RNSP staff.
1998.Redwood Creek Watershed Information, Humboldt County, California.
Redwood National and State ParksRedwood National and State Parks,1998.

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unpublished RNP data 1998

Introduction

Redwood Creek drains a 280 square mile watershed in the mountainous, coastal region of northern California. It is one of several major streams and rivers that flow from the Klamath Mountains and Coast Ranges into the Pacific Ocean. The creek rises near elevations of 5,000 feet and flows approximately 55 miles in a narrow, elongated drainage basin north-northwest to the Pacific Ocean near Orick, California (Figure 1). In its historic, pristine condition, the mountainous Redwood Creek basin was extensively forested. In 1963, the world's tallest measured tree, along with several others nearly as tall, were discovered in redwood groves on alluvial soils of the lower Redwood Creek basin.

Early harvesting of the coastal redwood forests in portions of the lower Redwood Creek basin near the turn of the century, using relatively primitive methods, were followed by rapid mechanized extraction of timber resources throughout the basin beginning in the 1940's. Spruce forests in the coastal strip near the basin's estuary were removed for uses in the war and to open lower floodplain areas for grazing and agriculture. Following World War II, timber harvest became the dominant land use in the upper half of the watershed. The post-war housing boom put great demands on the predominantly Douglas-fir forests of the upper basin. As the demand for specialty lumber increased, and more proximate forests had been logged, timber operations also increased in the redwood dominated coastal forests of the lower Redwood Creek basin.

Spurred by concerns of rapid timber harvesting in the 1960's and the discovery of the world's tallest measured trees, Congress established Redwood National Park in 1968. The park embraced a narrow, 1/4 mile-wide corridor of land along Redwood Creek which included superlative alluvial redwood groves containing the world's tallest known trees. The need to preserve entire watersheds, rather than just the magnificent alluvial groves of redwoods, became more and more apparent over time. Protection was recognized to require more than just ownership of redwood trees as downstream sedimentation effects threatened alluvial groves and showed few signs of improving. By 1978, when the National Park was expanded to include a number of tributary sub-basins in the lower watershed, approximately 90% of the conifer forests in the Redwood Creek basin, exclusive of Prairie Creek, had already been harvested (Best, 1984).

National Park Status

Redwood National Park was established in October 1968 to preserve significant examples of primeval coastal redwood (*Sequoia sempervirens*) forests and the associated streams and forests. The law which established the park (PL 90-545) fused three existing state parks into a 31 mile long national park through the addition of about 28,000 acres of privately owned lands. Parts of several watersheds were included in the original national park boundaries - roughly half of the watersheds of Lost Man Creek and Mill Creek (Del Norte County). Less than 10 percent of the Redwood Creek watershed was included in the park and this created a situation for potential adverse impacts from land uses upstream and upslope of the park .

Adverse impacts from land uses outside the park did occur and the Congress addressed these inherent problems in 1978. The "solution" was provided through public law 95-250 which expanded the national park boundaries by 48,000 acres to provide a more meaningful park for protection of natural resources of the initial national park. The creation and later expansion of Redwood National Park resulted in the inclusion of approximately 43,000 acres of cutover timberlands in the park. These lands, representing nearly 45 percent of the 106,000 acres included within the park boundaries, were intensely modified by pre-park logging activities.

Problems associated with cutover lands were addressed in the 1978 expansion legislation by authorization of up to $33 million dollars for a watershed rehabilitation program. The long term goal of the land rehabilitation program is to reduce sedimentation from past logging, to return the downstream portion of the Redwood Creek basin to a reasonable facsimile of the natural state and to protect irreplaceable park resources.

World Heritage Status

Since its creation in 1968, and its later expansion, Redwood National Park has developed into a national park of world stature. The Park and its resources becomes more valuable to future generations as other old growth forests on private lands quickly disappear. In 1982, as recognition of its national and international significance, Redwood National Park was named to the elite status of a World Heritage Site by the 21 member United Nations World Heritage Convention Committee under the auspices of UNESCO. It is one of 112 select natural and cultural sites in 33 separate countries around the world which are protected for their outstanding universal value to humankind.

The selection of the Park as a natural heritage site is based on fulfillment of one or more qualifying criteria. World Heritage Sites must be outstanding examples representing the major stages of the earth's evolutionary history; be outstanding examples representing significant ongoing geological processes, biological evolution, and man's interaction with his natural environment; contain superlative natural phenomena, formations or features or areas of exceptional natural beauty; or contain the most important and significant natural habitats where threatened species of animals or plants or outstanding universal value still survive. Redwood National Park meets virtually all these qualifying elements.

Redwood National Park has within its boundaries the tallest known living specimens on earth. These redwood trees, located on the active flood plain of Redwood Creek, are the surviving remnants of a species dating back millions of years. Their international interest and appeal is evidenced by visitation from around the world and by the willingness of many to contribute substantial sums for the purchase, preservation and protection of dedication groves. The Park serves as a major refuge for these magnificent trees and the flora and fauna which they are associated. They are considered to have international significance and to be irreplaceable treasures.

The World Heritage designation was established in 1972 because of global concerns over environmental deterioration and threatened loss of irreplaceable natural and cultural resources. In agreeing to accept the designation, each nation holds in trust for the rest of the world those parts of the world heritage that are found within its boundaries, that the world community has an obligation to support any nations discharging this trust, and that mankind must exercise the same sense of responsibility to the works of nature as to the works of man. The international honor bestowed upon Redwood National Park is a national trust and the citizens of the state and the nation share responsibility for protecting and preserving this natural resource for the enlightenment, use and enjoyment of future generations.

International Biosphere Reserve Status

Redwood National Park has also been designated as the California Coast Ranges International (CCRI) Biosphere Reserve by UNESCO. It is one of 243 units established in 65 countries which provide a worldwide network of protected areas where conservation is linked directly with sustainable development. The biosphere reserve designation recognizes the importance of an area in conserving the natural ecosystems and genetic resources of one of the world's unique natural regions. Through the biosphere reserve network, national parks are encouraged to function as mainstays of a region's environmental and economic health. Managers are encouraged to extend their horizon of concern beyond the park's boundary and to explore avenues of local, regional and international cooperation in underwriting its security. The biosphere reserve concept is a modern management approach and a new tool for fostering support for the protection, conservation and management of the world's outstanding natural resource areas.

Ideally, a biosphere reserve contains a core zone in which the conservation of natural ecosystems, and biological diversity, together with baseline ecological monitoring, is emphasized. The core area is typically a natural or minimally disturbed ecosystem which includes centers of endemism and genetic richness or unique natural features of scientific interest. Surrounding the core area are other zones which may include an experimental research area, an area(s) of modified or degraded ecosystem that is suitable for restoration (rehabilitation) to natural or near natural conditions, and a traditional use area. Overall, the biosphere reserve, such as Redwood National Park, serves as a bench mark for measurements of long-term changes in the biosphere and provides opportunities for ecological research, education, demonstration and training.

Activities within the core area and in surrounding areas can lay the scientific groundwork for attaining sustainable economic development that has minimal impact on natural ecological processes and genetic resources. Establishment of the CCRI Biosphere Reserve, with Redwood National Park as a core area and including a large watershed rehabilitation area and a comprehensive scientific research program, fits this model exceptionally well. Practical, applied research and education in conservation and rehabilitation can be applied to improve management of the upstream areas under private ownership. Working biosphere reserves can improve the security of protected natural areas, like Redwood National Park, through better cooperation and understanding and through scientific research and improved management of adjacent areas.

If genetic conservation is to be successful in weathering both natural and man-induced environmental change, a more flexible system of conservation and management is needed in which areas of undisturbed natural ecosystems, like the Park, are surrounded by sympathetic and compatible, sustainable land use. The indigenous fauna and flora within the core area are viewed as important reservoirs of genetic material. Such reservoirs are crucial to enhancing the stability and diversity of regional ecosystems and may provide for the re-establishment of populations in impacted areas where they have been eradicated. Such reservoirs can provide the seed for recovery of nearby areas as they re-establish their natural function.

Natural resources

The designations of National Park, World Heritage Site and International Biosphere Reserve are testament to the outstanding and unique natural resources of Redwood National Park. The most recognized of the Park's important natural resources are the superlative redwood groves growing on alluvial terraces and flood plains along the lower main stem of Redwood Creek. It is largely because of these redwoods, and the international attention they received when they were formally discovered in the early 1960's, that protective legislation creating the Park was assured. Yet these same groves are subject to impacts brought about by increased flooding and sedimentation effects which have their origins in the upper portions of the watershed, beyond the protective boundaries offered by their national and international status.

The health of the Park's most important alluvial redwood groves has been clearly linked to stream flow, sediment transport and channel morphology of the main stem of Redwood Creek, and these processes are most closely linked to events and conditions of the middle and upper drainage basin. The trees along Redwood Creek are sensitive to increased peak flows, aggradation, undercutting, and drowning associated with accelerated erosion and sedimentation from upstream watershed areas. Trees along Redwood Creek have been toppled in past floods aggravated by increased sedimentation and others have been killed by permanent flooding of their root systems. Many trees are currently at risk from lateral channel migration and flooding, including those in the world famous Tall Trees Grove, if elevated sediment yield from the upper watershed persists.

Redwood trees are not the only element of the forest ecosystem which continues to be threatened by human activities and physical processes occurring in the watershed. Redwood National Park (including Prairie Creek) occupies approximately the lower 40 percent of the drainage basin, and consequently receives and bears the brunt of increased sedimentation and altered flood flows which originate from upstream areas. Aside from documented impacts to riparian resources and alluvial redwood groves over the last four decades, human activities have caused a substantial decline in the ability of Redwood Creek to produce and support its unique and diverse native fish population (Ridenhour and Hofstra, 1994).

Redwood Creek contains a fish fauna that is relatively unique at this time for the streams of California (Ridenhour and Hofstra, 1994). Aside from the lingering effects of past hatchery operations in the Prairie Creek watershed, the basin is free from the effects of non-native species that have heavily impacted other nearby watersheds, such as the Eel River. At the same time, it still contains remnants of most of the diverse native fish populations that once inhabited the watershed in great numbers. Coho, winter chinook, winter and summer steelhead and cutthroat trout are still present, albeit in far fewer numbers than only a few decades ago.

The magnitude of declines in salmonids in Redwood Creek has been significant. Information suggests that runs of anadromous salmon and steelhead had declined to approximately 10 percent of their former numbers by the mid-1970's (Denton, 1974). Reviewing recent population data, Nehlsen et al. (1991) have identified Redwood Creek's fall chinook salmon, coho salmon and cutthroat trout as being at moderate risk of extinction, and summer steelhead as being at high risk of extinction. Higgins et al. (1992) have identified Redwood Creek chinook and coho salmon stocks to be "stocks of concern" and summer steelhead stocks to be at high risk of extinction. Other species, such as the endangered tidewater goby, are dependent on a healthy, productive, naturally functioning estuary. Much of the salmonid declines and decreases in productivity of the

Redwood Creek basin can be clearly attributed to the activities of humans (Hofstra and Sacklin, 1986; Ridenhour and Hofstra, 1994).

