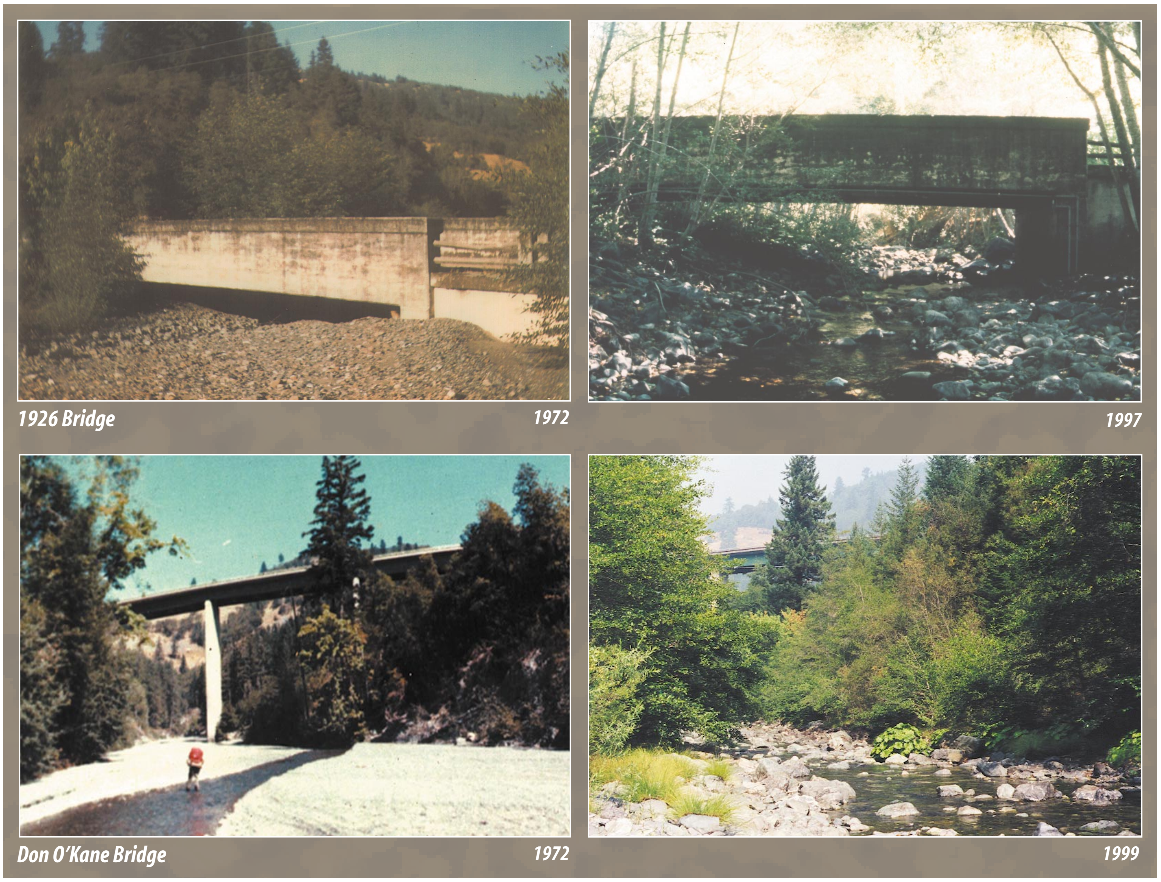
Prior to 1997, the last significant peak flow of Redwood Creek occurred in 1975.

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]

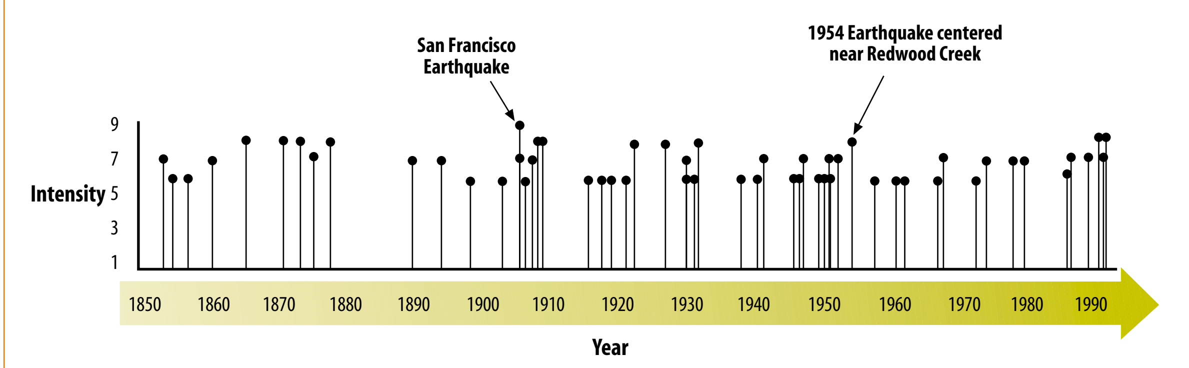
Severe fires can accelerate soil erosion processes.[65,66] Fire-induced accelerated sedimentation is usually greatest during the first year following a fire, and remains elevated for the next 4 to 6 years.[67] Increased sedimentation can also occur from removal of ground litter and vegetation cover as 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.

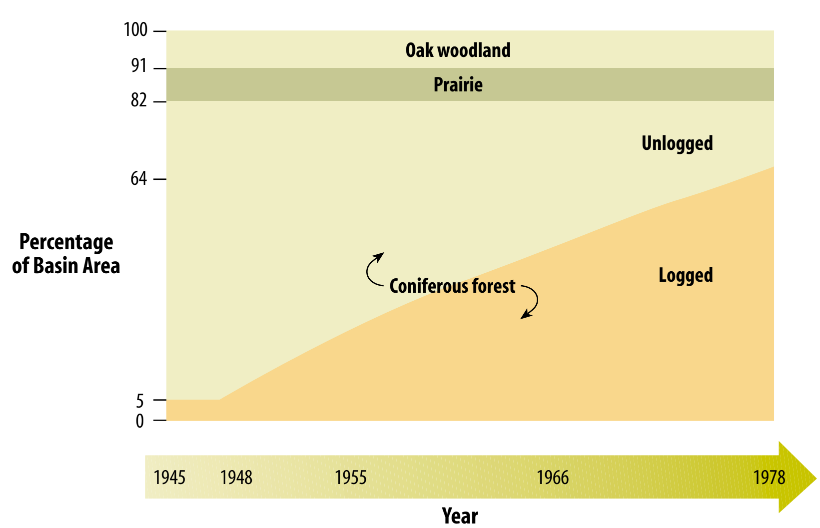
New, Smarter Land-Use Practices Minimize Erosion

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.

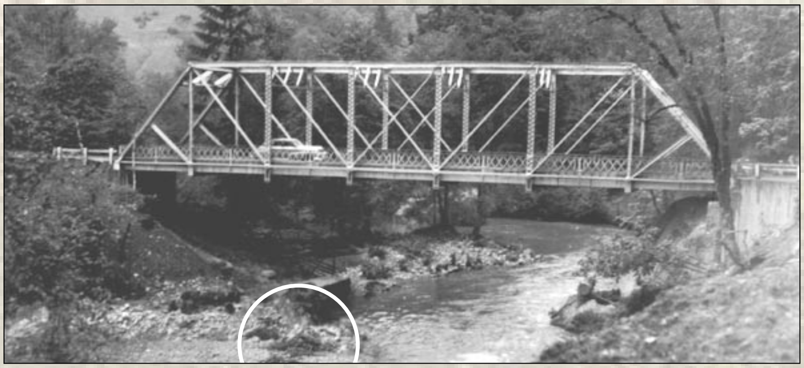
When land managers realized that simple improvements in road-building techniques could effectively minimize erosion, they began to adopt the new techniques.[101,102,103] These refined techniques were shown to be effective through a Critical Sites Erosion Study, which examined 179,000 acres of land in 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]

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.

