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A CLIMATOLOGICALLY-BASED ANALYSIS OF THE STORM AND FLOOD HISTORY OF REDWOOD CREEK

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ABSTRACT

The intent of this study is to place the recent flood history of Redwood Creek in a long-term perspective and to discuss the expected frequency of major storms and their associated flooding in north coastal California. The occurrence of the recent storm sequence (1953-1975) was the local consequence of a major hemispheric circulation switch from zonal to meridional flow. The high frequency of major storms since the switch, which occurred about 1950, is a normal result of circulatory persistence. Events such as those of December of 1964 and the winter of 1972 are a normal and permanent part of the area's climate. The anomalous, more moderate climate of the early to mid-20th century (1915-1950) is likely to have biased the region's discharge statistics. More realistic expectations can be gained if the entire record of the past 600 years is examined. During that period, the average recurrence interval of December 1964 magnitude storms is estimated to have been 45-50 years, while the recurrence of December 1955 size storms is estimated at 25-30 years. Redwood Creek floods with discharges of 1,420 cms (50,000 cfs) or larger at Orick are estimated to have had a recurrence interval of 10-12 years.

The current atmospheric circulation patterns are meridional in nature. They resemble those of the mid-19th century, and are conducive to the occurrence of precipitation extremes. It is highly probable that these patterns, or ones like them, will remain in place until at least the end of the century.

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I. INTRODUCTION

This paper discusses the recent flood history of Redwood Creek from a long-term (600-year) perspective. It deals primarily with extreme events, and does so from the position that the creek's discharge record is too short (28 years) to be effectively analyzed using traditional statistical methods. A historical, process-oriented analysis is adopted instead. The geomorphic area covered by the study is shown in Figure 1.

The Redwood Creek watershed covers an area of 720 km². The main channel is 108 km long, flowing northwest from its headwaters near Board Camp Mountain into the Pacific Ocean near the town of Orick. The elevation drop is about 1,550 m. The highly elongated basin (rarely more than 11 km wide) is a result of the structural control exerted by the Grogan fault, which bisects it. The climate is Mediterranean, with 90 percent of its rainfall occurring between October and May. Estimates of average annual rainfall range between 70 and 80 inches, with snow rarely falling except at the higher elevations. Detailed discussions of these and other basin characteristics can be found in Janda and others (1975).

Between 1953 and 1975, Redwood Creek experienced a series of large flood events (Table 1). These floods, and especially the December 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 of regional extent, and similar changes have occurred throughout northwestern California (Waananen and others, 1971; Lisle, 1981). For many years prior to these events, the climate of northwestern California was relatively benign. Localized flooding occurred, some of it quite severe, but no major, region-wide storm event had occurred since 1890 (Harden and others, 1978). The existence of this benign interval, followed by one of such concentrated storminess, raises questions concerning how representative the events of the last 30 years have been of the area's overall hydrologic regime.

Through a study of regional climatology, the long-term frequency of major storms and the extent to which currently available discharge statistics for Redwood Creek afford a realistic description of its actual runoff regime are analyzed. I will also assess the nature of the region's current climate, and make qualitative, predictive statements about future impacts.

A significant portion of the study involved a review and analysis of the climatological literature. Paleoclimatic reconstructions are also reviewed, along with the evidence for past major flooding. The results of these discussions are focused on Redwood Creek through the use of regional analyses of modern precipitation and discharge records.