Human activities have likely had significant impacts on the anadromous salmon, trout and smelt because of the changes in the habitat required for their production and sustenance (Ridenhour and Hofstra, 1994). Loss of riparian shade canopy and cover, filling of pools, altered channel morphology (brought about by excessive and persistent sedimentation), increased rates of coarse bedload transport and influxes of fine sediment, cemented and embedded spawning gravels, decreased summer flows and aquatic habitat volume, increased water temperatures, loss or removal of organic debris (Klein et al., 1987), reduced invertebrate production, sedimentation of nursery habitat in the estuary (Hofstra and Sacklin, 1987), and increased vulnerability to predation (especially in the levee section of the lower river) are all in-basin factors which have been identified as elements responsible for the fisheries decline and failure to recover to any substantial level (Ridenhour and Hofstra, 1994).

Redwood National Park Background

The Redwood Creek watershed is one of the most thoroughly studied drainage basins in the western United States. Scientific studies conducted by the U.S. Geological Survey and the National Park Service between 1970 and 1979 provided the data and information necessary to link natural processes and the effects of land use on downstream erosion and sedimentation processes. Janda's (1975) landmark treatise on the status and condition of the Redwood Creek watershed as of 1973 provided the launching platform for two decades of quantitative investigations on the causes and effects of erosion and sedimentation processes throughout the drainage basin. These studies, conducted on a number of topics and by a variety of researchers, continue to the present. They provide a nearly unmatched scientific research record on the causes and effects of erosion and sedimentation processes throughout the watershed (Nolan et al. 1995).

The park was established, in part, to provide permanent protection to the outstanding alluvial groves of the Redwood Creek basin. It became clear soon after the initial acquisition that simply purchasing the land and the trees would not provide the protection necessary to ensure survival of the most superlative alluvial groves along Redwood Creek. Not only was their survival tied to the health and condition of the immediate ecosystem, but, because of their tenuous location, processes and events occurring in the middle and upper drainage basin also threatened to impact their health and well being.

Shortly after the establishment of Redwood National Park, the Secretary of the Interior and the National Park Service launched a series of studies designed to understand the options available for protecting the park from the potential effects of upslope and upstream timber harvesting and erosion. The first of these studies (Stone et al. 1969) recommended restrictive buffers around the boundaries of the park and cooperative efforts to stabilize eroding lands in the upper Redwood Creek basin. A task force lead by Dr. Richard Curry (Curry, 1973) identified channel bank instability and landsliding as the main threats to the park's alluvial redwood groves and recommended increased efforts to change land management practices upslope and upstream from the park. These early investigations, conducted immediately after the creation of Redwood National Park, relied on a limited reservoir of available data for the watershed to describe natural processes and human-caused impacts to park resources (e.g., Stone et al. 1969). Threats to park resources, and the impact of human activities upstream and upslope from park lands, were largely inferred and the linkages between hillslope processes and stream channel impacts were poorly understood.

Understanding of the interactions among various geomorphic processes, human activities and watershed ecology was so incomplete that the Curry Commission (Curry, 1973) recommended initiation of an objective study of watershed processes needed to formulate management activities necessary for park protection. The U.S. Geological Survey, commissioned by the National Park Service, initiated the multi-year study in 1973 with three goals: 1) to describe park resources that are threatened by recent changes in watershed erosion and sedimentation, 2) to define the magnitude, frequency and duration of these threatening processes, and 3) to assess the impact of recent road construction and timber harvesting on those processes (Janda et al. 1975).

In his 1975 report, Janda outlines the status of the watershed and the nature of threats to park resources as of 1973. It is from this baseline that impacts and threats to park resources continue to be evaluated and measured. Have conditions changed since 1975? Are the current threats less than, greater than or are they unchanged from those that existed in 1975? How are past and current land use practices affecting park resources? Research conducted since Janda's initial evaluation of watershed conditions has provided a fairly clear picture of the current state of the basin and its stream channels; the nature, origin and level of continuing threats to park resources; the relationship between land use and downstream cumulative watershed effects; the connection between upper basin processes and events and lower basin impacts; and the expected persistence of cumulative watershed effects.

Climate and hydrology

Climatic events, and the peak streamflows they produce, represent the driving mechanism which produces significant geomorphic response and watershed change in Redwood Creek (Harden, 1995; Harden et al. 1995; Weaver et al. 1995). They trigger widespread sediment production and delivery to the channel system, channel aggradation and rapid, dramatic changes in channel morphology; processes which have the greatest potential to dramatically impact park resources.

Redwood Creek is dominated by a Mediterranean climate with mild, wet winters and cool, dry summers. Most (>75%) of the estimated 80 inches mean annual precipitation (Rantz, 1964) falls in the five months from November through March; 90% falls from October to May (Coghlan 1984). Annual precipitation has a relatively wide range from 50 inches (1939) to over 93 inches (1938) as measured at Prairie Creek State Park in the lower basin (Janda 1975). Variation in annual precipitation is also significantly dependent on altitude, proximity to the ocean and slope aspect. Orographic influences are thought to exert a significant control on precipitation. For example, in 1974 annual rainfall on ridges at the pre-expansion south park boundary was 25% to 30% greater than at Prairie Creek State Park (Iwatsubo et al. 1975). Even gages in relative close proximity display differences in annual precipitation. Average annual rainfall measured at 18 storage and 3 recording rain gages in or near the Redwood Creek watershed between 1976 and 1979 ranged from 42 to 66 inches (Kelsey et al. 1981).

Most precipitation in the basin falls as rain. Snow falls fairly frequently at altitudes greater than 1,600 feet and rarely at lower altitudes (Janda et al. 1975). Rain-on-snow runoff events have produced the largest floods in the basin (Janda et al. 1975), including the 1964 flood. Long-term rainfall data were analyzed by Janda and others (1975). They found that the years 1865-68, 1900-04, and 1951-58 were particularly wet and that the years 1869-75, 1882-89, and 1917-1937 were relatively dry. Rainfall amounts during the period encompassing the recent large floods of 1955, 1964, and 1972 were not unusually large in comparison to long-term records (Janda and others, 1975). Rainfall was relatively low between 1975 and 1995. Within this period, the highest rainfall amounts were recorded in 1982, 1983, and 1986 (NPS, 1995).

Between 1953 and 1975, Redwood Creek experienced a series of large flood events (Table 7). The floods, especially the 1964 event, resulted in severe and lasting geomorphic changes within the watershed. These changes included the initiation of widespread landsliding, gullying, channel widening and channel aggradation. Many of these storms were regional in extent, and similar changes have occurred throughout northern California (Waananen et al. 1971; Lisle 1981).

For many years prior to these series of flood events, the climate of northwestern California was relatively benign (Coghlan 1984). Localized flooding occurred, some of it quite severe, but no major, region-wide storm event had occurred since 1890 (Harden et al. 1978). In spite of such brief respites, Coghlan (1984) indicated that hemispheric circulation patterns favoring the development of storms such as those that produced historical large floods in the basin (Table 7) are a normal and permanent part of the area's climate and that such flood events should be expected to occur in the future.

Table 7. Peak discharges and recurrence intervals of geomorphically significant storms in the Redwood Creek basin, 1950-1980 (Harden et al. 1978; Coghlan 1984; Harden 1995)

Date	Discharge (cfs)	Unit discharge (cfs/mi^2)	Recurrence Interval (years)
January 18, 1953	50,000	180	25-30
December 22, 1955	50,000	180	25-30
December 22, 1964	50,500	182	45-50
January 22, 1972	45,300	163	10-12
March 3, 1972	49,700	179	10-12
March 18, 1975	50,200	181	?

Prehistorical evidence supports the concept that large floods are a common and regular part of local drainage basin history. For example, direct evidence of late Holocene storms is found in the depositional record of Bull Creek, a tributary to the nearby Eel River. Zinke (1981) recorded a minimum of 15 major depositional events in alluvial deposits at the mouth of Bull Creek in the past 1,000 years. He documented 10 major depositional events in the last 600 years (1 every 60 years).

Coghlan (1984) has summarized the pre-1950 geomorphic record of local watersheds in relation to evidence for comparably significant flood events[1]. Such evidence includes flood-deposited gravel bars, gravel waves (such as those deposited in local rivers by the 1964 flood) and widespread synchronous landslide deposits. The record reveals evidence for the occurrence of a number of large floods that could have significantly altered regional stream channel morphology and the depositional record. Over the last 400 years, there have been a minimum of five storms of similar recurrence interval to the 1964 event (1964, 1890, 1861, 1735 and 1590), and at least two of them are thought to have been larger (Coghlan 1984). This yields a storm frequency of at least one every 80 years.

[1] A "significant" flood event is one which results in substantial, lasting geomorphic change to a watershed and its stream channels. The largest flood event, in terms of peak flow, is not necessarily the most significant event. Flood duration and geographical distribution, rainfall intensity, antecedent moisture conditions and land use, in additional to peak discharge, are factors that affect the geomorphic significance of a flood event.

The regional record since 1850 contains two periods of storminess and two periods of storm absence. Because of the anomalous (storm-free) nature of the early to mid twentieth century climate, the 1954 to 1980 statistics for Redwood Creek are closer to the long-term values than might be suspected from the short length of record (Coghlan 1984)[2]. Based on available data, Coghlan (1984) has estimated a long-term recurrence interval for large floods on Redwood Creek to be 45 to 50 years. This applies to storms greater than or equal to that of December 22, 1964, both in terms of intensity and regional size. At least five such storms have been identified in the geomorphic record. Since 1855, there have been four or five storms of magnitude greater than or equal to that of the December 1955 flood. The estimated recurrence interval of the 1955 storm is placed at 25 to 30 years (Coghlan 1984).

Not all major storms leave geomorphic evidence, even though they may have had significant effects on channel geomorphology. For example, the flood of 1861 left only scattered deposits, in spite of being the largest runoff event observed in the past 130 years (Kelsey, 1977; Harden et al. 1978). Likewise, when significant floods occur in relatively close progression, the later of these floods may largely erase evidence of the earlier events. The process is analogous to alpine glaciers that may destroy depositional evidence of former advances that were not as large as the more recent event.

For example, field evidence indicates that nearly all the geomorphic deposits likely to represent the post-1950 storms were deposited between 1964 and 1975 (Coghlan 1984). Significant storms comparable to that of March 1972 are estimated to have a 10-year recurrence period, but field evidence for these events tends to be obscured in the geomorphic record. Thus, 200 or 300 years from now, only one event will be inferred during this period, when in fact there were six.