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]



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

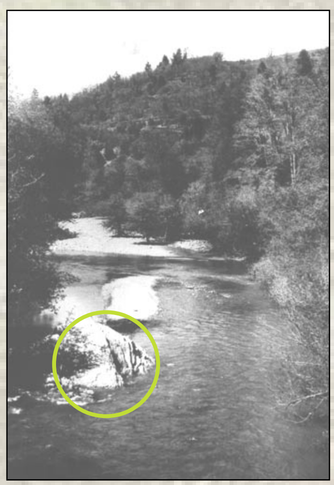
- High water 2 weeks after the 1964 flood
- High sediment elevation
- Damaged riparian vegetation

1890 Flood — 1902 — 1935 — 1948 — 1953 Flood — 1955 Flood — 1962 — 1964 Flood — 1965

1902

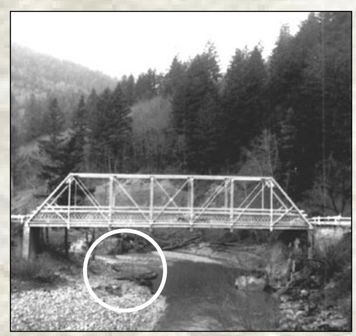
- Small and medium size streambed gravels left from 1890 flood
- Moderate sediment elevation; original covered bridge required a lateral brace
- Young riparian vegetation

1935



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

1962



- 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

1970

1972 Floods

1975 Flood

1972

1999

Large streambed gravel sizes; conditions are like 1948

Low sediment elevation

Young riparian vegetation is present mid-channel and on the gravel bar

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

1902, 1948, 1962   1935, 1970, 1999

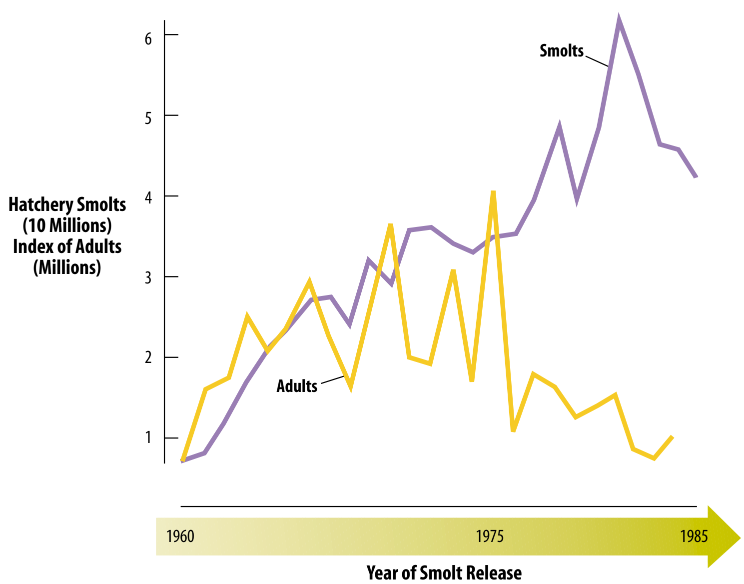
Another estimate that can be developed puts the amount of potential erosion from today's roads at less than 8 percent of what actually occurred from unattended roads during the 1972 and 1975 floods.[106,107,108] This suggests that erosion risk on private lands has been reduced by improved road building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

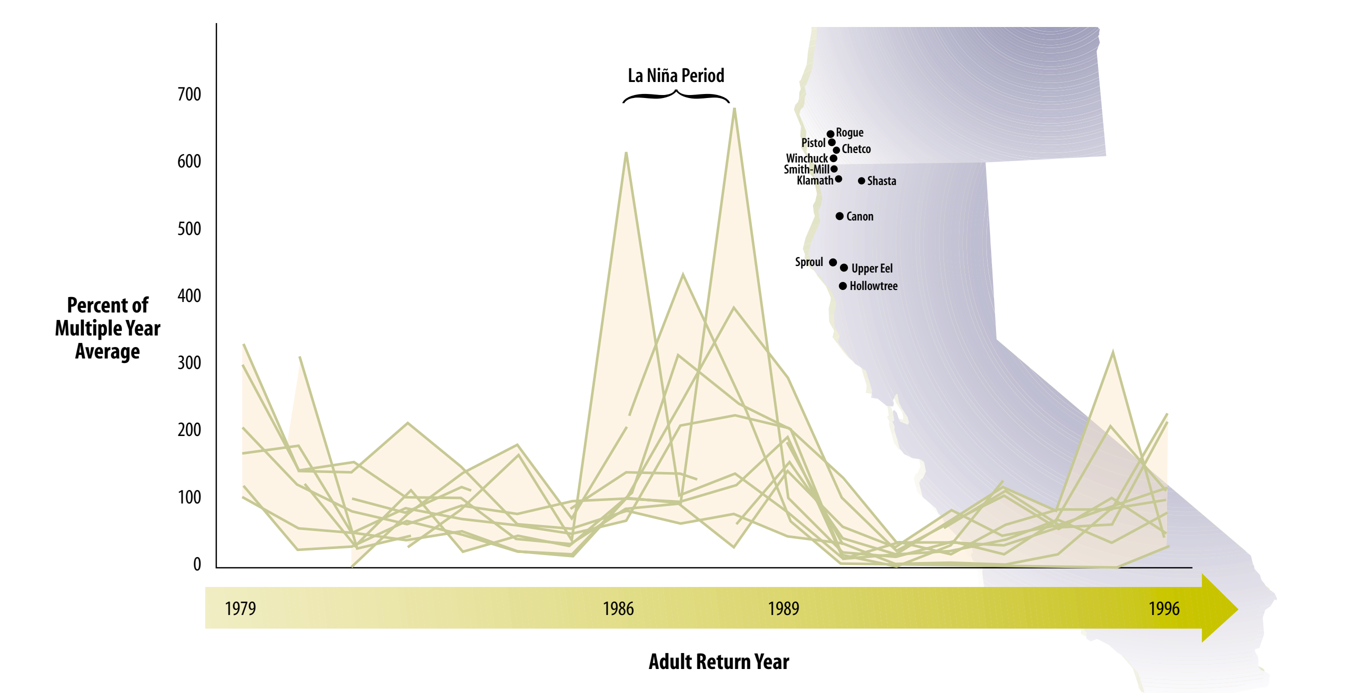
Source: D.L. Bottom. 1999. Northwest Power Planning Council.

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]

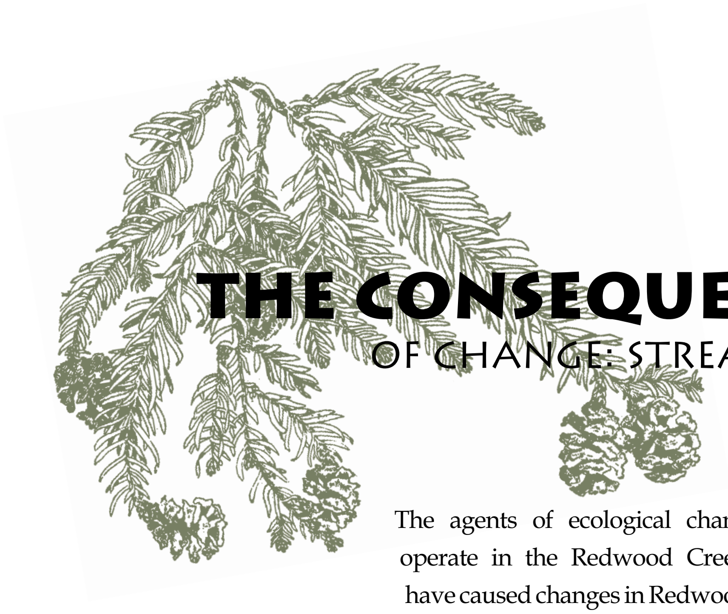
A dramatic climate regime shift to warm, dry conditions last occurred along the West Coast in 1977.[133,134,135,136] The unfavorable ocean conditions at that time may explain the increased mortality of hatchery-reared salmon.[137,138] The release of hatchery-raised coho increased sharply through the 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.



THE CONSEQUENCES
OF CHANGE: STREAM HABITAT

The agents of ecological change that operate in the Redwood Creek basin have caused changes in Redwood Creek channel morphology—the shape of the streambed—and the level of sediment in the streambed over time.