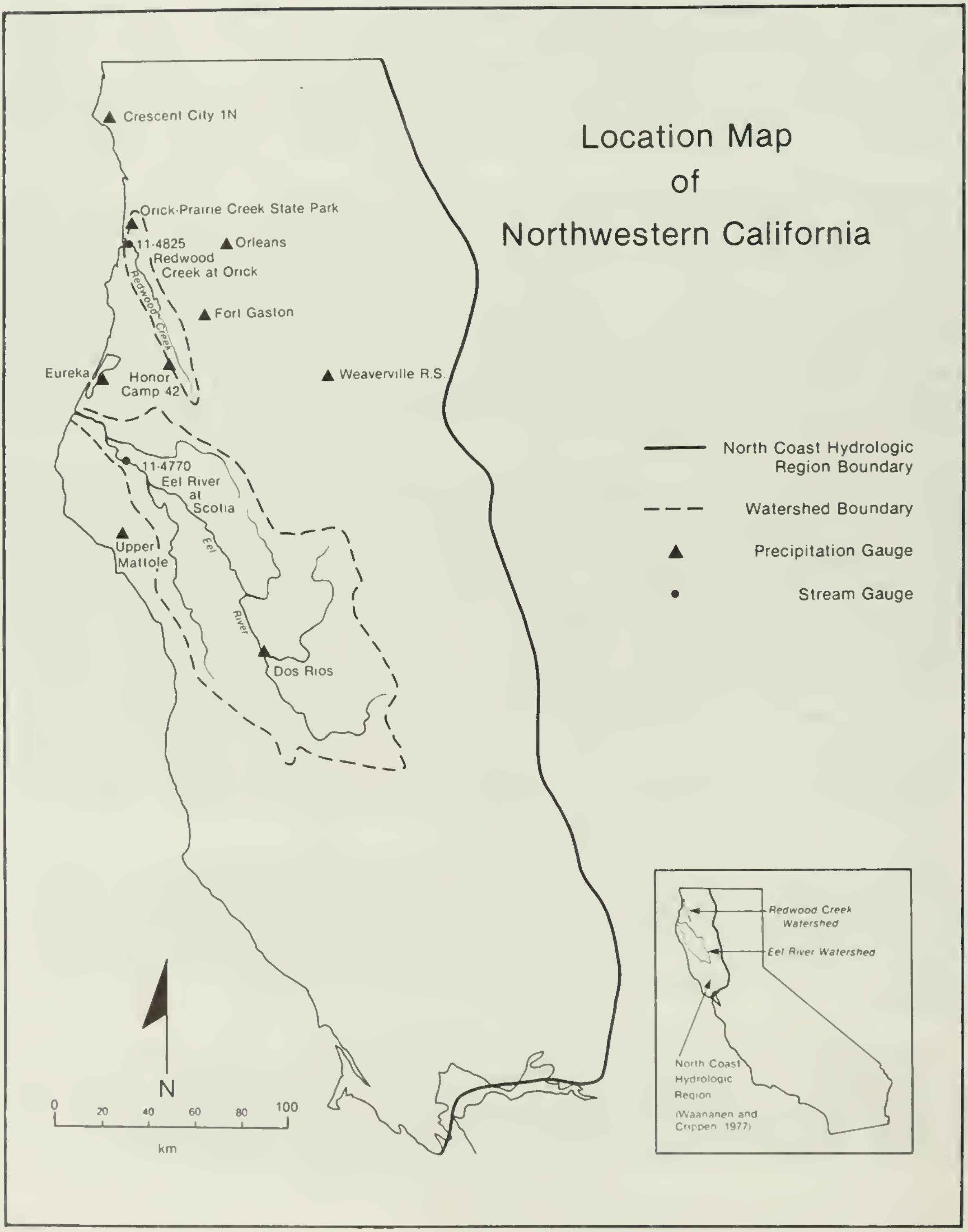


Figure 1. Location map of northwestern California.

TABLE 1

PEAK DISCHARGES DURING MAJOR STORMS
IN THE REDWOOD CREEK BASIN,
1950 - 1980

(Data from Table 4, Harden _et al._, 1978)

Date	Redwood Creek at Orick CFS*	Redwood Creek at Orick CFS/mi²
January 18, 1953	50,000	180
December 22, 1955	50,000	180
December 22, 1964	50,500	182
January 22, 1972	45,300	163
March 3, 1972	49,700	179
March 18, 1975	50,200	181

* Cubic feet per second

II. CLIMATOLOGY

A. Introduction

The climate of northern California is a consequence of interactions between the eastern Pacific high and low pressure centers. In the summer the region is dominated by high pressure, and disturbances are diverted to the north. In the winter the high pressure weakens and moves southward, allowing storm systems generated in the North Pacific to penetrate inland. The result is the highly seasonal rainfall regime and mild temperatures of a Mediterranean-type climate (see Janda and others, 1975, for a more complete discussion).

B. Teleconnections

During much of this paper, climatological data from other areas are used to infer local behavior relevant to northern California. This is possible because the circulatory state of the North Pacific is related in a regular and consistent way to the rest of the northern hemisphere. Such relationships are known as teleconnections. These relationships have been demonstrated statistically, primarily through the establishment of spatial cross-correlations in the character of large-scale, long-period pressure fields (Wallace and Gutzler, 1981). There are also theoretical reasons for these correlations, but most of the evidence for them is observational. As examples, pressure in the region of the Icelandic Low is negatively correlated with that of the Aleutian Low (Angell and Korshover, 1974). Downstream 500 mb heights have been observed to be preferentially influenced by heights in the Aleutians five days earlier (Edmon, 1981). Numerous well-documented teleconnections between the North Pacific circulation patterns and those downstream over eastern North America have been outlined by Douglas and others (1982). Such correlations are numerous and world-wide, and hold for contemporaneous rainfall, sea-surface temperature, and pressure variations, as well as for pressure alone (Barnett, 1977). Thus when major climatic shifts occur, the entire system changes.

Two such relationships are directly applicable to the extrapolations of this study. First, strong relationships exist between the contemporaneous circulation patterns of the North Pacific, and Europe and the North Atlantic. For example, Van Loon and Rogers (1978), and Rogers and Van Loon (1979), using data from 1840 to 1977, demonstrated that under conditions that occurred with significant frequency (40 percent of the time), winter sea level pressure anomalies and wind patterns over Europe and the North Atlantic were strongly correlated with those in the North Pacific. In addition, Treidl and others (1981) imply that the two areas in the northern hemisphere most likely to experience simultaneous high-pressure blocking are the Eastern Pacific-Alaska-Yukon-Canada region and the North Atlantic. Secondly, Schell and Sabbagh (1975), Sorkina (1975), and Angell and Korshover (1974), demonstrate a consistent synchroneity in the time-series trends of changes in the Atlantic and Pacific circulation centers. For example, decadally-averaged pressures in the Icelandic and Aleutian Lows tend to rise and fall in unison. Thus, given a knowledge of downstream conditions in Europe and the North Atlantic, one can make valid generalizations about those in the North Pacific.

C. Persistence

Persistence refers to the tendency for one large-scale climatic or circulatory state, and its associated weather patterns, to consistently dominate a region. The duration of this dominance can be more than a few years and is sometimes on the order of decades. Douglas and others (1982) specifically demonstrate persistence for the North Pacific and North America.

The mechanisms producing persistence appear to be strongly related to interactions between the atmosphere and the oceans. Most of these interactions involve the storage and exchange of heat. The long-term time scale of oceanic change, and the existence of positive ocean-air feedback mechanisms that reinforce existing sea-surface temperature (SST) distributions, are other major mechanisms of influence (Namias, 1972). A considerable amount of climatological research on the ocean/air system has been concentrated in the North Pacific, and bears directly on northern California storms. As examples, significant correlations have been shown to exist between Pacific SST distributions and west coast rainfall (Markham, 1979; McGuirk, 1982). Above normal heat flux over the eastern North Pacific is associated with below normal 700 mb heights there and over western North America (Clark, 1981). Although recent work continues to point out that the exact physical relationships between the SST and atmospheric circulation patterns are still unclear, there is no doubt they exist.