The flood-producing storms of the late 1800's were probably comparable to those from 1953 to 1975, both in terms of rainfall amounts and flood peaks (Harden et al. 1978). Considering the apparently unprecedented magnitude of the 1861-1862 floods, and the subsequent major flooding of 1867, 1879, 1881, 1888 and 1890, it appears that the floods of the late 1800's had the potential to be at least as geomorphically important ("damaging") as the more recent floods (Harden et al. 1978). The differing erosional response of the Redwood Creek basin, and other watersheds of the north coast, has been attributed to changes in runoff regimes, hillslope stability and stream sediment loads caused by human activities, primarily timber harvesting and road building (Harden et al. 1978). No other major changes in watershed conditions or differences in storm parameters were noted during this period which help might explain the exceptionally large watershed response.

Basin characteristics

General physiography - The 280 square mile Redwood Creek basin is located in the Coast Range Province of northern California and is contained entirely within Humboldt County. It flows to the Pacific Ocean near the town of Orick. The elongate drainage basin is approximately 56 miles in length and varies from roughly 4 to 7 miles in width (Janda et al. 1975). Total basin relief is

[2] With additional low precipitation years since Coghlan's (1984) report, the 1975 - present period is likely similar to that of 1954 - 1980.

approximately 5,300 feet and tributaries are characteristically rugged. The heavily dissected drainage basin is characterized by high local relief, moderately steep to steep unstable hillslopes and narrow valley bottoms. The average slope gradient is about 26 percent (Janda et al. 1975), but more than half of the hillslopes are in excess of 35 percent steepness, and over 30 percent are steeper than 50% gradient (Table 1). Significantly, over 70 percent of the slopes steeper than 65% are located on sensitive stream side inner gorges areas.

Table 1. Distribution of slope units of the Redwood Creek Basin upstream from R.N.P.

Slope unit	Middle Basin (PPZ) - (acres)	Upper Basin (acres)	Total (acres)
<50%	16,300	55,800	72,200
50% - 65%	5,200	17,000	22,200
>65%	4,100	5,600	9,700
TOTALS	**25,600**	**78,400**	**104,100**
Streamside slopes >65% (steep inner gorge slopes)	3,200	3,900	7,200

The steepest slopes are found along the eastern side of the watershed (e.g.., Lacks Creek and Minor Creek) in areas underlain by hard sandstone bedrock. In these areas, steep stream-side slopes often exceed 65 percent gradient. Debris slides and debris avalanches are largely restricted to slopes steeper than 50 percent, most of which occur as inner gorge slopes along incised stream channels (Janda et al. 1975). Most of the Redwood Creek basin has experienced substantial late Cenozoic uplift. This uplift, in concert with rapid channel downcutting, has resulted in the formation of steep, stream-side inner gorge slopes along the main stem Redwood Creek channel and most major tributary streams (Kelsey, 1988).

Geology - The basic geology of the Redwood Creek basin was most recently mapped and described Harden et al. (1981) and Cashman et al. (1995). The basin is underlain by the Franciscan Complex of unmetamorphosed sandstone and siltstone, schist and scattered blocks of chert, conglomerate, and volcanic blocks. The basin is bisected by the Grogan Fault Zone (which defines the course of the main channel for much of its length) and several other parallel faults. Faults typically form the boundaries between lithologic units of the Franciscan Complex in the watershed. In general, slopes west of the Grogan Fault are underlain by schist and slopes east of the fault are underlain by sandstone and mudstone.
The distribution of rock types in the Redwood Creek basin is depicted in Table 2. Harden et al. (1981) distinguished two basic sedimentary rock types east of the Grogan fault: the Coherent Unit of Lacks Creek and the Incoherent Unit of Coyote Creek. As the names imply, the Incoherent

Table 2 . Mapped bedrock units of the Redwood Creek Basin upstream from R.N.P.				
Bedrock Unit	Middle Basin (PPZ) - (acres)	Upper Basin (acres)	Total (acres)	
Kjfr (Redwood Creek schist)	8,120	34,370	42,490	42%
Kjfc (incoherent unit of ~~Lacks~~ Coyote Creek (silt- and mudstones))	12,750	22,300	35,050	} 46%
Kjfl (coherent unit of Lacks Creek (mostly sandstones)	4,110	6,740	10,850	10%
Kjfg (meta sandstones and mudstones of Grogan fault)	110	3,760	3,870	
Kjfsc (Snow Camp Mtn. sandstone and melange)	0	3,710	3,710	assume rest is like schist
Ql (landslide deposits)	500	2,540	3,040	
Qt (stream terrace deposits)	10	760	770	
Qal (modern alluvium)	20	440	460	
Ju (Klamath Mtn. rocks)	0	380	380	
unmapped	30	200	230	
s (serpentine)	10	0	10	
t (tectonic blocks)	5	0	5	
TOTALS	**25,665**	**75,200**	**100,865**	

84 - 90 Unit of Coyote Creek is largely composed of poorly bedded, highly fractured and sheared mudstones that are highly susceptible to both fluvial erosion and mass soil movement. Slopes display a rolling, subdued topography similar to that formed elsewhere on the Franciscan melange.

The Coherent Unit of Lacks Creek is composed of well indurated, interbedded sandstone and mudstone and the resulting units are relatively more resistant to erosion. It forms steep slopes and over 60% of steep inner gorge slopes in the basin are underlain by this rock type (Table 3). Slopes underlain by the incoherent unit are susceptible to gullying and earthflow activity while slopes in the coherent terrain are much steeper and dominated by rapid, shallow landsliding processes.

Table 3. Mapped bedrock units on inner gorge slopes of the Redwood Creek Basin upstream from R.N.P.			
	Middle Basin	Upper Basin	Total

Bedrock Unit	(PPZ) - (acres)	(acres)	(acres)
Kjfr (Redwood Creek schist)	200	920	1,120
Kjfc (incoherent unit of ~~Lacks~~ Coyote Creek (silt- and mudstones))	510	700	1,210
Kjfl (coherent unit of Lacks Creek (mostly sandstones)	2,530	1,960	4,490
Kjfg (meta sandstones and mudstones of Grogan fault)	10	290	300
Kjfsc (Snow Camp Mtn sandstone and melange)	0	20	20
Kjfs (South Fork Mtn. schist)	0	10	10
Ql (landslide deposits)	10	15	25
Qt (stream terrace deposits)	5	10	15
Qal (modern alluvium)	0	5	5
Ju (Klamath Mtn. rocks)	0	0	0
unmapped	0	0	0
s (serpentine)	0	0	0
t (tectonic blocks)	0	0	0
TOTALS	**3,265**	**3,930**	**7,195**

The aerially most extensive rock unit in the basin is the Schist of Redwood Creek (Table 2). It covers approximately 42% of the middle and upper watershed areas, and is the predominant rock type found west of the Grogan Fault. It consists of both metasedimentary rocks (mudstones and sandstones) as well as metavolcanics (basalts and tuffs). Most outcrops show extensive deformation and fracturing resulting in rock incompetence that contributes to high erodibility (Hagans et al. 1986) and slope instability (Kelsey et al. 1995).

Soils - Upland soils of the Redwood Creek basin were mapped at a scale of 1:62,500 as a part of the California Cooperative Soil-Vegetation Survey completed in 1962 (Alexander et al. 1959-1962). Soil-vegetation relationships were typically used to infer soil types from nearby sampled sites in other watersheds. More modern soil mapping has been undertaken in the lower Redwood Creek basin (USDI, 1992) and revised map units, land use interpretations and soil series descriptions have been developed based on 24 pedons for these areas (Popenoe, 1987). Additional, modern mapping of the upper basin awaits a new National Resource Conservation Service (NRCS; formerly the Soil Conservation Service) soil survey.

Differing lithologies and weathering stages have resulted in the development of distinctive soil units in the basin. These soil units, in turn, display different sensitivities to fluvial erosion and mass soil movement. In the lower basin, the depth of the regolith appears to be controlled by small scale relief (swales, ridges, etc) rather than hillslope position (upper, middle, lower) (Popenoe, 1985). In contrast, the degree of soil development appears to be more related to basin position with greater clay accumulation and iron oxidation in soils in upper, gentler slope positions. Increasing clay and iron content, in turn, have been associated with lower rates of soil erodibility (Durgin and Tackett 1981). Weaver et al. (1996) also identified increasing clay content and rock fragment content as significant natural deterrents to gully erosion on disturbed sites in the Redwood Creek basin.

In addition to specific land use variables, physical soil characteristics have been identified as strongly influencing rates of gully erosion and sediment yield from cutover and roaded lands in the lower basin (Weaver et al. 1995). Rocky, shallow soils are preferentially developed on the indurated bedrock of the Coherent Unit of Lacks Creek while clay- and iron-rich soils appear to be preferentially formed on the low gradient upland slopes and ridge-tops of the Schist of Redwood Creek. Both soil types resist gullying.

In contrast, soils developed on the Incoherent Unit of Coyote Creek often occupy large, poorly drained amphitheaters with relatively high drainage density and poorly incised stream channels. These soils are typically characterized by relatively low clay content (<35%) and low rock fragment content (<35%), poor drainage, mottling and areas of slope instability. In lower basin study sites, high gully yields were exclusively limited to relatively deep soils which contain comparatively low concentrations of clay and rock fragments (Weaver et al., 1996).

Erosional processes - Over the last 20 years, extensive research has been performed throughout the Redwood Creek watershed to characterize the nature, cause, magnitude and effects of natural and accelerated erosion and sedimentation in the basin. Serious, quantitative studies began with USGS studies in the 1970's (Janda et al. 1975; Nolan et al. 1976; Harden et al. 1978; Janda 1978; Iwatsubo and Averett 1981; Marron 1982, Marron et al. 1995; Nolan and Marron 1995) and continued with a variety of National Park Service sponsored investigations following the 1978 expansion of park boundaries (for example, Kelsey et al. 1981; Pitlick 1982; Coghlan, 1984 ; Best 1984; Madej 1984; LaHusen 1984; Ricks 1985; Sonnevil et al. 1987; Walter 1985; Varnum and Ozaki, 1986; Hagans and Weaver 1987; Hofstra and Sacklin 1987; Iverson and Major 1987; Ozaki 1988; Lisle and Madej 1992; Madej 1992; Kelsey et al. 1995; Pitlick, 1995; Weaver et al. 1995). Work has been conducted on both park lands in the lower basin as well as on private forest lands upstream from the park.

Previous erosional studies have documented and quantified each of the erosional processes contributing sediment to Redwood Creek and its tributaries. The importance of each erosional process, in relation to the protection of park resources, is dependent on the timing and quantity of sediment that is delivered to Redwood Creek. Erosion which occurs on lands upstream from the park, while perhaps important to the productivity of the lands where it occurs, is of little consequence to park resources unless it is delivered to stream channels that eventually feed Redwood Creek and pass through the park.