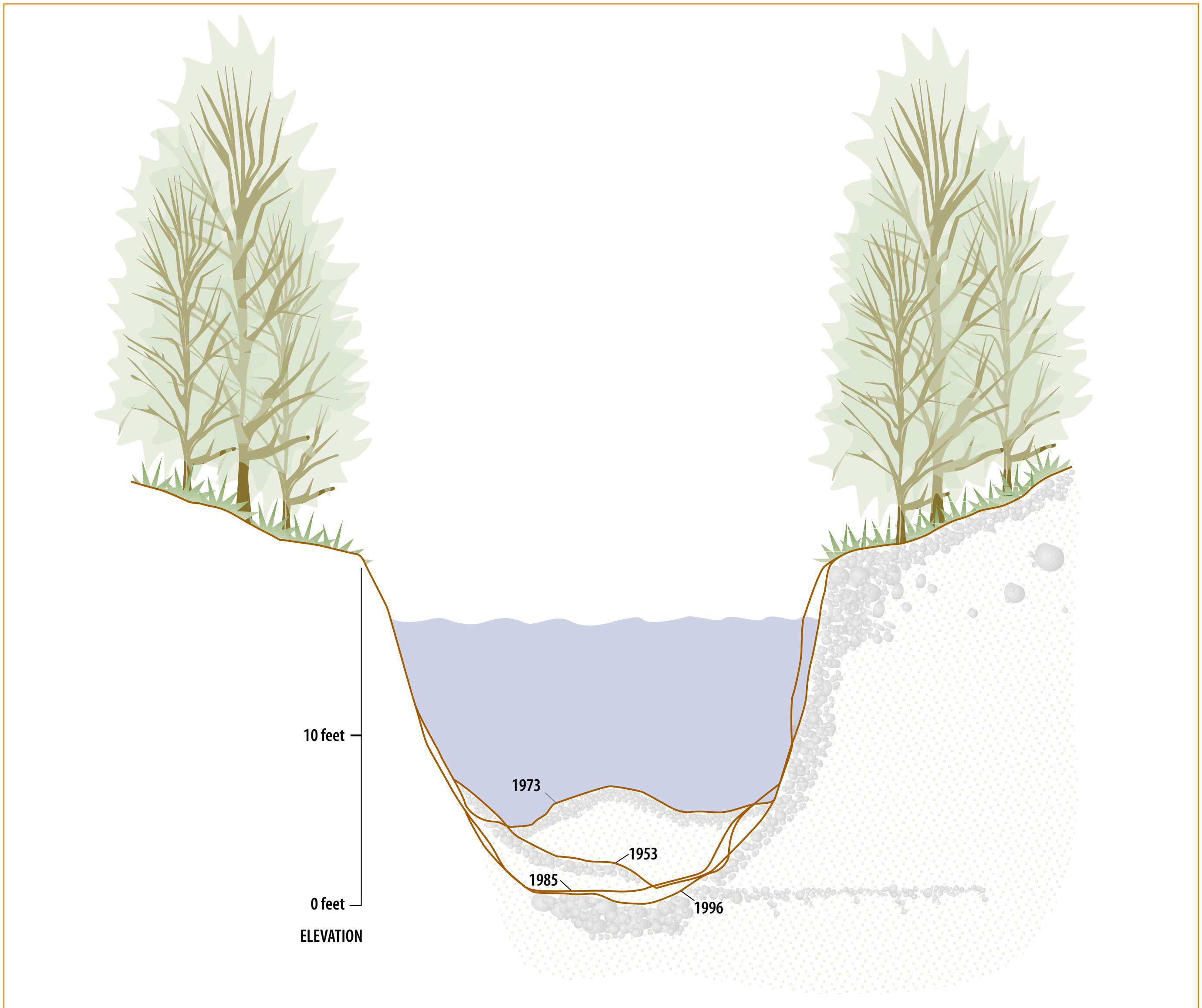
The Cycle of Channel Morphing

Upper Redwood Creek (above State Highway 299). The long-term record for the upper basin indicates that the streambed of Redwood Creek rose 10 feet—in some locations nearly 30 feet—between 1953 and 1973, and returned to its 1953 level by 1986.[148,149]

The lack of recent significant changes in the streambed suggests that conditions today are similar to pre-1953 conditions for much of the upper reach.[150] The large streambed particles, exposed bedrock, established riparian vegetation, and lack of flood debris present today indicate a very stable channel without much new sediment deposits.[151,152]

Middle Redwood Creek (State Highway 299 to Redwood National Park). The stream channel in the middle section of Redwood Creek has not changed significantly during the 1990s.[153] Apparently stable, this reach has likely joined the upper reach in returning to pre-aggradation conditions such as existed before 1953.[154,155]

Lower Redwood Creek (Redwood National Park to the Ocean). In 1985, a major channel constriction in the lower section of Redwood Creek between Copper Creek and the Tall Trees Grove caused some buildup and leveling above and erosion below the constriction.[156] By 1986, the reach was neither leveled above nor degraded downstream of the Tall Trees Grove.[157] More recently, about 8 inches of buildup was measured; this is a minor amount of change, given the drainage area above the reach.[158,159] Currently, the area shows short, braided reaches and secondary channels created by mid-channel gravel bars.[160] These are especially



Channel sediment elevations rise and fall with flood events.

Source: N. Varnum. 1984. Redwood National Park.

productive sites for rearing salmon and steelhead trout.[161]

Sedimentation and the Streambed Cycle

Redwood Creek was formed in a sediment-rich basin that experiences a constant, high level of erosion, punctuated by periodic dramatic sediment disturbances. Sediment commonly involves fine particles the size of clay, silt, and sand, but may include particles up to house-sized boulders.[165] Between 60-95 percent of the sediment entering Redwood Creek is fine sediment.[166,167,168,169] Once deposited in a stream, a house-sized boulder may never move, but a small, suspended particle may be transported all the way from a stream's source to its mouth in a matter of hours. The rate at which a sediment particle is transported by flowing water toward the sea depends upon its size; the smallest particle is capable of remaining suspended in still water for days or years. In Redwood Creek, suspended sediment—usually fine sediment of up to about one-tenth of an inch in diameter—is rapidly transported during high flow storms.[170]

The soft rocks that make up the streambed of Redwood Creek are themselves a vast supply of fine sediment. While rolling downstream, these rocks release fine sediment as they break down.[171,172] Together, these factors supply an abundant amount of nat-

CHANNEL MORPHOLOGY: IN A NUTSHELL

Streambed elevations changed along the entire length of the main stem of Redwood Creek between 1973 and 1988.[162] Overall, a large amount of channel deposits were moved, including the majority of sediment delivered from landslides occurring during the 1964 storm.[163] The relatively rapid return to pre-flood conditions was made possible by the force of water in the channel and the relatively small size of the sediment particles brought in by floods.[164]

ural sediment to the stream channel; but the story doesn't end there.

The rates at which sediments are being flushed out of Redwood Creek are among the highest in northern California streams, which have some of the highest sediment transport rates in the world.[173,174,175] These high erosion rates are caused by the active tectonic uplift, soft bedrock, and the climate that characterizes the North Coast region.[176,177,178]

The amount, composition, and distribution of sediment in Redwood Creek are forever increasing and decreasing as the volume and velocity of water rises and falls.[179] The moderate flows that occur a few days every year are responsible for transporting the bulk of the sediment in the stream over the long term.[180,181] At times, however, rare events transport large amounts of sediment from upstream sources to the downstream reaches of Redwood Creek, many times over the amount of sediment normally transported in an average year.[182,183,184,185] It is estimated that the amount of sediment transported downstream varies by as much as fifty times from year to year, depending on the intensity of local storms.[186]

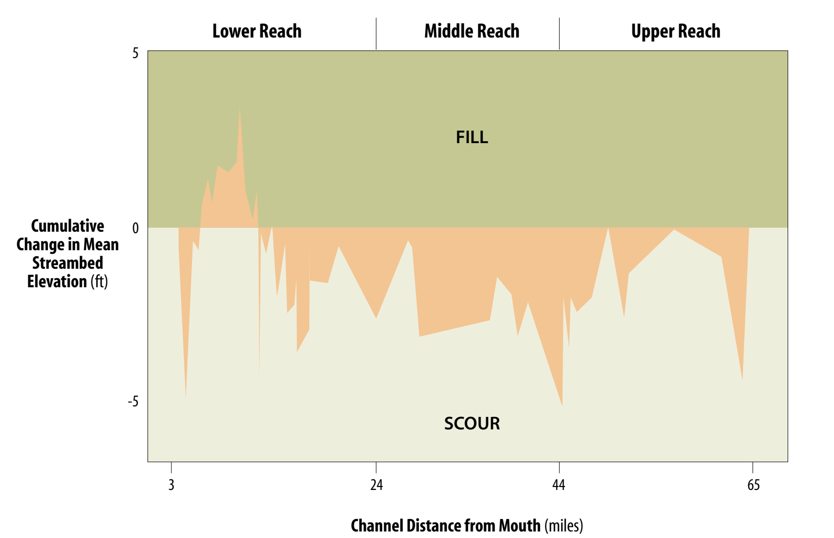
From rainfall and photo records, it appears that the amount and size mix of Redwood Creek sediment were changed by the storms of the late 1800s and returned to base levels by the 1920s and 1930s. Undoubtedly, the storms and land-use practices of the 1950s, 1960s, and 1970s again altered the sediment patterns. The particle-size distribution of streambed material in Redwood Creek prior to and during this period is unknown because no records were kept.[187] During August 1974, between the floods of 1972 and the flood of 1975, fine sediment composition was within the range of natural variability and varied slightly from the creek's headwaters to its mouth. The amount of fine sediment in gravels was highest (21.9 percent) in the upper reach, lowest (17.0 percent) in the middle reach, and intermediate (18.6 percent) in the lower reach.[188]