One key to persistence is that changes in SST distributions, and hence their effects on the atmosphere, are slow. The nature and scale of these changes can be illustrated by the following chain of events in the North Pacific (Namias, 1972; Rogers, 1976; Douglas and others, 1982). A relatively stable distribution of SST's existed for about a decade between 1948 and 1957. This regime changed completely in 1958. The new regime lasted another decade or so, changing again around 1969. The average atmospheric circulation patterns for the two regimes were different and have been statistically linked to the SST distributions. Rogers (1976), for example, found that in the Gulf of Alaska, a warm SST was associated with a mean pressure 8 millibars below average. Since 1969 the North Pacific has cooled appreciably, and contemporaneous and predictable changes in the circulation there and downstream over North America have occurred (Douglas and others, 1982).

World-wide SST relationships analogous to atmospheric teleconnections have also been shown to exist (Chiu and Newell, 1983). These relationships have been observed since 1861, the beginning of the data set. Furthermore, atmospheric circulation phenomena at the hemispheric scale, specifically the Southern Oscillation, have been linked to the SST distributions (Chiu and Newell, 1983). Changes in this system occur even more slowly than those noted above for the North Pacific. For example, Fletcher (1978, 1979) identified four coherent periods in his data set: pre-1870, 1870-1900, 1900-1940, and post-1940. These studies provide additional evidence that the ocean and air systems are coupled.

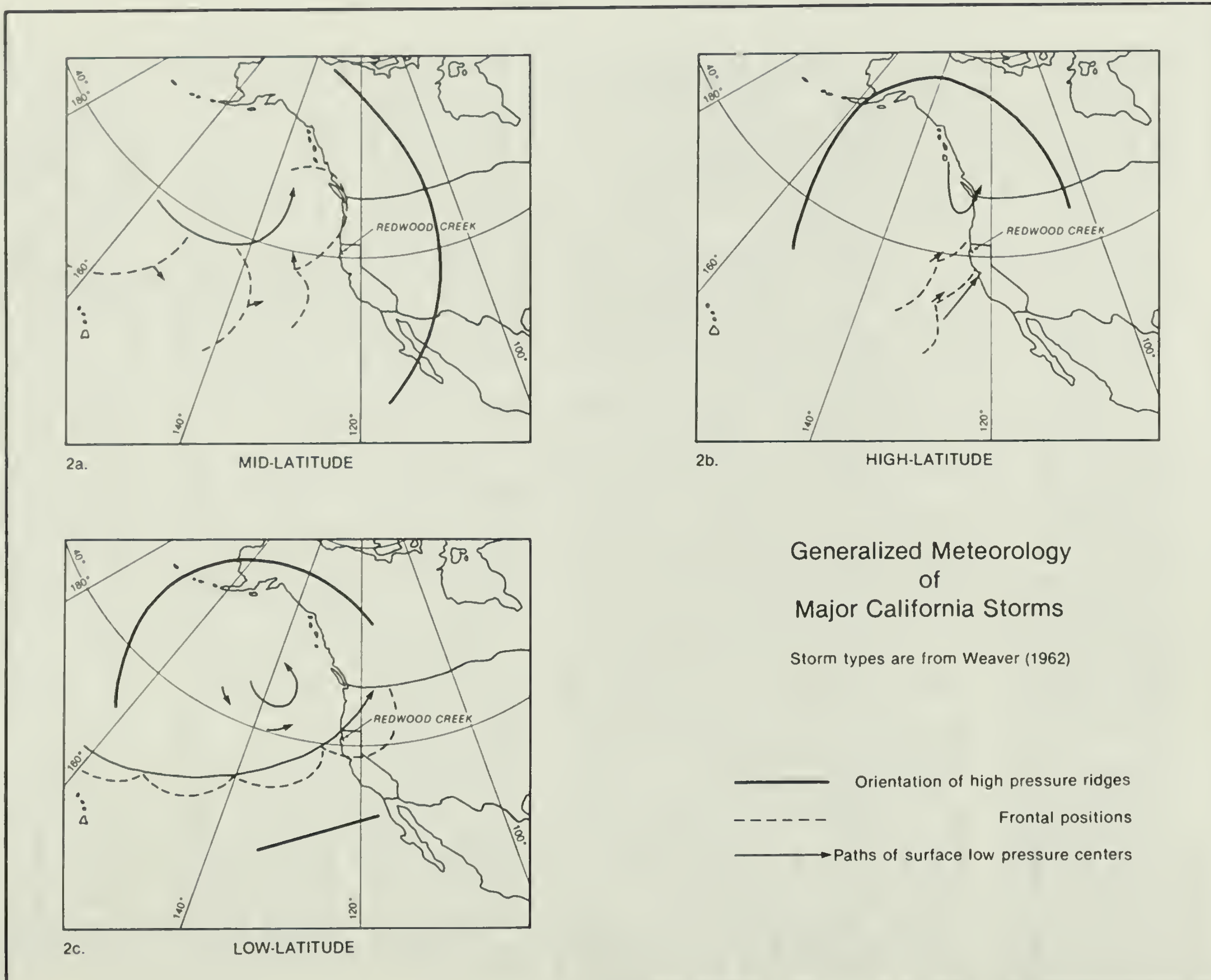


Figure 2. Generalized meteorology of major northern California storms. Storm types are from Weaver (1962).

D. High-Magnitude Storm Meteorology

There are three basic types of major storms in California. They were first characterized by Weaver (1962), and named according to the direction from which they approach the coast: high-latitude, mid-latitude, and low-latitude. Each type differs in their place of origin and in the configuration of the controlling general circulation (for example, the pattern of the upper level air flow and the distribution of the high and low pressure areas). However, in all of them, the occurrence of highly intense precipitation depends on the presence of a strong flow of moist air from low latitudes (as opposed to the polar regions). Figure 2 contains generalized meteorological maps of each storm type, as they commonly occur in northern California. Specific examples of each type, and the resultant peak discharges on the Eel River at Scotia (Figure 1), are presented in Table 2.