The dominant processes contributing to sediment yield in the Redwood Creek basin include several types of mass soil movement (landslide) and fluvial processes. Certain soil types and bedrock materials in the watershed are indicative of, or susceptible to, mass movement processes while others are sensitive indicators of susceptibility to fluvial erosion processes (Table 4). Nearly 40% of the watershed is underlain by unstable bedrock types (Table 2) or these "sensitive" soils (Table 4). Similarly, over 40% of the steep inner gorge slopes in the basin are underlain by sensitive soil units which are prone to either mass soil movement or severe gullying (Table 5). Land use activities in these areas are especially prone to accelerating naturally high rates of erosion, landsliding and sediment yield.

Many hillslopes in the Redwood Creek watershed are inherently unstable as a result of steep slope gradients created by recent uplift and subsequent stream channel incision, low shear strength of pervasively sheared and fractured bedrock, and seasonal saturation of soils and regolith. Several mass movement processes are active, including soil creep, slow persistent landslides (earthflows) and rapid episodic landslides (Nolan et al. 1976; Harden et al. 1978; Kelsey et al. 1981; Pitlick 1982; Kelsey et al. 1995). The historic distribution of these processes is primarily related to lithology, hydrology, slope steepness and land use.

Harden et al. (1978) concluded that deep gravitational ***soil creep***, as well as near-surface soil displacement from freeze-thaw and biogenic processes, are relatively ineffective at delivering sediment to Redwood Creek and its tributaries.

The most aerially extensive of the active mass movement features found within the drainage basin are ***earthflows*** (Nolan et al. 1976; Harden et al. 1978). These "soil glaciers" of slow moving landslide material cover about 10 percent of the watershed surface, and very active earthflows (some moving up to 20 feet per year) comprise approximately 2% of this land (Harden et al. 1978). Earthflows are largely bedrock controlled and are found preferentially on incompetent,

Table 4. Distribution of sensitive soil units of the Redwood Creek Basin upstream from R.N.P.

Soil Map Unit	Middle Basin (PPZ) - (acres)	Upper Basin (acres)	Total (acres)
Atwell (mass movement)	1,490	4,870	6,360
Yorkville (mass movement)	580	1,460	2,040
Colluvium (mass movement)	1,140	300	1,440
McMahon, Kinman, Orick, Sites, etc. (impaired drainage)	950	2,160	3,110
Hugo (fluvial)	5,740	6,030	11,770

Masterson (fluvial)	4,510	10,760	15,270
SUBTOTAL (sensitive soils)	**14,410**	**25,580**	**39,990**
Non-sensitive soils	11,230	53,450	64,670
TOTALS (all soils)	**25,640**	**79,030**	**104,660**

highly fractured bedrock (the Incoherent Unit of Coyote Creek) on south and west facing slopes in the basin (Harden et al. 1978). Studies in and near the Redwood Creek watershed by Kelsey (1978), Harden et al. (1978), Nolan et al. (1979), Iverson (1984) and Iverson and Major (1987) have shown that earthflows deliver sediment to stream channels through both mass movement and fluvial processes and that earthflow movement is related to annual rainfall and patterns of groundwater flow.

Previous studies have also shown that earthflows, despite their large size and apparent activity, cumulatively deliver relatively little sediment to Redwood Creek (Harden et al. 1978; Nolan et al. 1979; Kelsey et al. 1995). Detailed monitoring and instrumentation of the active Minor Creek earthflow (Iverson 1984; Iverson and Major 1987) supports this finding. Average long term movement rates of 1.6 feet per year for this well studied earthflow (Iverson and Driedger 1993) translates to approximately 250 cubic yards delivered annually to Minor Creek, a major mid-basin tributary to Redwood Creek (NPS, 1995).

Table 5. Distribution of sensitive soil units on inner gorge slopes of the Redwood Creek Basin upstream from R.N.P.

Soil Map Unit	Middle Basin (PPZ) - (acres)	Upper Basin (acres)	Total (acres)
Atwell (mass movement)	90	225	315
Yorkville (mass movement)	0	5	5
Colluvium (mass movement)	740	125	865
McMahon, Kinman, Orick, Sites, etc. (other impaired drainage)	5	0	5
Hugo (fluvial/gully)	555	775	1,330
Masterson (fluvial/gully)	165	295	460

SUBTOTAL (sensitive soils)	**1,555**	**1,425**	**2,980**
Non-sensitive soils	1,690	2,475	4,165
TOTALS (all soils)	**3,245**	**3,900**	**7,145**

If the Minor Creek earthflow is considered representative of the 3,050 acres of very active earthflows in the basin, average annual contributions from all such mass movement features totals only 3 percent of the average annual sediment load of Redwood Creek measured at the Orick gaging station. Studies elsewhere (Kelsey 1978) suggest that fluvial erosion from axial and marginal gullies on active earthflows may actually contribute significantly more sediment to stream channels than does mass soil movement.

Earthflow movement is a major process forming the physiography of large sub-basins and bowl areas on hillslopes underlain by weak, fractured bedrock in the Redwood Creek basin. Earthflow processes are thought to have played an even more significant role in landform evolution when climatic conditions were wetter than at present. These mass movement features, while natural, can be affected by human activities such as grazing, road construction, and other land use practices which alter hillslope water balances (Iverson 1984; Kelsey 1978). Land use practices which concentrate runoff or alter stream flows on earthflows can accelerate gullying (Walter 1986) and channel aggradation or undercutting by a large stream can reactivate movement or increase movement rates.

Forested ***block slides***, another type of slow moving landslide found in the basin, are typically located near shear zones on schist terrain (Sonnevil et al. 1987). They behave much like earthflows, but natural movement rates are typically slow enough to permit the establishment and maintenance of a coniferous forest. Land use activities, such as timber harvest and road building, are thought to significantly increase the level of activity and rate of movement of forested blockslides (Sonnevil, et al. 1985). Movement rates may increase to the point that all large trees on the slide are toppled in a few years time. Because of their limited areal extent and number, forested blockslides probably contribute a relatively small proportion of the total sediment yield of Redwood Creek. However, their contribution to the sediment yield of some west side tributaries, especially in the lower basin, may be relatively important.

The most significant of active mass movement processes in the Redwood Creek basin are rapid landslides which deliver large quantities of sediment directly to stream channels during winter storm events. These include debris torrents/flows and debris slides (Harden et al. 1978; Nolan et al. 1979; Pitlick 1982; Kelsey et al. 1995). Those that are in close proximity to streams and those located on steep inner gorge slopes, have the greatest likelihood of delivering sediment to stream channels. Both debris torrents and debris slides have been found to be significantly affected by land use activities including timber harvest and road construction (Janda et al. 1975). Other processes, such as natural debris avalanches and slumps, are relatively uncommon processes in the basin and are thought to contribute relatively little to total sediment yield (Harden et al. 1978).

Debris flows and torrents are long, shallow, rapidly moving landslides that often originate on steep inner gorge slopes, below significant slope breaks and in steep headwater swales where subsurface water converges within colluvial deposits (LaHusen 1984). Some torrents originate where loose materials sidecast onto steep slopes become saturated during winter storms. Others occur where roads have been constructed across steep headwater swales and subsurface groundwater flows have been altered. Once initiated, debris torrents can travel thousands of feet downslope, increasing their mass by scouring native colluvial material, until they come to rest in relatively low gradient stream channels or on hillslope benches.

Debris slides are shallow translational landslides that typically involve the rapid failure of layers of soil and colluvium on steep slopes. In the Redwood Creek basin, debris slides are found on all bedrock types and are often associated with steep streamside slopes or logging roads built on steep hillslopes. Debris slides are clearly an important source of sediment to Redwood Creek and its tributaries, both because of their large number, their cumulative volume and their close association with steep streamside slopes and high gradient tributary streams where delivery rates are relatively high. The erosional landform map of Nolan et al. (1978) shows streamside landslides, most of which are debris slides, along much of the mainstem and major tributary streams of the middle and upper Redwood Creek basin. In contrast to earthflows, sediment delivery from streamside landslides (mostly debris slides) has been estimated at about 291,000 tons per year along main stem and 176,000 tons per year along tributary stream channels (sample period 1954-1980; Kelsey et al. 1996). This represents approximately 60 percent of the long-term mean annual basin-wide sediment discharge at Orick (Madej et al., unpublished data).

Fluvial erosion has been determined to be a significant contributor to basin-wide sediment production and yield in the Redwood Creek watershed (Kelsey et al. 1981; Hagans and Weaver, 1986). Fluvial erosion includes processes such as rill erosion, gullying and bank erosion. In natural settings, fluvial erosion is concentrated on disturbed topography, such as active landslides, earthflows and burned areas. On forested slopes fluvial erosion may occur in subsurface macro-pores (pipes) and root channels (Janda et al. 1975; Ziemer 1992). On logged slopes, rill and gully erosion are commonly associated with ground disturbance in tractor yarded harvest areas and with the collection and concentration of runoff along thousands of miles of roads and skid trails (Janda et al. 1975).

Fluvial erosion is much more difficult to quantify than mass soil movement, because the location and size of specific features are not amenable to identification or measurement on stereo aerial photography. Fluvial erosion in the Redwood Creek basin is widespread but generally dispersed and composed of a large number of small linear features (gullies) or areas. For this reason, field studies aimed at quantifying the magnitude and causes of fluvial sediment production and yield in the Redwood Creek basin have used techniques such as terrain sampling (Hagans and Weaver 1986; Walter 1985), concentrated studies of relatively small sub-basins (Weaver et al. 1982) or residual analysis of larger sediment budget studies (Kelsey et al. 1981).

Previous studies have documented large increases in fluvial sediment production and yield from harvested and roaded hillslopes in the basin (Janda et al. 1975; Nolan et al. 1978; Walter 1985; Hagans and Weaver 1986; 1987; Weaver et al. 1996). Kelsey et al. (1981) estimated fluvial sediment yield to account for up to 68 percent of the total sediment delivered to stream channels in the upper basin (upstream from Highway 299). Based on large sample areas, Hagans and Weaver (1987) estimated that fluvial sediment production in the lower basin accounted for roughly half of total sediment yield to stream channels for the period 1954-1980. Madej (1997, unpublished data) has recently estimated fluvial sediment sources to account for approximately 34% of basin-wide sediment production. Fluvial sediment sources were estimated to include surface erosion from bare soil areas, stream crossing washouts and gullies created when culverts plug and streams are diverted down roads and across unchanneled hillslopes.