A significant discovery was made at Prairie Creek regarding fine sediment processes. It was found, during a 7-year period, that the fine sediment infiltrating into clean gravels reached a maximum amount, above which further deposition was hindered by a seal formed near the streambed surface.[189] In this case, the maximum amount of fine sediment was 25 percent of the streambed.[190] The formation of this surface seal appears to be inevitable once streambed sediment is moved by a storm flow.[191]

Extensive sampling of Redwood Creek's streambed in 1988 and 1989 showed the amount of fine sediment to be 9 to 25 percent of the subsurface streambed material, and sediment conditions were favorable for salmonid spawning.[192,193]

Indicators suggest that Redwood Creek's streambed has stabilized. There is a prevalence of well-winnowed gravel areas where surface layers of fine sediment have been removed by storm flows, and a high frequency of coarse particle sizes in reaches where sediment has been deposited or eroded.[194]

Over the past 25 years, the amount of fine sediment in Redwood Creek has become generally, though inconsistently, reduced, due in part to fewer intense storms than during previous periods of history.[195] Fine sediment has decreased at four sites, remained unchanged at one site, and increased at two sites.[196]



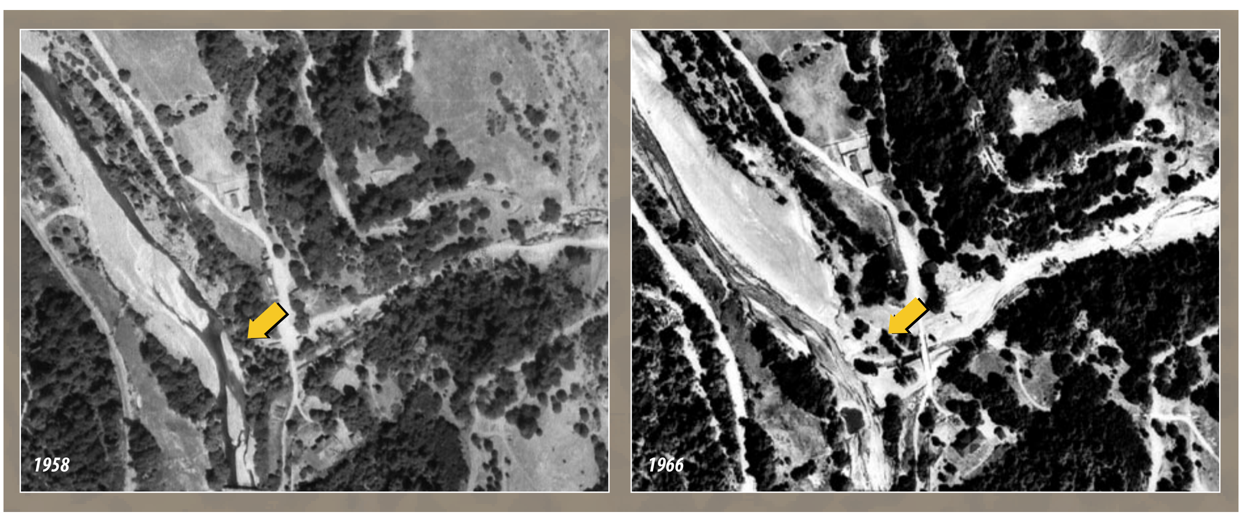
A sediment wave moved downstream between 1973 and 1988 during an inflooding.

Source: M.A. Madej and V. Ozaki. 1996. Earth Surface and Landforms 21:911-927.

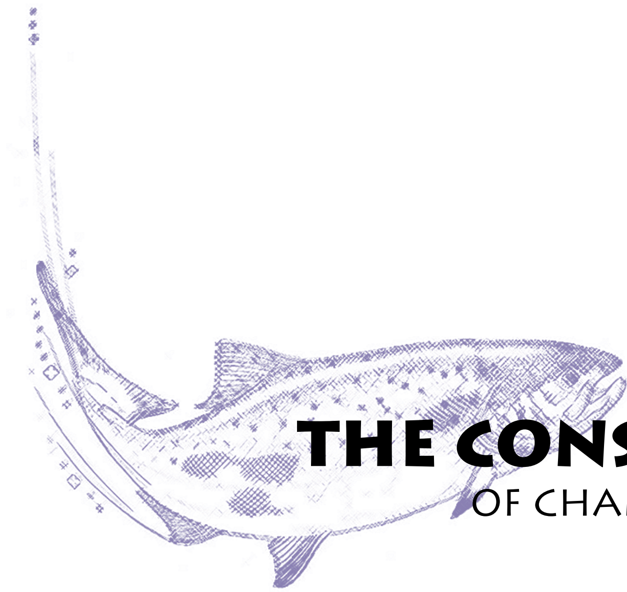
SEDIMENTATION: IN A NUTSHELL

Cyclical sedimentation patterns in Redwood Creek are governed by local geology, tectonics, and climate, but normally shift very quickly. Most sediment is **deposited** during rare dramatic ecological events, but most sediment is **transported** by continual flows.[197,198,199] Primarily due to fewer intense storms in recent years, sediment levels in Redwood Creek have nearly returned to levels that preceded the 1953 to 1975 flooding period. It appears that Redwood Creek has cycled back, as it has in the past, from the changes brought on by the significant storms that began in the 1950s.

The periodic depositions of large amounts of sediment in Redwood Creek appear to be a result of natural events that have occurred periodically, and changes in channel morphology are inherently characteristic of this phenomenon.[200] Consequently, sedimentation is viewed by stream experts as an integral part of the cycle of any stream: it is necessary to forming and maintaining the natural system.[201,202] The input of new sediment appears to be essential to the process of replenishing the sediments that are continuously transported out of the stream system, and the natural rates at which sediments are being flushed out of Redwood Creek are among the highest in northern California—and the world!



These aerial photographs show changes in the channel shape and sedimentation levels from the flood of December 1964.



The Consequences of Change: Salmonids

Salmon Biology: One Million Years of Adapting

Salmon are remarkably resilient. Pacific salmon are approximately 1,000,000 years old and have survived four major ice ages, four warming periods, and the extinction of 35 genera of mammals, including wooly mammoths, camels, lions, and sabertooth cats.[203]

A salmon spends its life in two distinct places: a freshwater stream and the ocean.[204] Life begins when the female salmon lays about 2,000 to 4,000 eggs in a gravel nest in a streambed.[205,206] After it has hatched, juvenile salmon will live in the stream for 3 months to 3 years before leaving for the ocean as smolt.[207]

The salmon spends up to 95 percent of its life and grows to maturity in the ocean.[208] Before an adult salmon returns to its birth stream to breed, its weight will have increased by 20 to 160 times.[209,210]

The salmon returns to streams such as Redwood Creek to spawn in the late fall as water stages of the stream rise as a result of the first large storm. It is at about this same time that silt and clay particles begin to be transported to the sea and the creek becomes turbid and dark with suspended sediment.

Salmon and Sediment: A Love-Hate Relationship?

One of the great scientific debates has focused on the relationship between salmon health and sediment levels. More than 80 years of study have left us with ambiguous, inexact conclusions regarding the level at which the amount of fine sediment becomes a hindrance to salmonid reproduction and smolt production.[211,212,213]

A big part of the problem is that most attempts to define this relationship have been based on laboratory studies and single-factor analyses, both of which have run into difficulties extrapolating and applying findings to natural environments.[214,215]

SALMON 101

- **REDDS** A series of egg nests in one distinct grouping from one salmonid female in stream gravels
- **ALEVINS** Newly hatched, but incompletely developed, juvenile salmonids that are still in the redd or inactive on the stream bottom and are living off of their yolk sac
- **FRY** Life stage of a salmonid that begins after the yolk sac has been absorbed and active feeding has begun
- **FINGERLINGS** Fish life stage after fry
- **JUVENILES** Young salmon up until the time they have reached the sea
- **SMOLTS** A juvenile salmon that has undergone physiological changes to cope with the marine environment
- **ADULTS** Salmon that have returned from the sea

Even in the sediment-rich environment of Redwood Creek, measuring the effects of fine sediment on salmon survival has been difficult.[216]

Conventional thought is that the large amounts of sediment deposited into streams during great floods are harmful to fish and fish habitat.[217] Indirect evidence from laboratory studies suggests that salmonid embryo mortality increases and emergence of salmonid alevins declines as the percentage of fine sediment in redds increases.[218] Eggs can be smothered and alevins entrapped if the interstitial spaces in redds become clogged.