TABLE 2

EXAMPLES OF THE NORTHERN CALIFORNIA STORM TYPES ILLUSTRATED IN FIGURE 2*

Storm Type	Date	Peak Discharge, Eel River at Scotia (CFS - Date)	Comments
High-Latitude	Jan. 20-23, 1943	315,000-01/21/43	Mid-latitude breakthrough sub-type of Weaver (1962)
Mid-Latitude	Dec. 9-11, 1937	345,000-12/11/37	Highest recorded peak prior to the storm of December 1955 (record begins 1911)
Low-Latitude	Dec. 18-24, 1955 Dec. 19-26, 1964	541,000-12/22/55 752,000-12/23/64	The meteorological patterns of these two storms were very similar; peak discharge of December 1964 is the highest recorded.

* - Data from Weaver (1962), California Department of Water Resources (1966), and U.S. Geological Water-Supply Papers.

Synoptic events related to the storms of Jan. 1943 and Dec. 1955 are discussed in detail by Weaver (1962). The Dec. 1964 storm is discussed by the California Department of Water Resources (1966).

High latitude storms originate in the Gulf of Alaska and travel south down the coast before turning inland (Figure 2b). They are surrounded on three sides by a ridge of high pressure that effectively blocks and diverts the normal westerly airflow and confines the storm's movements. Because the air is of polar origin, it is relatively dry, and the occurrence of high precipitation in most of these storms depends on the inducement of a flow of moist air from the south. Since these constraints cause most of them to be centered in the southern part of the state, severe high-latitude storms are relatively rare in northern California.

Low-latitude storms, like the high-latitude type, are characterized by a broad, crescent-shaped ridge of high pressure over the central North Pacific and Alaska (Figure 2c). However, instead of originating in the Gulf of Alaska, their area of origin is in the western Pacific. As they move eastward they are diverted around the high pressure ridge generally just north of Hawaii, and from there they move northeastward towards the coast. These storms, and the floods associated with them, have historically been the most severe. This severity results first, because low-latitude storms are the most likely to be accompanied by strong flows of moist tropical air and, second, because low pressure centers from the Gulf of Alaska often migrate southward during the storms and promote the maintenance of a coastal low pressure trough. This latter development insures a higher probability of further storm development and of continued advection of moist air from the south and southwest. For example, it was the smaller, southward moving storms generated in the Gulf of Alaska at the beginning of the 1955 storm that primarily determined the circulation patterns responsible for its most intense, flood-producing rainfall (Weaver, 1962).

Mid-latitude storms are not associated with the Pacific high pressure ridges. Instead, the North Pacific is dominated by widespread areas of low pressure, with cyclones (low pressure areas) moving eastward in a relatively straightforward manner (Figure 2a). Although the air masses comprising these storms are originally of polar origin, they can be extensively modified during their passage over the Pacific, and their moisture content on arrival at the coast may approach that of tropical air. In addition to the example given in Table 2, the January 1953 storm (Table 1; Hughes and Row, 1953), was also of this type.

The occurrence of one type of storm versus another is a function of the prevailing state of the general circulation (Weaver, 1962; California Department of Water Resources, 1966). Two major patterns can be distinguished (e.g. Lamb, 1972a). The first occurs when the mid-Pacific high pressure centers are absent, and the west-to-east airflow (the mid-latitude westerlies) continues more or less without interruption. Such airflow, termed zonal flow, tends to favor the occurrence of mid-latitude storms. In contrast, meridional flow occurs when the westerlies develop a large north-south component. This type of flow favors the high and low latitude storms. The terms meridional and zonal are also used in an analogous manner to describe world-wide circulation patterns. In that context they function as large-scale averages, and refer in a spatially-integrated way to the predominance of one type of flow over another. For example, one northern hemisphere winter might be characterized as being meridional, another zonal. The first may have experienced many mid-latitude blocks, the second very few. During the rest of this paper the terms zonal and meridional will be used in this larger-scale context.

E. Climatic Intervals of the Last Century

There have been three general types of circulation patterns since 1900 (Table 3). The first was a period of meridional flow that ended in the early part of the century. The second was a sustained period of strong zonal flow that lasted until the early 1950's. The third is a post-1950 period of strong meridionality. Contemporaneous changes in the nature of weather patterns have also been noted (last three entries in Table 3). The timing of these intervals is consistent with those observed in the world-wide SST and wind field distributions observed by Fletcher (1978, 1979).

The specific wintertime circulation changes occurring during this period in the North Pacific have been partially documented by Sorkina (1963). His study covered 1899 to 1939 and 1954 to 1959. As part of the study he observed and classified a blocking circulation pattern similar to that occurring during the high and low latitude storms. It consisted of a continuous ridge of high pressure, stretching south from the Aleutians at 175° west and splitting the Aleutian Low into two distinct cells. The frequency of this pattern during the winter (November-February) between 1899 and 1911 was 10.7 occurrences per year. From 1911 to 1939 the frequency was only 4.3. The transition between the two periods was very sharp. The 1954-1959 frequency was 7.4. Consistent changes in the occurrence of the zonal circulation types were also noted. Beginning in the early 1920's and lasting until at least 1939, the zonal types became increasingly important. This correspondence between the observed local North Pacific circulation changes, and those implied by changes in world-wide indices, is taken to mean that the meridional-zonal-meridional progression observed on a hemisphere-wide scale also occurred in the north Pacific. This leads to the conclusion that these world-wide indices provide valid insights into the processes affecting the occurrences of severe northern California storms.

The contrast of the period 1950-1975 with the relatively storm-free period preceding it is one of the outstanding characteristics of the northwestern California discharge record (Harden and others, 1978). From the early part of the century until around 1950, the circulation conditions in the North Pacific were not generally conducive to the generation of extreme storm events. Since 1950, however, storm conditions have been much more prevalent. This has resulted from increased Northern Pacific, and hemispheric, meridionality. The duration of these periods is not viewed as unusual, but rather as the normal result of circulatory persistence.