Developing a quantitative ***sediment budget*** which describes sediment sources, delivery, storage and transport for a watershed is an accepted method to depict the importance of the various erosion processes active in a drainage basin. Several preliminary sediment budgets have been developed for portions of the Redwood Creek basin (Kelsey et al. 1981; Hagans and Weaver 1987) and sufficient data is available from other studies for computation of a generalized budget for the entire watershed (NPS 1995). In a sediment budget the inputs of sediment, together with material which is stored in the channels, are balanced in equation form against the outputs or discharge of sediment from the basin outlet (available from USGS sediment sampling records). Major inputs include streamside landslides and fluvial hillslope erosion while sediment storage is represented by the material which has temporarily accumulated in the basin's stream channels as bars, flood plains and aggraded streambeds (Madej 1984).

Fluvial erosion and yield is the least certain term in the sediment budget equation, but because the other three terms (landslide inputs, sediment storage and basin-wide sediment yield) are better understood and quantified, fluvial erosion is simply computed as the residual term. Inputs include an estimated 291,000 tons/year from main stem landslides and 176,000 tons/year from tributary landslide processes for a total mass movement influx of approximately 467,000 tons/year for the watershed during the two decades from about 1954 through 1980. Most of these "pulse" inputs occurred during the storms of 1955, 1964, 1972 and 1975.

The bulk of stored sediment in the Redwood Creek watershed was initially deposited in stream channels during the 1964 flood (Madej 1984). Most of the coarse sediment currently stored in the watershed resides in and along the main channel of Redwood Creek. With few exceptions, tributaries have largely scoured their channels and flushed previously stored sediment into the main stem where it has been redeposited (Pitlick 1982). Stored sediment in the main stem has shifted position over time, but the bulk of it still remains in and alongside the active channel and it is expected to remain in storage for decades to come (Madej 1992). Averaged over the longer time period, the average annual increase in sediment storage is computed to be about 162,000 tons/year.

Finally, data from U.S. Geological Survey stream gaging and sediment sampling records have been used to estimate the average annual total sediment load during approximately the same time period (1960's and 1970's). Average annual sediment discharge, as measured at the Orick gaging station, has been estimated at 1,860,000 tons/year (computed by Knox (USGS), as referenced in Harden et al. 1978). This figure is useful because it estimates sediment yield during a period which contained three years with peak flood flows of approximately 20- to 50-year recurrence intervals (1964, 1972, 1975).

The final sediment budget is depicted in Table 6. Mean annual sediment production, delivery and discharge, as shown in the table, are "fictitious" numbers that probably never occur in any given year during the period of record. That is, average sediment discharge rates are controlled by the effects of a few, highly episodic events which account for most long term sediment movement within the basin. Landslide ~~and gully erosion proce~~sses, which account for the bulk of documented erosion and sediment delivery in the Redwood ~~Creek watershed~~, are storm-driven processes. Similarly, sediment storage in tributaries and the main stem channel is highly episodic and dependent on large pulses of sediment from the hillslopes followed by long intervals of gradual routing through the channel system. These episodic erosion and sedimentation events are separated by relatively long periods of comparatively low sediment production and discharge.

It should be noted that fluvial hillslope erosion represents approximately 84% of the estimated sediment inputs to the Redwood Creek basin. This has important implications for future land management, for park protection and for the management and control of sediment delivery to

Table 6. Sediment budget for the Redwood Creek watershed for the period from approximately 1954 - 1978 (NPS 1995).

Streamside landslides	+ fluvial erosion	- channel storage	= sediment discharge
467,000 tons/year	1,555,000 tons/yr	162,000 tons/year	1,860,000 tons/year
25%	84%	9%	100%
(% of total annual basin-wide inputs)		(% of annual yield)	(total output at Orick)

1668 t/y/mi² + 5554 t/y/mi² - 579 = 6643 t/y/mi²

stream channels throughout the basin. Sources of fluvial sediment production and delivery are much more easily controlled or prevented than are mass movement processes, and a suite of cost-effective measures have been developed for implementation on private and public lands throughout the Pacific Northwest over the last decade.

2

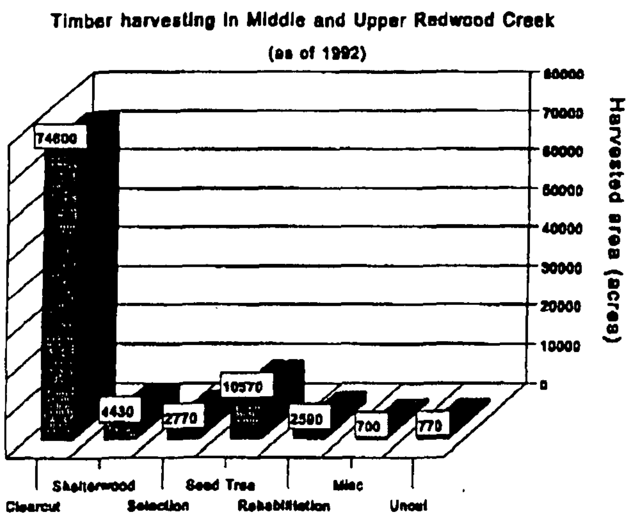
Past Timber Harvest and Road Building Practices

Forest Practice regulations - Forest practices on private lands are regulated by the California Department of Forestry and Fire Protection. Timber harvest regulation by the state began in 1945, but became more effective following passage of the Z'berg-Nejedly Forest Practice Act of 1973. This act established the Board of Forestry with authority to develop rules and guidelines for management of non-federal forest lands in the state. On August 25, 1975, following hearings and modifications of initial rules, forest practice rules that would guide timber harvest practices for nearly a decade became effective.

Although the Forest Practice Act of 1973 recognized forest values of recreation, wildlife, fisheries, and water quality, it emphasized the management, replenishment and maintenance of forest lands. Significant amendments became effective in October of 1983 that established watercourse and lake protection zones (WLPZs), new standards for logging roads and landings, and erosion control requirements. The WLPZs provided new definitions of streams based on their biological productivity and placed certain restrictions on timber harvest and heavy equipment operations in areas immediately adjacent to most Class I (fish-bearing) and Class II streams. Additional amendments to road construction and WLPZ rules have been added in the 1990s.

Past timber harvesting - Timber harvest has been the most widespread land use in the Redwood Creek watershed in historic times. Logging began as early as the 1850's, but commercial harvesting to supply markets outside the local area started in the 1930's. Early logging operations were localized along the southern margins of the lower basin where rail access had been developed. Typical harvest areas can be seen in Panther Creek, just upstream from the south park boundary where advanced second growth timber now exists. Early harvests consisted of large clearcuts, yarding was done with steam donkeys and logs were transported south by rail.

Large-scale logging in the basin began after the Second World War, when both tractors and gasoline-powered chain saws became available, and when the expanding post-war economy created a high demand for lumber (Janda and others, 1975). Logging during the 1950's was generally done by selective cutting, but clearcutting became the dominant silviculture in the 1960's as timber companies experienced poor success with thinning and natural reseeding (Janda and others, 1975). Tractor yarding has been used much more commonly than cable yarding. Intensive logging was concentrated in the upper-basin stands of Douglas-fir in the 1940's and 1950's but shifted to redwood groves of the middle and lower basins in the 1960's as redwood became more popular for home construction.



Only about 5 percent of the watershed area upstream of the confluence of Prairie and Redwood Creeks had been logged as of 1948 (Best, 1984). Approximately 62 percent of this area had been logged as of 1978 (Best, 1984) and over 85% of the conifer forests upstream from what are now park lands had been harvested (Figure below, and Table 8). Logging in the basin was most intensive between 1949 and 1962, when about 31 percent of the entire basin was logged (Best, 1984).

Prior to 1978, 95% of the logging in the middle and upper watershed consisted of clearcutting. Typically, clearcut logging consisted mostly of tractor yarding wide tracts of land, including entire subwatersheds and tributaries, in short periods of time (Janda et al. 1975). Over 90% of the yarding prior to 1978 was done by tractors (Table 8) which created widespread ground disturbance and disruption of natural hillslope drainage. The extent and intensity of historical ground disturbance caused by timber harvest and road construction in the Redwood Creek watershed has been extreme (Janda, 1977). By the mid-1970's not only had 60% of the watershed been harvested in a 25-year time period, but most harvesting consisted of sequential tractor yarded clearcuts hundreds of acres in size (Janda, 1977).

Logging from 1978 through 1995 involved smaller, more dispersed patch-cuts. Only 30% of the area logged during this period was clearcut (Table 8). During this time period, tractor yarding was still the preferred method for moving logs across the hillslope. Improvements in regulations have also resulted in operations that are better tailored to site-specific conditions. Increasingly, timber harvesting in the upper Redwood Creek watershed has been in advanced second-growth stands. Many areas have been logged two or more times, sometimes using different yarding techniques. The remaining old growth in the basin is scattered primarily as residual stands of seed trees and as small old growth stands in steep, unstable areas, such as inner gorge slopes along upper Redwood Creek and along its major tributary streams (Janda 1977).

Few remaining old growth forest areas remain in the middle and upper basin. Most large trees are those that remain from past seed tree harvests. Most future harvesting will occur in areas of second growth forests and hardwood forests that have grown since the initial old growth harvesting. The legacy of past land use, including widespread tractor logging and road construction, will still influence sediment production from these areas, as will the advent of reentry, harvesting and road reconstruction. Studies in the lower Eel River basin suggest that landslide rates in recently harvested second growth areas underlain by Franciscan bedrock are more common and larger than those in areas of advanced second growth forests (PWA, 1998). Pitlick (1982) found that slides in managed areas were no more common but were larger than those in uncut inner gorge slopes. Both studies suggest that second growth logging of steep inner gorge locations will set the stage for additional sediment production by landsliding.

Recent harvesting (post-1978) - Timber harvest plans filed with the California Department of Forestry and Fire Protection since 1978 were analyzed to assess trends in logging since park expansion. During the period 1978-92, a total of 31,836 acres of private timberlands were logged in the Redwood Creek watershed. This total is equivalent to 18% of the entire watershed area, or about 30% of the 108,000 acres located upstream from the current park boundary. Of this total, 24,139 acres (76%) were logged using intensive silvicultural methods that remove all or almost all trees from most logged areas (Table 8). Over 26,200 acres were logged using tractor yarding methods, which causes greater ground disruption than other yarding methods (Table 8).

Roads - Roads are a major cause of accelerated erosion (Kelsey et al. 1981; Hagans and Weaver, 1987; Weaver et al. 1995). The erosion potential of roads is related to maintenance, location, and design (Janda et al. 1975; Best, 1984; Klein, 1987). Common erosion problems associated with roads include stream diversions at stream crossings, stream crossing washouts, failure of unstable fills and sidecast materials (along roads and landings), triggering of native hillslope failures, failure of undercut cutbanks, and interception and diversion of surface and subsurface water by cutbanks and inboard ditches. Poor road location and construction methods, and inadequate road maintenance, have been identified as the source of some significant accelerated erosion and sediment yield experienced in the basin (Janda et al. 1975; Pitlick 1982; Hagans and Weaver 1987; Weaver et al. 1987, 1995).