In addition, suspended sediment can harm gill tissues of fish and make it difficult for them to find food; but turbid conditions also provide cover from predators.[219,220] The tolerance of juvenile coho salmon to suspended sediment varies seasonally. The highest tolerance is in the fall when increases in suspended sediment normally occur.[221]

However, there are numerous scientific studies that provide an alternative to the conventional thought about salmon and sediments. Studies have, for example, found that streams affected by landslides have enhanced fish production, and streams unaffected by recent landslides have reduced fish production.[222,223,224,225] Because sediment is what creates salmon habitat, streams with low sediment levels have low salmon production.[226]

Fish experts believe that the presence of sediment in streambeds is necessary for optimum survival of the salmon eggs laid there. Pea-gravel and sand-sized sediment helps form a sealing layer over the incubating eggs.[227] This seal prevents injurious stream agents such as predatory insects and organic matter from coming into contact with the eggs, and prevents deep penetration of fine sediments that could trap emerging salmon in their nests.[228,229] So, fine sediment can benefit egg survival because egg survival can be higher in streams rich with fine sediment.[230]

One of the adaptations developed by salmon for life in sediment-rich environments is the large size of their eggs, which provides an alevin with the food resources to swim out of a deep, gravel nest.[231] Another adaptation is the ability of female salmon to cleanse their nest of fine sediment during nest construction. Spawning females have been found to remove from 30 to 40 percent of the fine sediment in the streambed.[232,233,234]

Although the sediment conditions of Redwood Creek vary widely and certain land uses have increased the sediment load, few adverse effects on aquatic life have been measured. Several scientific studies at Redwood Creek found no adverse effects from higher levels of fine sediment on salmon. The findings held true for all aquatic organisms, with the exception of an isolated, temporary reduction in the numbers of three species of amphibians (see Case Study: Sedimentation and Salmon at Prairie Creek).

In addition, one researcher found that although recent logging apparently increased fine sediment levels in gravels from about 15 to 25 percent, the amount of dissolved oxygen was greater in logged areas, possibly compensating for the elevated sediment levels.[249] He concluded that salmonid production would not be limited by the increased levels of fine sediment, or dissolved oxygen concentrations, in any of the areas.[250]

SALMON AND SEDIMENT: IN A NUTSHELL

Laboratory tests reveal that high levels of fine sediment on nests can hinder the success of salmon spawning, but research in the field fails to support this theory. Perhaps several compensating and external factors confound the outcomes.

Numerous studies have concluded that: (1) streams draining timber-harvested areas with roads temporarily contain higher amounts of fine sediment after logging when compared with "control" streams, (2) temporary increases in fine sediment have virtually no short- or long-term adverse effects on aquatic organisms, and (3) salmon are physiologically and behaviorally adapted to living in a dynamic, sediment-rich environment.

CASE STUDY: SEDIMENTATION AND SALMON AT PRAIRIE CREEK

In 1989 to 1990, an accidental discharge of sediment into the tributaries of Prairie Creek, the largest tributary to Redwood Creek, created an opportunity to study the effects of sediment on salmon in a natural setting. A highway construction project—the Redwood Highway Bypass—had left a layer of fine sediment in streambeds measuring 0.1 to 2.0 inches thick.[235] Observations of redds test the hypothesis that higher amounts of fine sediment in redds affects the amount of emerging fry.

After 1 year, the affected reaches of the creek had greater amounts of suspended sediment when compared to unaffected sections. Also, the amount of fine sediment in salmonid nests in the affected reaches was either unchanged or at higher levels.[237,238]

Despite the sedimentation that had occurred, salmonid egg survival was often no different—or even higher—in affected streams than in unaffected streams.[239,240] Also, higher rates of emergence of fry were found in stream reaches with more fine sediment.[241,242,24] Most importantly, the number of salmon smolts was not reduced in streams that had large volumes of fine sediment washed into them.[244] Also, the aquatic insect community showed no obvious differences between the sedimented reaches and either the unaffected reaches or reaches prior to the sedimentation incident.[245] This indicates that the food available for juvenile salmon was not reduced.

By 1992 and 1993, fine sediment in salmon egg hatching baskets was 9.0 to 24.1 percent in affected reaches and 12.2 to 20.9 percent in unaffected reaches.[246]

The 1994 spawning salmon and steelhead runs were at abundances found prior to the incident, in spite of lingering fine sediment levels that as late as 1996 were still higher in the affected reaches.[247,248]

The State of the Salmon and Steelhead Trout Populations

Distribution and Density of Juvenile Salmonids

Perhaps the best measure of stream health and salmonid productivity is the level of juvenile salmonid production. (The level of adult fish production is more indicative of ocean conditions.)

If adult returns are adequate and habitat is available, the amount of salmon fry production will far exceed the carrying capacity of the creek. Under consistent habitat conditions, the number of smolts migrating toward the sea may not vary at all, even though the number of spawning adults returning can vary dramatically from year to year by as much as a factor of ten.[251]

Periodic surveys of Redwood Creek portray juvenile fish distribution and density over time. In the earliest survey on September 22, 1945, fourteen casts of a net caught 128 small young steelhead, but no coho or chinook salmon at the State Highway 101 bridge.[252]

Subsequent surveys confirmed juvenile chinook, coho, and steelhead around Orick, including the Redwood Creek estuary.[253] Juvenile coho have been found no farther upstream than the lower Redwood Valley, and in Prairie Creek and its tributaries.[254,255,256] Young chinook have been found farther upstream. Steelhead trout were encountered throughout the Redwood Creek basin.[257,258,259,260,261]

The original field notes from a 1966 survey describe finding fry and larger steelhead that exceeded 7 inches, suggesting that the larger fish were in their third year of life.[262] Apparently as juveniles, these fish were present in the stream during the December 1964 flood and weathered the storm.

Throughout the surveyed period from 1945 to 1997, summertime "densities" of the juvenile salmonid populations in Redwood Creek ranged from 0.2 to 1.5 fish per foot of stream length without a discernible trend.[263,264,265,266,267,268] Within this range, the number of juvenile salmonids living in Redwood Creek can vary significantly from year to year under natural conditions. For instance, the numbers of juveniles in Godwood Creek and other pristine streams in northern California can vary by nearly 50 percent annually, and sometimes some species are completely absent.[269]

The data on natural out-migrations of juvenile salmonids is less clear. Most estuary surveys since 1980 were taken after the majority of juvenile salmon had migrated to the ocean.[270] The surveys have estimated juvenile chinook salmon populations between 4,000 and 117,000; juvenile steelhead populations between 3,400 and 46,000; juvenile coho salmon populations between 2 and 200; and few cutthroat trout.[271,272,273,274,275,276,277,278]

The only estimates of downstream juvenile salmon migration above the estuary were made at pristine Prairie Creek. Yearly trap catches have yielded between 30,000 and 40,000 migrating chinook, coho, steelhead, and cutthroat trout.[279,280,281]

Eggs from adult salmon caught at a Chilula dam like this one supplied the Redwood Creek fish hatchery.