TABLE 3

LATE 19TH AND 20TH CENTURY CLIMATIC INTERVALS

Source	Method of Analysis	Interval	Comments
Dzerdzeevskii (1966, 1969)	Classification of daily circulation maps, northern hemisphere.	1900-1920's	Merdional circulation.
		1920's-1950's	Zonal circulation.
		Post-1950's	Meridional circulation.
Lamb (1972b)	Classification of daily circulation maps, British Isles.	1875-1900 (Approx.)	Blocking predominant, westerly zonal circulation type less frequent.
		1900-Approx. 1954	Zonal westerly type very prevalent.
		1955-1972	Blocking predominant.
Kutzbach (1970)	Eigenvector analysis of mean January and July sea-level pressure maps, northern hemisphere.	1900's-Early 1920's Early 1920's-Early 1950's Early 1950's-1970	Analysis mostly mathmetical, interval circulation patterns noted as being different.
Kalnicky (1974)	Eigenvector analysis of Dzerdzeevskii's classification time-series.	Pre-1950	Zonal circulation.
		Post-1950	Meridional circulation.
Makrogiannis and others (1982)	Calculation of a zonal index between 35 and 55 degrees north, 10-60 degrees west.	1873-1905	Comparatively low frequency of westerly zonal circulation.
		1906-1939	Very high index, complete contrast with first period.
		1940-1972	Consistently low zonal index; 1962-1972 characterized by blocking; post-1950 January index very low.
Yamamoto (1975)	Classification of summer monsoonal climate in Japan.	1891-1910	Cool-rainy.
		1911-1950	Hot-dry.
		1951-1970	Cool-rainy.
Diaz & Quayle (1980)	Statistical analysis of areally-weighted monthly mean temperatures for the contiguous U.S.	1893-1920	Cool.
		1921-1954	Warm.
		1955-1977	Cool.
McGuirk (1982)	Eigenvector analysis of West Coast (U.S.) precipitation records.	1890-1904	Generally higher precipitation in northern regions, high variability.
		1905-1945	Low variability, generally lower precipitation in northern regions.
		1945-1975	Almost precisely the same statistical properties as the first period.

F. Climatological Summary

The climate of northwestern California is determined by the character of the atmospheric circulation patterns occurring over the north Pacific Ocean. These patterns fall into two general categories. Meridional circulation, characterized by the presence of high-pressure blocking and significant north-south air movement, is conducive to the development of severe northwestern California storms. Zonal circulation, characterized by more or less unobstructed east-west airflow, is not. These patterns can be related on a larger scale to those occurring elsewhere via the spatial cross-correlations known as teleconnections. As a result, world-wide circulation indices provide valid insights into the north Pacific circulation behavior. This behavior is also influenced by the spatial distribution of sea-surface temperature, which tends to produce climatic persistence. On a hemispheric scale, and in the north Pacific, a switch from zonal to meridional circulation dominance occurred about the early 1950's. The local result was the occurrence of the major storms outlined in Table 1.

III. PALEOCLIMATOLOGY

A. Introduction

A considerable amount of research has been conducted on the paleoclimatology of western North America. The results of these studies have a direct bearing on questions concerning the frequencies, magnitudes, and persistence characteristics of northcoast storms. Two types of paleoclimatological studies are particularly useful in placing the 20th century climatic record in a long-term perspective. The first deals with the world-wide circulation events implied by the occurrence of the Little Ice Age, and the second concerns the results of analytical dendrochronology. The emphasis in both discussions will be events of the last 500-600 years.

B. Little Ice Age Climatology

The world-wide climates of the centuries immediately prior to this one were dominated by a partial return to glacial conditions. This period, known as the Little Ice Age, began about 1500 A.D. and may not yet be over (Denton and Karlen, 1977). The climate of this period was characterized by great extremes of weather, intense storms, generally cold conditions, and widespread glacial advances. These phenomena were in turn associated with much high-pressure blocking, and large north-south components in the mid-latitude westerlies; in other words, the circulation was in large part meridional. For most of the world, the peak of the Little Ice Age occurred about 1700. Amelioration of these conditions began in the late 19th century, foreshadowing a period of widespread glacial retreat in the first half of this century (Lamb, 1977, 1979, 1982a).

A definitive understanding of the Little Ice Age climatology of northwestern California is hindered by the lack of direct observational data. The closest long-term homogeneous data come from Japan. These data concern trends in weather extremes and are consistent with the European record, specifically England, since at least 1400 (Yamamoto, 1975). Comparable climatic observations were not made in the United States until the mid-1500's (Ives, 1954; Ludlow, 1966). Most of the early observations are descriptive rather than instrumental, and are found in the form of letters, diaries, mission records, newspaper accounts, and so on. The instrumental record in the U.S. is largely confined to the past 100-150 years (Wahl, 1968). This is especially true west of the Mississippi (Bradley, 1976). California, since it was settled late, has very little data of any kind prior to about 1800. The first sustained weather observations in California were not made until 1837-41, by the Russians at Fort Ross (Roden, 1966). The first instrumental record in northwestern California did not begin until 1854 (at Fort Humboldt, 5 km south of Eureka, Figure 1). Because of this scarcity of data, insights into the area's climatological processes must be gained from other sources.

One of the best sources of paleoclimatic evidence is the record left by the Sierra Nevada glaciations (e.g. Curry, 1969). Three major points are evident. First, the latest period of climatic degradation began around 1250 A.D. This corresponds to the initiation of the European climatic transition, noted by Lamb (1982a) as beginning around 1200 A.D. Second, the major advances of the Sierra glaciers began around 1550, with wetter conditions becoming prevalent somewhat earlier. This corresponds to the generally accepted starting point of the Little Ice Age climatic dominance. Third, Curry's (1969) comparison of historical data from North Africa, Europe, and the western Soviet Union shows that periods of climatic extremes in those locations generally occurred within 20 years of similar occurrences in the Sierra Nevada. These three points demonstrate the essential synchroneity of California's recent climatic trends with the rest of the northern hemisphere.