About 1,200 miles of forest roads and 5,400 miles of skid trails were built within the Redwood Creek watershed as of 1978 (Best 1984). Another 127 miles were constructed between 1978 and 1992 (Table 8). About 300 miles of roads and 3,000 miles of skid trails were included within present park boundaries as a result of park expansion in 1978 (Steensen and Spreiter 1992). In Roads

Table 8. Timber harvest and related land use in the Middle and Upper Redwood Creek basin - pre-1978 and 1978-1992[3] (Best, 1984; RNP written comm., 1995)			
Cutting Method	Land use data as of 1978 (acres)	Land use data from 1978-1992 (acres)	Land use data (total acres)
Uncut conifer forest	9,910	770	770
Clearcut	65,485	9,140	74,625
Shelterwood	unknown (unk)	4,425	4,425+
Selection	2,770	0	2,770
Seed Tree	unk	10,575	10,575+
Rehabilitation	unk	2,590	2,590+
Miscellaneous clearing	700	NA	700
TOTAL CUT	68,955	26,730	95,685
Yarding Method			
Tractor	62,645	26,260	88,905
Cable	5,610	3,730	9,340
Tractor/cable	700	1,820	2,520
TOTAL	68,955	31,810	100,765
Road Construction and usage in THP's		Road length (miles)	
New	unk	127	
Rebuilt	unk	111	
Existing	unk	236	
Streams and stream crossings in THP's			

[3] From 1993 through 1997, an additional 7,700 acres of timber harvesting occurred in the watershed. The bulk of the new harvesting consisted of clearcutting (1,790 acres), rehabilitation cutting (1,528 acres), seed tree removal (1,388 acres) and alternative prescriptions (1,168 acres). Of this harvesting, 4,857 acres were tractor yarded, 1,144 acres were cable yarded, 935 acres untilized a combination of cable and tractor yarding, and 705 acres were yarded by helicopter. Twenty nine miles of new road was built and another 29 miles of old road was reconstructed. 102 new stream crossings were constructed, and 113 were reconstructed.

Streams (miles)	unk	381	
Stream crossings (#)	unk	1,421	

Roads upstream of the park boundary as of 1992 totaled about 1,110 miles[4] (Figure 2). About 66% of these road miles were constructed before 1964, 14% were constructed between 1964 and 1978, and 20% were constructed between 1978 and 1992 (Figure 3; Table 9). Because 80% of the roads in the Redwood Creek watershed were constructed before 1978, most have been built to lower standards than those of the present forest practice rules as amended in 1983. Of the total 1,110 miles of roads upstream of the park, about 65% were judged to be drivable as of 1992 (Table 10). Approximately 55% of the roads in the basin are not maintained. These unmaintained roads are more likely to fail during a large storm than the maintained roads as a result of plugging and rusting of culverts, undersized culverts, failure of unstable fills and diversion of streamflow (LaHusen 1984; Hagans et al. 1986; Hagans and Weaver 1987; Weaver et al. 1995).

Table 9. Roads in the Redwood Creek Basin upstream from RNP as of 1992[5]

Age class	Middle Basin (PPZ) - (miles)	Upper Basin (miles)	Total (miles)
pre-1964	141	590	731
1964-1975	33	122	155
post-1975	59	167	226
TOTALS	**233**	**879**	**1,112**

About 75 percent of total road miles constructed upstream of the park is found on relatively gentle slopes of 50% or less, 18 percent were constructed on slopes between 50% and 65%, and 7 percent were constructed on slopes greater than 65% (Table 11). A significantly greater percentage of effectively abandoned roads are located on steep slopes, compared to maintained roads. About 5% of total road miles are in steep (>65%) inner gorge areas adjacent to stream channels where road failures are most common and the impacts of failures are most serious (Table 12). Of the 50 miles of roads constructed on steep inner gorge slopes in the middle and upper Redwood Creek basin, 43 miles (over 85%) had been effectively abandoned by 1992 and 32 miles (64%) were no longer driveable.

[4] Information on the road network upstream of the park is based on analysis of sequential aerial photographs and local field verification.

[5] From 1993 through 1997, an additional 29 miles of new seasonal and temporary roads have been constructed, and another 29 miles of road have been reconstructed, in the Redwood Creek watershed.

Roughly one-third of the road network upstream of the park has been constructed on notoriously unstable bedrock units such as the incoherent unit of Coyote Creek and the sandstone and melange unit of Snow Camp Mountain (Table 13). About 40% of the network was constructed

Table 10. Maintenance status of roads in the Redwood Creek Basin upstream from RNP as of 1992			
Maintenance status	Middle Basin (PPZ) - (miles)	Upper Basin (miles)	Total (miles)
Abandoned, not driveable	118	243	361
Effectively abandoned, but may still be driveable	49	157	206
Maintained	33	457	490
Unclassified	33	22	55
TOTALS	**233**	**879**	**1,112**

Table 11. Maintenance status of roads on inner gorge slopes in the Redwood Creek Basin upstream from R.N.P.			
Maintenance status of inner gorge slopes	Middle Basin (PPZ) - (miles)	Upper Basin (miles)	Total (miles)
Abandoned, not driveable	11	21	32
Effectively abandoned, but may still be driveable	6	5	11
Maintained	1	6	7
TOTALS	**18**	**32**	**50**

on "sensitive" soils that are susceptible to landsliding (81 miles), gully erosion (301 miles), or impaired drainage (15 miles)(Table 14). On average, nearly 80% of roads constructed on "sensitive" soils had been abandoned as of 1992, while only 52% of roads built on non-sensitive soil units were abandoned.

Table 12. **Maintenance status of roads in the Redwood Creek Basin upstream from Redwood National Park** (as of 1992)									
Maintenance status	Middle Basin (PPZ) (miles)			Upper Basin (miles)			Total (miles)		
	<50%	50-65%	>65%	<50%	50-65%	>65%	<50%	50-65%	>65%
Abandoned, not driveable	75	27	16	331	90	29	406	117	45
Abandoned, driveable	31	10	7	117	30	9	148	40	16
Maintained	47	7	3	198	35	9	245	42	12
Unclassified	0	0	0	5	0	0	5	0	0
TOTALS	**153**	**44**	**26**	**651**	**155**	**47**	**804**	**199**	**73**

Table 13. Maintenance status and geologic setting of selected roads in the Redwood Creek Basin upstream from Redwood National Park (as of 1992)				
Maintenance status	Road miles on selected geologic units (mi)			
	Coherent Unit of Lacks Creek	Incoherent Unit of Coyote Creek	Metasediments of the Grogan Fault zone	Redwood Creek and South Fork Mountain Schist
Abandoned, not driveable	53	146	28	303
Abandoned, driveable	17	77	5	92
Maintained	16	98	14	138
Unclassified	0	0	0	1
TOTALS	**86**	**321**	**47**	**534**

651 unstable, abandoned!

Table 14. Maintenance status of roads located on sensitive soils in the Redwood Creek Basin upstream from Redwood National Park					
Maintenance status of roads	Roads on sensitive soil units (mi)				
	Soils highly prone to mass soil movement	Soils highly prone to gullying	Soils with slow permeability and impaired drainage	All roads on sensitive soils	Non-sensitive soils
Abandoned, not driveable	38	185	5	228	290
Abandoned, driveable	16	56	4	76	108
Maintained	27	59	6	92	179
Unclassified	0	1	0	1	2
TOTALS	**81**	**301**	**15**	**397**	**579**

Based on records of Timber Harvest Plans (THPs) filed for commercial timber lands in the Redwood Creek watershed, a total of 127 miles of new roads were constructed and 111 miles of existing road was rebuilt for logging within THP units between 1978 and 1992[6]. In addition, 236 miles of existing roads were used for access and hauling. Rebuilt roads therefore represent almost one-quarter of total logging road mileage used during this period. The high proportion of roads and stream crossings that required rebuilding suggests that road failures have been frequent along these abandoned routes. Roads used for timber harvest during this period included over 1,400 stream crossings (Table 8). Roughly 50% of these crossings were on smaller Class III streams, and many required rebuilding due to partial or complete failure. From 1993 to 1997, another 102 new stream crossings were constructed and 113 were rebuilt on haul roads in timber harvest areas of the basin.

Although a more thorough and precise analysis of the maintenance status and condition of roads upstream of the park will require field inventories, the road analysis based on aerial photographs usefully indicates the extent of potential problems. On the basis of road maintenance status, hillslope gradient, geology, and soil types, stream crossing failures are likely to occur about one-third of the 1,110 road miles upstream of the park during any given large storm. Most roads in the watershed were designed under much less restrictive standards than exist today, and are thereby more susceptible to flood damage and potential failure. Only a small proportion of the present road network upstream of the park was constructed under existing Forest Practice Rules (Table 9).

Impacts of Past Practices and Large Storms

Basin response - A number of research studies conducted in the Redwood Creek basin by both the U.S. Geological Survey and the National Park Service have documented the response of hillslopes and stream channels to the combined effects of land use and storms (Janda et al. 1975; Harden et al. 1978; Pitlick 1982; Kelsey et al. 1978; Kelsey et al. 1995; LaHusen 1984; Hagans and Weaver 1987; Hofstra and Sacklin 1987; Iverson and Major 1987; Madej 1992; Nolan and Marron 1995; Walter 1985). The conclusion reached by researchers in the basin is that past land use has had a profound effect on erosion rates and sediment yield in the basin over at least the last three decades, and that these effects are persistent and recurring. Not only did land use have an effect at the time and location of the original disturbance, but that effect is often displaced in both space and time from the original land use disturbance. The Redwood Creek basin has been left with a legacy of past practices and their impacts (most of the watershed was cut and most of the roads were built prior to the modern Forest Practice Rules)(Hagans and Weaver, 1987).

[6] From 1993 through 1997, an additional 29 miles of new seasonal and temporary roads have been constructed, and another 29 miles of road have been reconstructed, in the Redwood Creek watershed.

Specific land use practices in the basin have caused multiple on-site and off-site geomorphic effects which will only become apparent years following the original land use disturbance (Janda 1977; Hagans and Weaver 1987). Different processes have contributed differently to total sediment yield (Table 15). This relative contribution of each sediment production mechanism also likely changes with location in the drainage basin (for example, upper basin fluvial sediment yields have been estimated to be significantly higher than in the lower watershed (Kelsey et al. 1981; NPS 1995)).