Photo courtesy of Phoebe Apperson Hearst Museum of Anthropology

Distribution and Abundance of Adult Salmonids

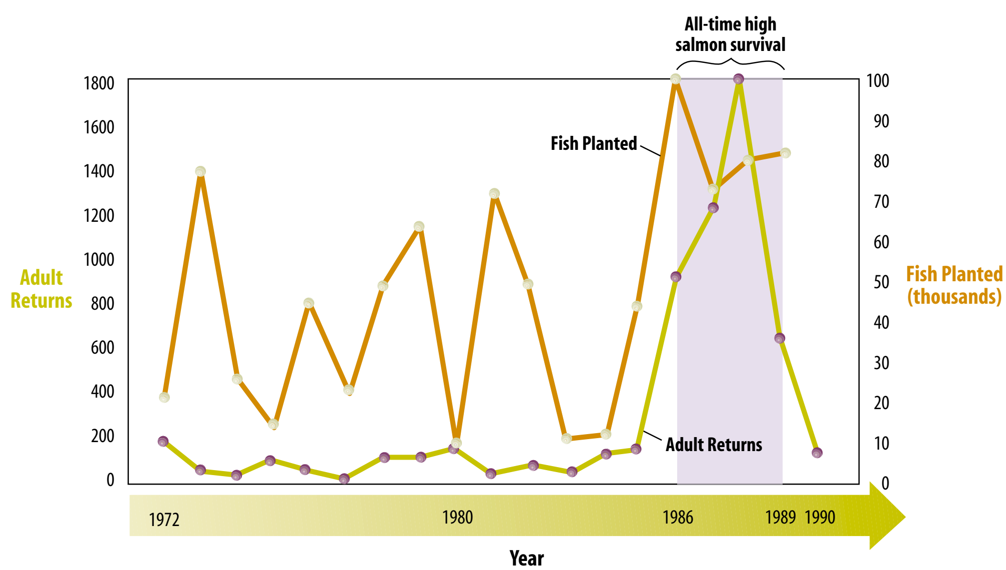
Many ask, "how do anadromous salmon and steelhead populations today compare with those of the past?" Unfortunately, few historical records of the numbers of adult salmon returning from the ocean to spawn in Redwood Creek were kept; thus, only qualitative comparisons between the current and historical populations of spawning salmon are possible.

Indigenous people found the salmon of Redwood Creek to be "negligible," less than nearby streams.[282] As early as the 1890s, there were concerns that salmonid populations in northern California were becoming extinct from over fishing.[283,284] Consequently, a salmon hatchery was established at that time to alleviate the apparent declines in local fisheries.[285] The salmon egg collecting station and fish hatchery were located in the upper portion of Redwood Creek, near the mouth of Minor Creek. Adult chinook, coho, steelhead, and trout were captured by means of a government-built weir just above the confluence of Minor Creek, and from an Indian-operated trap in the same vicinity.[286]

Salmon eggs collected at the station supplied hatcheries at Fort Gaston and Blue Lake, California, as well as the Redwood Creek hatchery. Apparently, the absence of canneries on Redwood Creek made it the most profitable source for salmon eggs relative to other local rivers.[287] The earliest records for the years 1892 to 1898 show that about 49 to 563 female chinook and coho salmon and about 17 to 375 female steelhead were collected annually.[288]

Another hatchery was located on Prairie Creek near Lost Man Creek.[289] During the first year of operation in 1928, 208,000 coho eggs and 1,400,000 steelhead eggs were collected, which would have required about 83 native coho females and 560 native steelhead females.[290] By fall of 1937, the salmon population immediately below the junction of Prairie Creek and Lost Man Creek was reported as "about 500 [coho] salmon" and only a "few" chinook salmon came in each year, "perhaps seven or eight."[291]

Most fish records over the last century provide little more than sketchy information about the strength of populations; however, it is believed that the number



Adult coho returns to Prairie Creek Fish Hatchery are independent of the number of juvenile coho salmon planted each year.

Source: L.R. Brown and P.B. Moyle. 1991. Report to National Marine Fisheries Service.

of coho salmon adults between 1986 and 1989 were dramatically higher than known returns before or after these years, probably due to documented favorable ocean conditions around that time.[292,293,294,295,296]

In 1960, the adult salmon runs in Redwood Creek were estimated to be about 17,000 fish—5,000 chinook, 2,000 coho spawners, and 10,000 winter steelhead—based on estimates of available spawning habitat, not actual counts.[297,298,299] There are only three other estimates for salmon run sizes in Redwood Creek. The first, for 1973, reported 2,000 coho salmon adults.[300] The second, for the 1990s, reported 2,000 coho salmon adults.[301] The third, for 1979, reported 1,850 chinook salmon adults.[302] Adult summer steelhead counts in Redwood Creek have ranged from zero to 44 fish annually since 1981.[303]

The removal of wild Redwood Creek salmon ended when hatchery operations ceased in 1992.[304,305,306,307,308]

Spawner surveys that began in the early 1980s provide the longest record of standardized population data on Redwood Creek. Three Redwood Creek tributaries where standardized spawning surveys have been conducted are Prairie Creek, Bridge Creek, and Tom McDonald Creek. For the period from 1990 to 1994, the number of live salmonids observed in Bridge Creek and Tom McDonald Creek ranged from 0.00 to 0.01 fish per foot of stream length.[309] The range for Prairie Creek and its tributaries over the same time period was 0.00 to 0.08 fish per foot, but only half that if the heavily supplemented hatchery fish of Lost Man Creek are ignored.[310]

Salmon: The Big Picture

Offshore salmonid harvest records can help us understand the extent to which adult salmon populations of Redwood Creek are influenced by the ocean more than the conditions of the creek.[311]

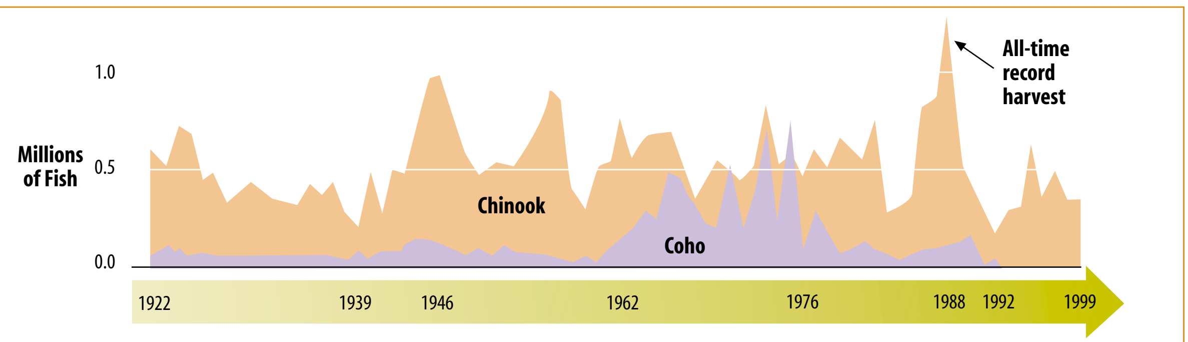
Between 1922 and 1999, the California Department of Fish and Game estimated that chinook salmon ocean harvests varied greatly within short time periods. For example, the harvest increased five-fold between 1939 and 1946 when the second highest catch of 988,000 fish was made. In a three-year span in the late 1950s, the harvest fell to one-third of the peak numbers, then it more than doubled in the following 3-year span. The most dramatic shift occurred in the 1980s, when a record high and low occurred within 2 years of each other. The all-time peak harvest of 1988—1,317,000 fish—occurred during the shortest commercial salmon fishing season allowed by the California Department of Fish and Game.

According to the California Department of Fish and Game, the ocean catches for coho from 1922 through 1962 were generally less than 100,000 fish annually. There was a substantial decline between 1955 and 1958; but during the 18-year period of 1958 through 1976 there was a gradual and significant

Salmon Populations: In a Nutshell

In general, juvenile coho salmon have been found in the lower reaches of the Redwood Valley and farther downstream, and chinook salmon and steelhead trout have been found throughout the system. Summertime densities of the juvenile salmonids ranged from 0.2 to 1.5 fish per foot of stream length, which could represent the natural expectation for juvenile fish densities in the creek. However, the number of juveniles may vary by nearly 50 percent from year to year under natural conditions.

The sizes of the adult salmon and trout populations probably fluctuated widely throughout history. This is as true for Redwood Creek as it is for other salmon spawning streams throughout northern California and southern Oregon.[312,313] However, the available historical data are incomplete and biased, making definitive conclusions about population trends and patterns of abundance elusive.[314,315,316]



The California commercial salmon catch increased after favorable ocean conditions and with improved harvest efficiency.

Source: California Department of Fish and Game.

increase. The ocean catch for coho went from 9,000 in 1958 to 695,000 in 1976.