One interesting piece of corroborative evidence comes from archaeology. Working on the Chowchilla River in the central Sierra foothills, Moratto and others (1978) found that a major change in cultural characteristics occurred approximately 1350 A.D. The pre-1350 cultures exhibited small, dispersed, and poorly structured social groups, with restricted trade and a tendency towards violence (more than 50 percent of the adult males appear to have been killed). The post-1350 cultures consisted of dense populations located in well-nucleated villages, with well-developed social structures and extensive trading relationships. The study took place in an area whose carrying capacity is highly dependent on moisture. Moratto and others (1978) suggest that favorable, climatically-induced environmental changes, reflecting a switch from warm/dry to cool/moist conditions, were a major cause of the cultural differences.

California's recent climatic history has therefore paralleled that of the rest of the northern hemisphere. The increased meridionality, storminess, and widely fluctuating weather patterns that are documented in Europe and Japan can be expected to have occurred in the North Pacific and California as well. Curry's (1969) analysis of Sierran glacial advances and snowfall records supports such expectations. He suggests that periods of Sierran glacial advance experience a greater frequency both of wet, cold winters, and of drought, and that there were more but not necessarily larger storms. It is significant that similar conclusions have been reached independently by studies of tree-ring chronologies.

C. Climatic Implications of North American Dendrochronology

The tree-ring studies discussed here were carried out by the Laboratory of Tree-Ring Research at the University of Arizona. Their data base is a collection of ring-width chronologies obtained from sites located throughout western North America. Fritts (1965) summarized the early work in terms of growth patterns dating back to 1500 A.D. Subsequent work has been mostly statistical in nature, involving the use of principal component analysis to infer large-scale, quantitative representations of regional pressure, temperature, and precipitation patterns (e.g. Fritts, 1976; Fritts and others, 1979).

Fritts (1976) and Blasing and Fritts (1976) classify North America and North Pacific winters (December through February) into four different types. Each represents a different combination of temperature, pressure, and precipitation patterns. The characteristics of each type are presented in Table 4. The typing criteria were statistically defined through an analysis of monthly mean sea-level pressure anomalies for the period 1899 to 1966. Reconstructed pressure patterns for winters from 1700 through 1899 were then statistically compared with the winter type standards, and each year classified according to which type it resembled the most closely. The years from 1899 to 1966 were classified through comparison with the actual observations. Winters dominated by Type 3 and 4 patterns favor the development of major northwestern California storms, while those of Type 1 in general do not. Type 2 circulations can exert an influence either way. As examples, the storm of December 1964 occurred during a strong Type 4 winter. The years 1907, 1904, 1956, all strong Type 3's, were also winters of large northcoast storms. While it is possible for winters of Type 1 to generate large storms, and that of January 1953 is a good example, they would tend to be of the less severe, zonal, mid-latitude type.

Table 4

Characteristics of North American and Northern Pacific Winter Types*

Winter Type	Best Examples** (1899-1966)	Circulation Patterns	Remarks
1	1931, 1953, 1945 1912, 1927	Strong Aleutian Low. Tendency for a broad ridge over the Western United States.	Fewer storms along West Coast. Anomalous NE airflow into Canada and NW United States.
2	1937, 1949, 1932, 1911, 1952	Higher than normal pressure pressure over central North Pacific	Storms tend to enter United States along Oregon and Northern California coast.
3	1907, 1916, 1956, 1904, 1909	Higher than normal pressure over Alaska and NW Canada. Upper air ridge over North Pacific. Well-defined trough off West Coast.	Large numbers of West Coast storms. Opposite to Type 1 in all respects except ring-growth patterns.
4	1962, 1963, 1957 1965, 1930	Higher pressure than normal over south coast of Alaska. Below normal pressure and above normal cyclone occurrences in central north Pacific.	Slightly higher than normal number of storms off North Coastal California.

* - Adapted from Fritts (1976), and Blasing and Fritts (1976).

** - Listed in descending order of fit.

Because the winter classifications were derived using monthly mean pressure values, and describe the entire season, they are averages and must be used with caution when discussing individual storm events. This is particularly true since most years will consist of a mixture of all four circulation types and will correlate to one degree or another with all of them. For this reason, the most effective use of these analyses appears to lie more in determining how each pattern is represented rather than in which one is dominant. This can be accomplished by studying the time series trend in winter type correlation coefficients. Figure 3 shows an example of this time series using the 1950's [the entire series is reproduced as Figure 9.16 in Fritts (1976)]. It would appear that circulation patterns featuring positive components of winter Types 2, 3, and 4 (especially 3 and 4), and a zero or negative component of Type 1, are the most favorable for the generation of a major storm. Such correlation structures would result from the presence of ridges or blocks in the mid-Pacific (around 165° W; see Blasing and Fritts, 1976), a coastal low-pressure trough, and lower pressure and abundant cyclone occurrences in the central Pacific. Storm tracks leading through northwestern California are also highly likely, especially given a strong component of Type 2. These are all characteristics of low latitude storms.

A good example of the reliability of the winter type classifications is the winter of 1956. That winter was dominated by Type 3 circulation, and also had a very strong Type 4 component. Characteristics of Type 2 were of lesser importance, while those of Type 1 were absent completely (Figure 3). A month after the major storm of December 1955, another smaller storm occurred having almost exactly the same pressure field [peak on Redwood Creek = 496 cms (17,500 cfs)]. The only difference was that the later storm was displaced 15 to 20 degrees to the west. A shift in position of that magnitude would have produced another storm equal in magnitude to the earlier one (Weaver, 1962). Such conditions result from the fact that large-scale, long-period averages such as those discussed here are determined largely by the configuration of planetary-scale atmospheric waves (Shukla, 1981). The rate of change of these systems is slow enough to preserve circulatory continuity on the scale of several weeks to a month or more (Shukla, 1981; for an example see Namias, 1974). Pressure environments of the scale necessary to favor major storms are therefore likely to be either long-lived or numerous enough to exert a major influence on the season's pressure averages. Additional support for the validity of this relationship is presented later, in the section on the pre-1950 geomorphic record. Data were not available for 1965.