Table 15. Measured sediment sources in the <u>lower</u> Redwood Creek basin (1954-1980, excluding Prairie Creek (Hagans and Weaver 1987)

Sediment source	Volume (m^3)	Proportion of total yield (%)
Gullies	1,157,400	37
Eroded stream crossings	225,600	7
Surface erosion	124,400	4
Streamside landslides	1,600,000	52
TOTAL	3,107,400	100

In the undisturbed state, ***surface erosion*** in the basin was confined to natural sites of bare soil. These typically included active landslides, eroding stream banks and earthflow gullies. Extensive ground disturbance created by widespread tractor yarded clearcuts and road construction in the basin created extensive areas of bare soil, and erosion rates increased dramatically (Marron et al. 1995). Surface erosion processes are thought to have accounted for an estimated 4% of total sediment yield from the lower Redwood Creek basin from 1954-1980 (Hagans and Weaver, 1987).

Today, while ground disturbance from yarding activities is significantly lower than in the 1970's and 1980's, fine sediment production is still thought to represent a significant and deleterious process in Redwood Creek (Ridenhour and Hofstra 1994). Timber harvesting plans submitted from 1978 and 1992 showed there to be approximately 3.7 stream crossings for every mile of road in the basin. With over 1,100 miles of identified road (Table 9), there are likely in excess of 4,100 stream crossings and an estimated 100 to 385 miles of road-side ditch delivering runoff and eroded sediment directly to Redwood Creek and its tributaries.

Fluvial erosion associated with forest land use practices includes both stream crossing washouts and gully erosion. Research in the basin has shown that both processes are very important contributors to basin-wide sediment production and yield (Hagans et al. 1986; Weaver et al. 1995; Kelsey et al. 1981). In the lower basin, where fluvial processes are thought to be less important compared to the upper basin (Weaver et al. 1995), stream crossing washouts have been documented to account for approximately seven percent of total sediment yield from 1954-1980. Stream crossings typically erode and wash out during large storms when culverts plug, when undersized culverts are overwhelmed with flood flows, or when log crossings rot and collapse.

Detailed erosion inventories have clearly revealed certain land management practices to be the actual cause of at least 80% of the increased fluvial erosion in the lower watershed (Hagans and Weaver 1986). Studies throughout the basin have identified large gullies formed as a result of stream diversions at logging road stream crossings to be the single largest source of fluvial sediment production and yield in the basin (Kelsey et al. 1981; Weaver et al. 1995). Stream diversions trigger hillslope gullying, landsliding and scouring of natural channels. Large, individual gullies can deliver several thousand cubic yards of eroded sediment to local stream channels, and diverted streams can trigger landslides and debris torrents on steep inner gorge slopes. Diverted streams and increased sediment loads in natural stream channels often cause the receiving channels to undergo rapid downcutting and bank erosion. Road-related stream diversions are human-caused and easily preventable, provided efforts are made to locate and prevent their occurrence before a triggering storm event occurs.

The temporal distribution of ***streamside landslides*** in the Redwood Creek basin was first studied by Harden et al. (1978). Debris slides were seen to increase four-fold in number between 1947 and 1976, with most occurring between 1962 and 1966 (probably during the 1964 storm event). Similar, though less abrupt increases in landsliding were associated with subsequent storm events in the basin. Observations since 1978 suggest that few streamside landslides have been initiated in the relatively dry period since 1975. Landslides are thought to represent from 20% to over 50% of basin wide sediment production and yield during the three decade period of major land use and storms in the watershed (NPS 1995; Hagans et al. 1986; Weaver et al. 1995). As with fluvial erosion, they occur episodically, in response to large storm events.

A clear cause-and-effect relationship between land use and mass wasting is far more difficult to establish than for fluvial processes. Analysis of streamside landslides along the main stem of Redwood Creek (Kelsey et al. 1995) and along its major tributaries (Pitlick 1982) reveals that human influences have likely been significant. Both studies found that all the large, volumetrically significant landslides occur on steep slopes of the inner gorge adjacent to the main channel and its main tributaries. Pitlick (1982) found that the landslides associated with both roads and harvested areas along steep tributary inner gorge slopes were roughly equal in number to those in uncut areas but they accounted for nearly 80% of the total mass erosion. Landslides associated with roads accounted for 40% of the total mass erosion. LaHusen (1984), in an investigation of debris torrenting following a moderate size storm in the lower basin, found that debris flows were highly correlated with road construction in geomorphically sensitive terrain. The most suspect terrain included steep colluvial-filled swales, and inner gorge slopes located immediately below the major break-in-slope.

Although virtually all major instances of landsliding in the basin have been triggered by storm events, storms and logging together were found to be the causes of widespread landslide activity (Kelsey et al. 1995; Pitlick 1982; LaHusen 1984). These human influences are expected to continue to occur, both as a result of older harvesting, as well as continuing timber harvesting on steep inner gorge slopes throughout the basin. Because triggering storms have not occurred in the Redwood Creek watershed since 1975, streamside slopes have likely been "primed" for future failure by two decades of continued harvesting and road construction, and occassional moderate size storms. The effects of these continuing land use activities will not show until the next major storm and flood event.

Stream channel morphology along the main stem of Redwood Creek, as well as in tributary watersheds, has witnessed significant changes over the last four decades. The types of off-site impacts to stream channels that have been quantitatively documented include: 1) increases in the overall volume of stored sediment, 2) increases in the volume of stored sediment in "compartments" displaying long residence times, 3) increased incidence of bank erosion, and decreases in pool numbers (Madej 1992; Hagans et al, 1987).

Changes in channel geometry are not as persistent in steep, lower order tributaries (where stored sediment is quickly re-eroded and flushed), as compared to small streams on the hillslopes and low gradient main stem reaches. The lack of persistence is a result of high stream power and efficient sediment mobilization and transport in steep tributary streams (Pitlick 1982). These main tributary channels have stored between 5% and 30% of the sediment delivered to them during major storms (Hagans et al. 1986). In contrast, small channels on hillslopes may be permanently "gutted" or gullied by large increases in sediment transport or stream discharge caused by stream diversions. Similarly, low gradient main stem reaches can act as long-term repositories for eroded sediment which originated in upland watershed areas. This stored sediment can affect channel and valley morphology for centuries (Madej 1992, 1995).

In contrast to the steep tributary streams, the geomorphic effects of increased watershed erosion and sediment delivery to the main channel has had dramatic and persistent impacts on channel morphology. Pools have filled, gravel bars have widened, and sediment has been deposited on floodplains to accomodate this influx of sediment (Madej 1992, 1995). More sediment has been supplied to the low gradient main stem that it can successfully transport through the system. The most severe channel aggradation occurred in the upper reach, but this relatively high gradient section had removed roughly half the sediment deposited in the 1964 flood within 20 years. Residents in the upper watershed consistently report recovery of the upper main stem, where boulders that have been buried by sediment for 20 years are now emerging as the gravels are removed from the channel (Van Kirk 1994). The lowest gradient channel segments, those within Redwood National Park, are still aggrading and receiving sediment reworked from upstream reaches which are recovering (Madej 1992, 1995).

It is clear that widespread erosion and sedimentation, such as that which occurred during the 1964 storm, and of which over 40% has been associated with stream diversions at logging road stream crossings, can affect volumes of channel-stored sediment for many years to come (Hagans and Weaver 1987; Weaver et al. 1995). In fact, studies suggest that the persistence of recently deposited sediment in the upper reaches ranges from 25 to 100 years, and sediment in the lower basin is expected to remain in storage for up to 100 years, or more (Madej 1995).

Another indicator of changes in stream channel morphology brought about by increased watershed erosion is the occurrence of bank erosion. In one 18 mile lower-basin section of the main stem of Redwood Creek, for example, 51 locations of active bank erosion (erosion for over

20 linear feet of bank) were identified (Hagans et al. 1986). These sites were on relatively straight reaches where natural erosion is not typically expected. At 71% of these locations the channel remained wider for decades following the initial erosion. In lower Redwood Creek, where channel aggradation is still on-going, one bank eroded by 120 feet between 1973 and 1977 with little subsequent recovery. Channel changes in the lower main stem within Redwood National Park include widened channels, elevated and smoothed channel beds, reduced pool numbers and depths, reduced canopy, dead riparian vegetation, toppled alluvial redwood trees (at the Tall Trees Grove), and increased stream temperatures are expected to persist for many decades - until excess sediment has moved through the lower basin (Hagans et al. 1986).

In summary, hillslopes and stream channels within the Redwood Creek basin have responded in a variety of ways to both natural geomorphic processes and land use activities. Geomorphic processes, including both erosion and sedimentation, have been dramatically affected by human land use activities, especially forestry-related activities beginning in the 1950s. The nature, magnitude, causes and persistence of these effects have been thoroughly documented by a variety of researchers (Nolan et al. 1995). They include both on-site effects (at the location of the land use) and off-site effects (both downslope and downstream from the disturbance). Large storms have been the main triggering event for watershed change in Redwood Creek, and the geomorphic response of the landscape has manifested itself with both physical and biological changes. The resulting impacts are often displaced in both time and space from the disturbance event. Past land use practices continue to affect erosion and sedimentation processes in the watershed, and these effects are expected to continue to have a negative effect on both geomorphic processes and aquatic habitat for many decades.

Sum.

Aquatic and fishery resources - Outside of Prairie Creek, the main tributaries to Redwood Creek are short and steep. There is relatively little habitat available, in the best of conditions, for anadromous salmonids (Ridenhour and Hofstra, 1994). Brown (1988) found 58 miles of the mainstem and 50 miles of tributaries accessable to anadromous fish. Most of the tributaries have natural barriers close to Redwood Creek. In all locations, large amount of fines in the gravels and high rates of bedload transport are thought to have reduced the suitability of spawning habitat. Increased sedimentation has reduced nursery habitat by widening and shallowing summer flows, thereby increasing summer water temperatures and reducing cover. Riparian vegetation, reduced through direct harvesting or channel widening, has also affected stream temperatures (Ridenhour and Hofstra, 1994). Increased sediment transport and reduced organic debris, such as have occurred in Redwood Creek, can result in a reduction in cover, a potential reduction in macroinvertibrate food production available to fish and increased predation (Klein et al. 1987). Historical accounts of fish populations and channel conditions (Van Kirk 1994) suggest salmonid populations were still relatively high through the late 1960's, but that significant declines have since occurred.

Redwood Creek was already considered damaged and in poor condition in 1966 for the production of anadromous fish (Fisk et al. 1966; Denton 1974). Sixty-four of the 84 miles of stream in the watershed were considered "damaged." Ridenhour and Hofstra (1994) have identified upper basin logging and the channelization of lower Redwood Creek between flood control levees as the two most serious causes of impacts on fish habitat in the basin. Declines in fish populations have been partially attributed to poor land use practices that have changed the streams from "deep, tree-lined channels with frequent pools and long riffles carrying cool water" into streams that are "shallow, warm, and barren of streamside vegetation" (Denton 1974; Higgins et al. 1992). These conditions are especially prevalent in the lower basin where Redwood Creek passes through Redwood National Park.