The ocean harvests of coho show occasional dramatic year-to-year fluctuations similar to the chinook. For example, the catch dropped from 695,000 in 1976 to 64,000 in 1977, then rose to 238,000 in 1978. These fluctuations occurred in spite of continuous and high hatchery smolt production.[317]

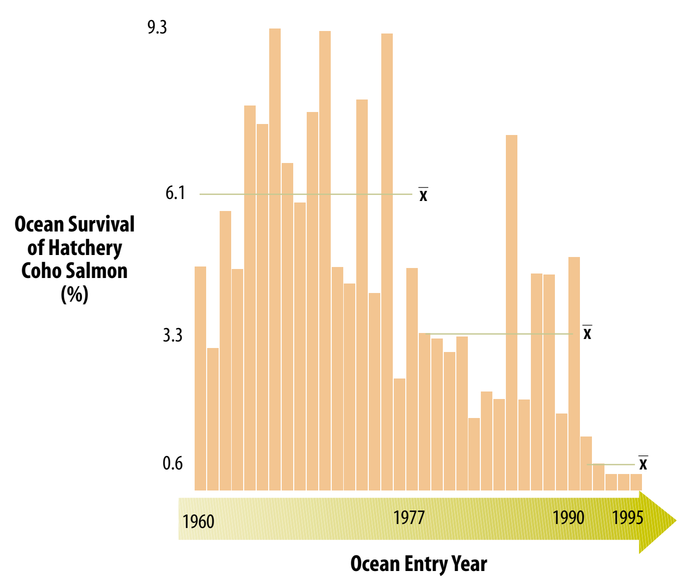
There is an almost unbelievably high number of salmon that meet their demise in salt water, with ocean mortality rates of south coast coho salmon averaging close to 99.5 percent.[318,319]

Reduced growth rates of smolts during their first year at sea, based on poor ocean conditions (i.e., low productivity), appear to be the cause of this high mortality rate.[320,321,322] Ocean survival of coho salmon along the West Coast has decreased by 90 percent since the 1970s, attributed to generally declining ocean productivity.[323,324]

The ocean mortality rate for California salmon populations has not been less than 98 percent recently, which is the rate below which salmon populations need to stabilize.[325] Unfortunately, coho salmon mortality in the ocean increased to about 99.4 percent after 1990.[326,327]

The Regional Salmon Picture

The regional commercial salmon harvest—chinook and coho combined—at ports located in Humboldt and Del Norte Counties ranged from 1.2 to 3.8 million pounds between 1916 and 1930.[328] During this time, major year-to-year fluctuations were apparent—the high and low are separated by only 2 years—just as the statewide ocean catches showed. The regional salmon harvest from 1986 to 1998 ranged between one thousand to one million pounds (the peak year was 1987 during La Niña conditions; the low year was 1992 during El Niño conditions).[329] Apparent differences among the annual regional harvests should not be taken at face value because the amount of effort it took to catch the fish varied over time. The recent regional harvests reflect a reduced fishing season and a diminished fishing fleet.[330]



Along the West Coast, ocean survival of hatchery coho salmon has decreased in recent decades.

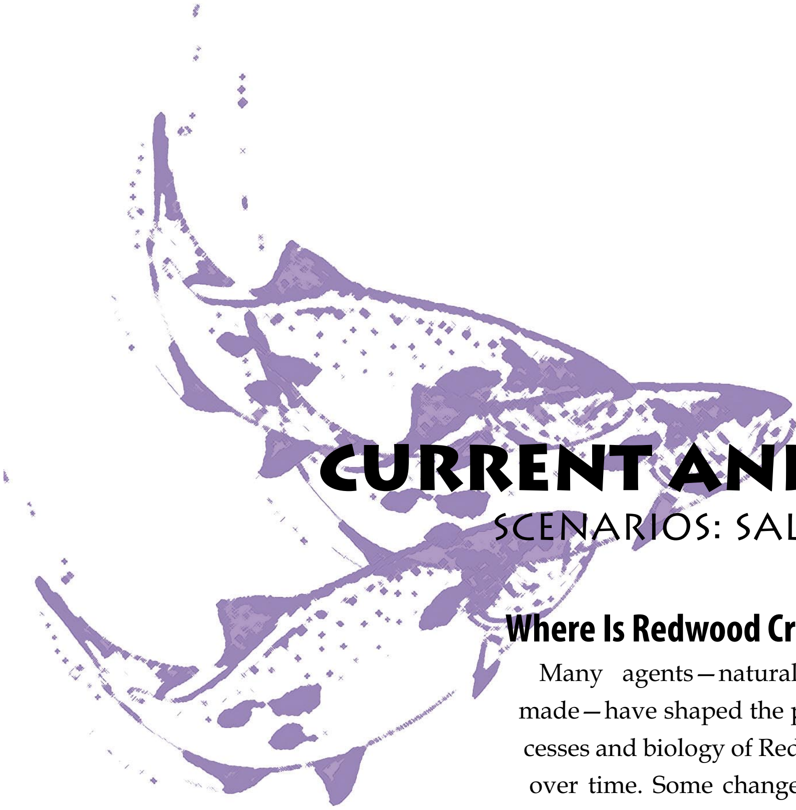
Source: D.W. Welch, B.R. Ward, B.D. Smith, and J.P. Eveson. 2000. Fisheries Oceanography 9:17-32.

THE OVERALL SALMON PICTURE: IN A NUTSHELL

The state of Redwood Creek's salmonid populations—whatever they may be—is largely governed by fluctuating ocean conditions. Because of the fluctuations, returning adult salmon counts are ineffective measures of the quality of the freshwater habitat.[334] Undoubtedly, ocean conditions have had a dramatic impact during the generally unfavorable conditions from 1977 through 1994. The effects of sediment deposition and transport on freshwater stream habitat may affect reproductive success, but have relatively minor effects on population strength.[335]

During 1916 to 1930, salmon were mostly caught in the 6-month period from April through September.[331] However, the season was reduced during 1986 to 1998, with most salmon caught during the 4-month period from June through September.[332]

Taking the shortened season and fleet reduction into account, it appears that the regional salmon harvests of the 1990s have been the most efficient since 1976. The average catch per day that a commercial fishing boat reported during the period from 1978 to 1980 was 11 salmon.[333] The average catch per day during 1986 to 1990 more than doubled to 26 salmon per day. In the 1988 La Niña period, the average commercial fisher was catching 41 salmon per day. The relatively low amount of effort fishers have had to expend to catch a salmon in the 1990s possibly indicates that the regional abundance of adult salmon has increased.



Current and Future Scenarios: Salmon in Redwood Creek

Where Is Redwood Creek Now?

Many agents—natural and man-made—have shaped the physical processes and biology of Redwood Creek over time. Some changes have been naturally occurring and uncontrollable; others have been influenced by controllable land uses. The biggest influences appear to have been major natural events. The changes in sediment conditions that Redwood Creek has experienced over the last 50 years are within the natural range of variability when compared with historical changes in channel morphology and sediment loading. Historical photographs of the shifting bedload leave little to imagination.

Linkages among the patterns of local annual rainfall, peak flows, sediment yield, and ocean salmon catch have been witnessed over time.

Over the decades, above-average rainfall has been associated with higher sediment yields and above-average salmon harvests. The relationship of these factors at Redwood Creek mirrors what has been found throughout the Pacific Northwest.[336,337]

Quantitative studies at Redwood Creek have found no lasting adverse effects on aquatic life as a result of measured increases in the levels of fine sediment. The number of juvenile salmonids present in Redwood Creek in the summer has not been correlated significantly with the volume of fine sediment in the streambed.[338] Furthermore, the later life stages of anadromous fish seem to show no discernible changes even though sediment levels affecting salmonid reproduction may vary.[339] These observed outcomes on aquatic life are not uncommon. At least two dozen field studies on the effects of sedimentation on salmonids throughout the Pacific Northwest have led experienced researchers to conclude:

"[a]lthough some studies indicate a localized reduction in emergence success or reduced biomass of rearing juveniles, with one exception, none of the studies demonstrated an overall reduction in seaward migrant anadromous salmonids because of sedimentation."[345]

Unfortunately, it is impossible to make definitive comparisons of the strength of today's salmon and steelhead populations with those of the past. The long-term records are incomplete, and a lack of documentation for adult salmon populations in the Pacific Northwest is, unfortunately, a common problem. However, it appears that the biggest obstacle to creating viable comparisons is the natural patterns of cyclical ecological change that are constantly occurring.

Some evidence suggests that the range of summertime juvenile salmon between 1945 to 1997—about one fish for every 1 to 5 feet of stream length—describes the range of natural variability, without a discernible trend.

From the few historical records available, we can conclude that the adult coho salmon runs of Redwood Creek have not changed since 1960. The adult chinook salmon population decreased from about 5,000 fish in 1960 to about 1,850 fish in 1979. Nothing can be concluded about the adult steelhead population, except that their abundance was estimated to be 10,000 fish in 1960.

Where Is Redwood Creek Going?