The paleoclimatic significance of this analysis is that is shows the 20th century climate (pre-1966) to have been markedly different from the climates that preceded it (Blasing and Fritts, 1976). For example, Table 5 shows that the frequency of winters dominated by circulations of Types 3 and 4 was consistently higher prior to 1900. In addition, winters whose correlation structure were similar to those of 1956 were also more common. Based on data from Fritts (1976), the frequency of such high potential winters was about 1.9 times higher prior to 1915 than it was from 1915 to 1960. Thus these analyses comprise independent corroboration of the Little Ice Age climatology discussed earlier.

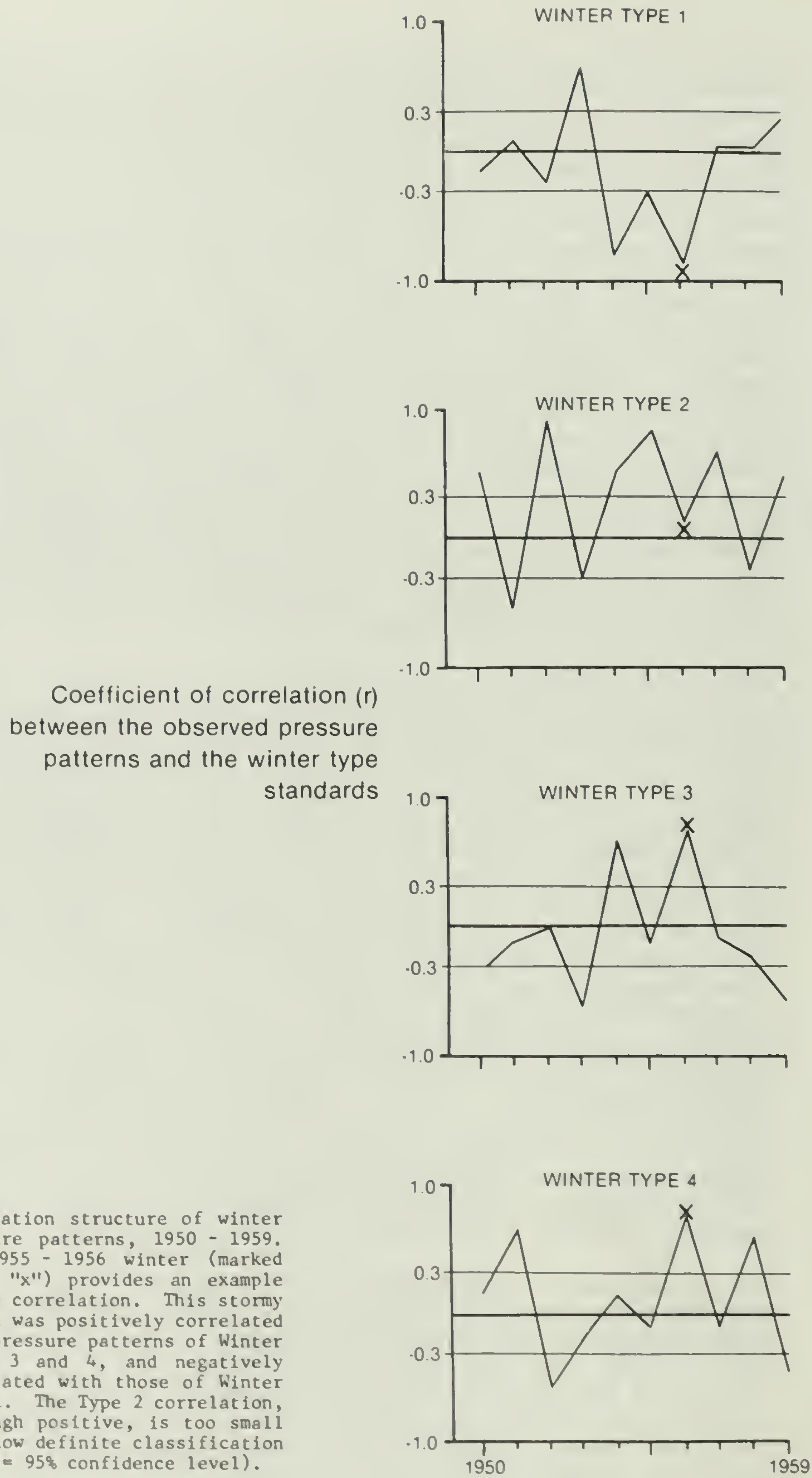


Figure 3. Correlation structure of winter pressure patterns, 1950 - 1959. The 1955 - 1956 winter (marked by an "x") provides an example of the correlation. This stormy period was positively correlated with pressure patterns of Winter Types 3 and 4, and negatively correlated with those of Winter Type 1. The Type 2 correlation, although positive, is too small to allow definite classification (±0.3 = 95% confidence level).

TABLE 5

Comparison of 18th, 19th, and 20th Century Winters (adapted from Figure 10, Blasing and Fritts, 1976).