Conclusion

Redwood National Park was established, in part, to provide permanent protection to the outstanding alluvial groves of the Redwood Creek basin. The designations of National Park, World Heritage Site and International Biosphere Reserve are testament to the Park's outstanding and unique natural resources. The health of the Park's most important alluvial redwood groves has been clearly linked to stream flow, sediment transport and channel morphology of the main stem of Redwood Creek, and these processes are most closely linked to events and conditions of the middle and upper drainage basin, beyond the protective boundaries offered by their national and international status (Nolan et al. 1995). In addition to the documented impacts to riparian resources and alluvial redwood groves, human activities have contributed to a substantial decline in the ability of Redwood Creek to produce and support its unique and diverse native fish population, including anadromous salmon and trout (Ridenhour and Hofstra 1994).

The Redwood Creek watershed is one of the most thoroughly studied drainage basins in the western United States. Several decades of scientific studies conducted by the U.S. Geological Survey, the National Park Service, and others have provided a clear picture of the current state of the basin and its stream channels; the nature, origin and level of continuing threats to park resources; the relationship between land use and downstream cumulative watershed effects; the connection between upper basin processes and events and lower basin impacts (including impacts on park resources); and the expected persistence of cumulative watershed effects. These studies, conducted on a number of topics and by a variety of researchers, continue to the present (e.g., Nolan et al. 1995). They provide a nearly unmatched scientific research record on the causes and effects of erosion and sedimentation processes throughout the watershed.

Suggested Erosion Prevention and Mitigation Measures

Background
A variety of research projects have been conducted in the Redwood Creek watershed over the last 20 years to identify practices that have been most responsible for accelerated erosion and downstream sedimentation. Field research, inventories and formal inspections have been conducted both on cutover lands within Redwood National Park as well as on private forest lands throughout the remainder of the watershed. Many of these investigations have focused on the causes and effects of land use related erosion and mass soil movement.

Some results, and the recommendations stemming from this research, have general and immediate application throughout the State and within the Coast Forest District on both private and public forest lands. These include the cause, effect and prevention of stream diversions at culverted road crossings, and erosion prevention techniques for treating temporary roads (especially the removal of temporary stream crossings). These and other measures have gradually found their way into the Forest Practice Rules. Other recommendations have not yet received general application or are more specifically targeted to the setting and problems of the Redwood Creek basin.

An ongoing program to review land use practices (primarily timber harvesting and related activities) upstream from Redwood National Park was initiated in 1976 and continues today. Part of this program includes an overall analysis of current land use practices and forest practice rules (as they continue to evolve) as well as the development of general and site-specific mitigations aimed at reducing cumulative watershed effects on downstream areas within the park. When land owner permission can be secured, NPS geologists or hydrologists attend pre-harvest field inspections to locate potential or on-going erosion sources and recommend prevention and mitigation measures to the landowner and/or Department of Forestry and Fire Protection for incorporation into the approved THP.

Intent and general requirements
Protection and mitigation measures outlined for the Redwood Creek watershed necessarily focus on minimizing surface erosion, gullying, and mass wasting which delivers fine and coarse sediment to all watercourses, as well as maximizing canopy retention and reestablishment and retention of large woody debris and large streamside trees and snags for eventual recruitment within riparian zones.

Road inventories - complete inventory and erosion potential analysis of forest and ranch roads historically used for timber hauling in the basin is a first step. Ideally, at least 10% of each ownership would be inventoried each year until all roads have been assessed. In cooperation with RNSP when possible, landowners should be encouraged to develop and implement cost-effective erosion prevention work along all roads. A prioritized list of roads for eventual closure and erosion-proofing which currently deliver or threaten to deliver large quantities of sediment to Redwood Creek or its tributaries should be the first product to come out of the road inventory.

Road upgrading - All existing all-season, seasonal and active temporary roads should be upgraded to current design standards as soon as feasible. Among other things, upgrading should include the following practices and standards:

1. replacing Humboldt log crossings and undersized culverts (even if they are currently functioning),
2. employing a minimum 24" culvert diameter for stream crossings, and a minimum 18" culvert diameter for ditch relief installations,
3. upgrading all stream crossing culverts to pass the 50-year flood discharge (using an accepted computational method),
4. eliminating diversion potentials at all stream crossings which display a diversion potential by dipping the road through the crossing or by installing a permanent "critical rolling dip" on the down-road hinge line,
5. installing trash barriers to prevent culvert plugging and downspouts to prevent outfall erosion (where conditions warrant),
6. excavating and removing unstable road and landing fill (sidecast) which could otherwise fail and enter a watercourse (as identified by a geologist), and
7. eliminating ditch contributions of water and sediment runoff to stream crossings by road outsloping, or the installation of up-road rolling dips or ditch relief culverts immediately adjacent each stream crossing.

Ideally, upgrading work on all roads would be completed in not less than 10 years. CDF should encourage landowners to employ temporary roads, rather than all-season or seasonal roads, that can be permanently or temporarily decommissioned following timber harvest operations.

Roads within WLPZ - roads and road segments located largely within a WLPZ (not including designated stream crossings) should be considered for eventual closure. Where a road must remain in the WLPZ, it should be upgraded and maintained to minimize erosion and sediment delivery to streams. Methods to be used include road rocking, outsloping, construction of rolling dips, installation of ditch relief culverts and downspouts, ditch armoring, excavation of unstable sidecast fill, bank stabilization and other methods.

Culvert sizing - Culvert sizing for all new, reconstructed or upgraded stream crossings on every all-season, seasonal and temporary road should include written peak flow calculations based on rainfall intensity data available from Redwood National Park. Discharge calculations and culvert sizing methods must employ standard, quantitative techniques. Culvert size should be based on barrel-full capacity or less (to allow for woody debris and sediment transport through the culvert at peak flows) and should not employ additional head-wall height in culvert capacity calculations.

Road inspection and maintenance - All roads should be classified as maintained or abandoned. Abandoned roads should be decommissioned (closed) as soon as possible on a schedule prioritized by potential sediment delivery to streams. All maintained roads should receive regular inspection and maintenance annually, during winter storm events, and following storms exceeding the 5-year recurrence interval (as gaged on Redwood Creek at Orick). Maintenance should include both preventive summer maintenance (winterizing) and winter storm maintenance. Inspections, and needed maintenance, should be performed on the following sites:

1. road and landing sidecast fillslopes (check for signs of potential instability)

2. road surface and ditch inspections (check for signs of concentrated runoff, erosion, sediment delivery to streams, and build-up of debris along ditches which could plug culverts),
3. ditch relief culverts (check for signs of plugging), and
4. stream crossings (check for signs of culvert plugging, undersizing, outlet erosion, and inlet plugging, as well as other signs of potential erosion or crossing failure.

Road closure (decommissioning) - Currently unused, unmaintained and/or abandoned roads (those which have not been used for hauling within the preceding three years) should either be brought up to current standards or proactively closed. The schedule for upgrading and decommissioning should be based upon erosion potential, as indicated by road inventories, and by logistical considerations. "High risk" roads identified in the watershed road inventory should be considered for permanent closure. Road closure techniques include complete stream crossing excavation, permanent surface drainage (by outsloping or construction of deep cross-road drains), and removal or stabilization of potentially unstable sidecast fill along roads and landings which could deliver sediment to a stream channel. All excavated spoil should be placed where neither runoff nor mass movement will cause it to enter a stream.

Full bench roads - Construct new roads as full bench roads, with all spoil endhauled to stable storage locations, where roads are to be constructed or reconstructed across steep (>50%) slopes which extend, continuously and without lessening, to a downslope stream channel. These conditions occur most commonly on approaches to stream crossings where hillslopes are steep (>50%) and along steep inner gorge slopes.

Unstable sidecast - Excavate all unstable or potentially unstable landing or road sidecast fill (including organic debris) resting on steep (>50%) slopes which extend continuously or have access to a stream channel. Unstable or potentially unstable sidecast fill may be found along roads of all ages. Unstable or potentially unstable sidecast fill is that which has been identified as such by a geologist or which shows evidence of scarps, cracks or other signs of potential failure.

Timber Harvesting and Related Activities

Harvesting on sensitive slopes - Defer or strictly limit timber harvesting on and within 400 feet up slope of *visibly unstable inner gorge slopes*, depending on site specific field reviews at the time of the pre-harvest inspection. Strictly limit harvesting on all *stable and potentially unstable inner gorge slopes* and on *steep (>50%) stream-adjacent slopes* along Class I and Class II streams. In these areas, utilize uncut buffers, light selection cuts, a combination of these, or other methods which retain understory vegetation and at least 75% of the existing basal area of overstory vegetation, especially conifers, with re-entry intervals not less than 10 years apart.

Tractor yarding - Tractor yarding should not occur on slopes exceeding 50%, except on existing stable skid trails (those not requiring physical reconstruction) as inspected and approved during the pre-harvest THP field inspection. No new skid trails should be constructed on slopes exceeding 50%.

Winter operations - There should be no winter period operations within the WLPZ except at designated crossings that are rocked or surfaced, and that remain stable. Only surfaced roads may be used during wet winter periods. A detailed, site-specific winter operating plan should be submitted for any proposed winter operations which describes adequate sediment control measures for the road surface and for each crossing. All hauling operations should immediately cease when turbid road or ditch water enters a stream. There should be no wet winter period tractor operations, or road or landing construction or reconstruction (except as required to prevent erosion and sediment delivery to streams).

Professional Forester responsibilities - All harvesting, yarding, and road building operations conducted on slopes over 50% or within a WLPZ should be overseen by the responsible Registered Professional Forester (RPF). The RPF should be responsible for personally meeting with the Licensed Timber Operator, prior to commencement of any harvest or road road-related operations, to discuss requirements outlined in the THP.

Stream Protection

A. WLPZ on steep (>50%), unstable slopes - Extend the watercourse and lake protection zone which crosses landslides or visibly unstable slopes to above the upper limit of observed instability. All trees on the unstable slide mass, and within 50 feet of the upper limit of observed instability should be retained and left uncut. Any management-related water sources to unstable areas should be eliminated.

B. Broad cast burning - Watercourse and Lake Protection Zones on Class I or Class II streams should not be broadcast burned.

C. Watercourse and Lake Protection Zones (WLPZ) - The WLPZ for all Class I and Class II streams should include inner gorge slopes (slopes exceeding 65% which extend to the stream) and steep, unstable stream side slopes (>50%).

D. Class III watercourse protection - Class III watercourses should be protected with a WLPZ using the same requirements as for Class II watercourse protection (14CCR916.5 and Table 1, 14CCR916.5). Class III watercourses which exceed 65% slope gradient should be inspected by a geologist, evaluated for debris flow potential and protected from harvest and road construction if slopes are deemed unstable or potentially unstable.

E. Temporary stream crossings - All temporary stream crossings should be removed by October 15 of each year, or they should be designed to accommodate the 50-year flood discharge.

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