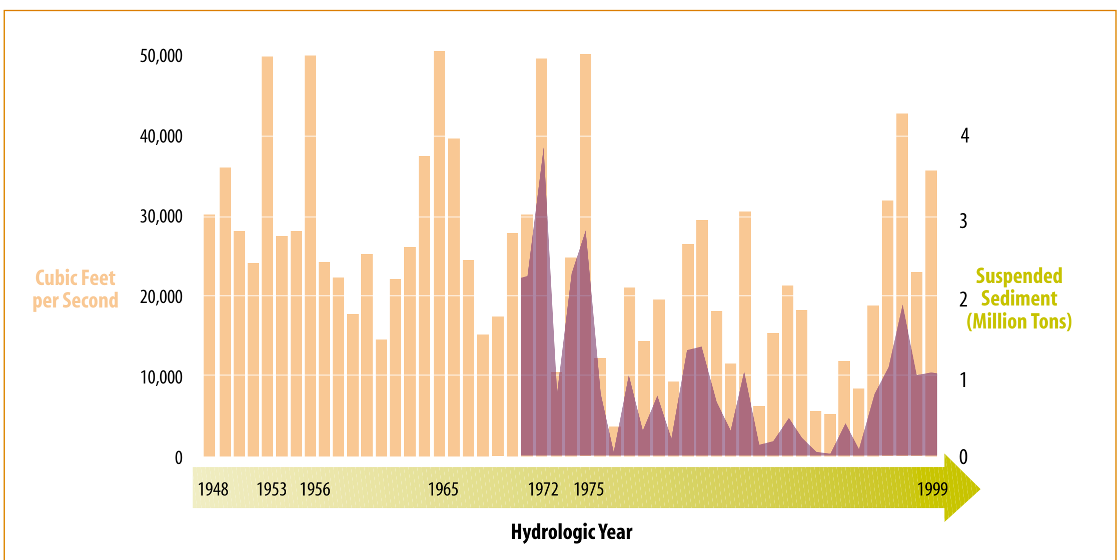
The essence of science is knowledge gained through observation—the greater the number of observations, the greater the accuracy in interpreting the observations. It is the process that incorporates all available information that provides the best resource stewardship.[340,341] The Redwood Creek story, beginning in the 1800s and continuing to the present, is perhaps more complete now than ever before, and the time is ripe for re-examination of salmonid ecology as it relates to the stream's habitats, sediment conditions, and compatible land uses.

We can expect the past patterns of change to continue into the future. Under a probable future scenario of fluctuating climate and ocean conditions, episodic natural disturbances, and regulated land uses, including forest practices, we should rethink the speculative conclusion that the salmonid productivity of Redwood Creek has been impaired by sediment in the past or that it will be in the future. There seems to be broad middle ground between what amount constitutes too much and too little sediment in salmonid habitats.

The data presented in this recapitulation indicates that man-made sediment is not adversely affecting salmon production in Redwood Creek. Regardless, it is possible to modify and enhance stream habitat through sound management practices.[342,343,344] Careful, improved erosion control of roads in the basin today has reduced the potential to contribute sediment to stream channels.

Perhaps a more holistic view of the role of sediment in stream ecosystems is necessary.[345] For better or worse, sediment loading and transport are constantly changing states of the stream. Healthy aquatic habitat depends on it.[346,347,348] If sediments were not being replenished to replace sediment transported out of the stream, there would eventually be no suitable spawning gravels.[349] Consequently, geomorphic changes, including rare dramatic events, must be recognized as inherently characteristic and should not necessarily be viewed as negative forces.[350,351]

Also, it is impossible to choose a spe-



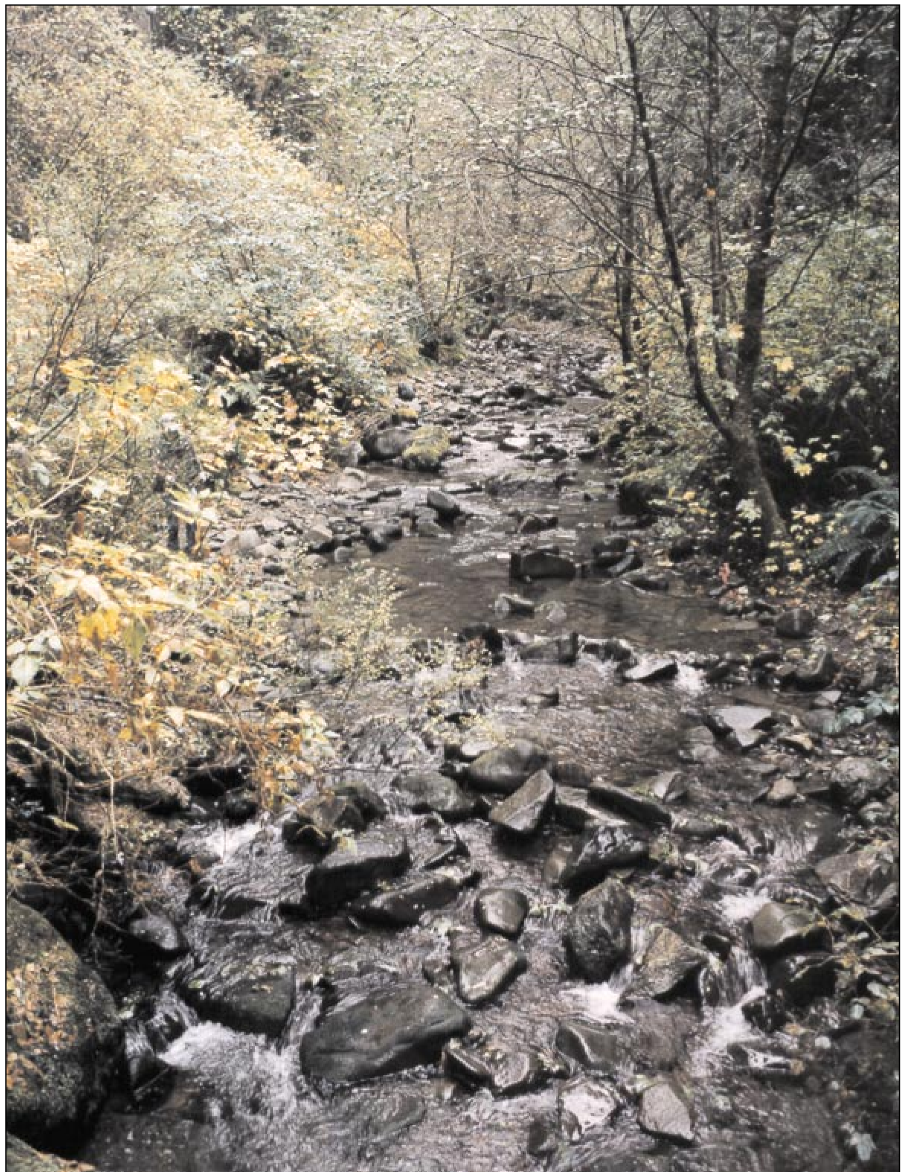
Suspended sediment increases when peak flows occur.

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

cific sediment condition from any one time in the past and attempt to achieve that condition now or in the future. In the words of prominent scientists *"All ecosystems have flows of things—organisms, energy, water, air, nutrients—moving among them. And all ecogystems change over space and time. Therefore, it is not possible to draw a line around an ecosystem and mandate that it stay the same or stay in place for all time."*[352]

Our understanding of Redwood Creek's natural history has increased through observation and study, and investments in our understanding are continuing. For example, the *Redwood Creek Downstream Salmonid Migration Study*, undertaken by the Redwood Creek Landowner's Association, is underway and is already yielding valuable insights.[353] The study is a vehicle for addressing uncertainties and finding answers to questions about the presence, relative numbers, migration timing, and health of anadromous salmonids in the upper Redwood Creek basin.

If the identified salmonid population patterns continue, the low ocean survival rates of the early 1990s may represent a natural low point. Fortunately, rainfall patterns since 1994 resemble those associated with past periods of high salmon abundance.[354] Also, coastal upwelling along northern California in 1999 is among the highest in more than 50 years.[355] As a result, smolts that enjoy such favorable early-life growing conditions may produce higher adult salmon abundance over the next few years.[356]



Little Lost Man Creek is captured in a moment of time.

Photo courtesy of Barnum Timber Company

Consequently, land management policies for Redwood Creek must take into consideration the cyclical agents of change when addressing issues related to salmon and trout populations and freshwater aquatic habitats. Managing ecosystems means working with the processes that cause them to vary and to change. And the regulatory climate must take into consideration natural histories and ecological potentials. Only with realistic expectations for sediment loading capacities and water quality can compatible land management activities be implemented with appropriate flexibility.

In nature, cyclical patterns of change are inevitable. With continued well-reasoned land management and the salmon's innate ability to adapt to a changing environment, we will continue to enjoy the benefits of wild salmon populations in Redwood Creek for generations to come.

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