Winter Type	Ratio of Occurrences 20th/18th	20th/19th	20th/Total 1700-1966
1	0.92	1.21	1.03
2	3.43	1.85	1.85
3	0.92	0.72	0.87
4	0.52	0.57	0.61

Many other dendrochronological studies with similar implications have also been made. For example, model reconstructions show that northwestern California lies on the southern edge of a region that was both cooler and wetter back to at least 1600 A.D. (Fritts and others, 1979; Fritts, 1981; see Wendland and Bryson, 1981, Figure 1; and Mitchell, 1976, Figure 3, for the positioning of the northcoast). At the same time drought in California was reconstructed to be more frequent. Storm tracks during those droughts, however, were not diverted as far north as they have been by the modern drought circulation (Fritts and others, 1979). Many of these studies also provide quantitative evidence for the past operation of climatic processes such as persistence and teleconnections (Lofgren and Fritts, 1977; Lofgren and Gordon, 1979; Fritts, 1981). More qualitative reconstructions based on the bristlecone pine chronology of the White Mountains of eastern California are summarized by LaMarche (1974). These studies show that cool-moist conditions became established there a little after 1300 A.D. Cool-dry conditions became dominant around 1600. Both sets of conditions are consistent with meridional flow patterns (LaMarche, 1974). The record further demonstrates that since at least 1000 A.D., the long-term climatic anomalies in eastern California have tended to be in phase with those occurring in England (LaMarche, 1974).

D. Permanence of Storm-Conducive Climates

The dendrochronological and climatological studies discussed above have both pointed out that the period generally known as the Little Ice Age was one of increased storminess and meridionality in California. They further show that the California climatic record is in general synchroneity with that of the rest of the northern hemisphere. Such storm-producing climates have not been limited to the past 600 years. For over 40 percent of Holocene time, California can be characterized in the same cool-wet manner as is the Little Ice Age (Moratto and others, 1978). Evidence for the existence of a general storm climate exists for full glacial conditions as well. For example, Johnson (1977), concludes that glacial winters may have resembled those of today, but that summers were probably March-like. Thus stormy conditions may have prevailed year-round. Numerous other characterizations and numerical simulations of northern hemisphere Ice Age climates (Newell, 1974; Lamb and Woodruff, 1970; Slatzman and Vernekar, 1975; Williams and others, 1974) lead to the same general conclusions: harsh summers, general meridionality, and heightened storminess.

Direct evidence of Holocene storms is found in Bull Creek (Location G, Figure 6). Zinke (1981) recorded a minimum of 15 major depositional events there in the past 1000 years. Stone and Vasey (1968) identify storm-related sedimentation in the early Holocene. Based on floodplain stratigraphy, they date three depositional events at 9540 ± 120, 9500 ± 120, and 9450 ± 120 B.P. These occur at depths of 9, 16, and 26 meters respectively. Seventeen meters of sediment therefore were deposited very quickly about 9500 years ago. This was a period characterized by Moratto and others (1978) as being cool and wet.

Confirmation of Ice Age conditions comes from Clear Lake (Figure 1). A climatic transfer function, developed using modern pollen data, has been applied to a continuous 130,000 year pollen sequence obtained by coring Clear Lake sediments (Adam and West, 1983). Annual precipitation at Clear Lake during full glacial conditions was reconstructed to have been up to 2 meters greater than modern values. Though the numerical values must be used with caution, the investigators conclude that glacial winters must have been much stormier or longer than at present. This same pollen record shows that the climatic trends in northern California over the past 130,000 years have generally been synchronous with the rest of the northern hemisphere (Adam and others, 1981).

E. Paleoclimatic Summary

Three major points can be made concerning the paleoclimatology of northern California. First, modern climatic processes such as teleconnections and persistence operated in the past as they do now. Second, the occurrence of circulation patterns favoring the development of major storms is a normal and permanent part of the area's climate. Climates much more severe than those recently experienced are possible. Third, Little Ice Age conditions in northern California were in general stormier, cooler, and wetter than at present. At the same time droughts were more frequent, though not so much so as they were in the southern part of the state. This climate was the local expression of a general, world-wide climatic deterioration. The Little Ice Age climate has dominated the world for the past 600 years, as well as for much of the Holocene. Most of the circulation patterns present during this period are meridional in nature. In a long-term sense, climates analogous to the zonal circulation of the early part of this century have been very unusual (see also Bryson and Hare, 1974; Lamb, 1969).

IV. HYDROLOGY

A. Introduction

Discharge measurements on Redwood Creek were first made in September of 1911. Two gaging stations were operated, one at Orick (at the site of the present gage, Figure 1), and one about 40 km upstream at Minor Creek. Both stations were discontinued in August of 1913. Discharge measurements were not resumed until June of 1953. As a result, Redwood Creek's discharge record is too short, and meridionally-biased, to by itself be of much use in a long-term analysis. However, there is a considerable amount of hydrologic and geomorphic data available for northwestern California as a whole, particularly from within the Eel River watershed (Figure 1). This data can be used to supplement and extend Redwood Creek's runoff record.

B. Regional Extrapolation of Hydrologic Data

The use of regional data in a discussion of localized flood events can be justified both statistically and physically. The statistical basis lies in the region's hydrologic homogeneity. As examples, the coefficient of variation for precipitation totals is essentially constant throughout the region (California Department of Water Resources, 1976). Physiographically-based peak discharge predictions in the northcoast region (Figure 1) are by far the most accurate of any California hydrologic region, having a standard error of estimate of about 0.25 log units (Table 2, Waananen and Crippen, 1977). Waananen and Crippen's northcoast hydrologic region boundary is shown in Figure 1. This hydrologic homegeneity has been confirmed by a number of different methods. Rantz (1969) and the California Department of Water Resources (1976) used regional boundaries that were only slightly different than those derived by Waananen and Crippen (1977). The boundaries of all three of these studies, for northwestern California, are only slightly different from those of the northwestern California precipitation region derived by Willmott (1978). Larger-scale studies by Bartlein (1982), and Balling and Lawson (1982) also depict the northcoast as being regionally homogeneous. Their boundaries differ only in detail from the other studies. The region's homogeneity was not affected by the 1950 transition from zonal to meridonial flow (Balling and Lawson, 1982). The variables treated by the studies included peak discharge, annual and monthly precipitation, monthly stream discharge, winter precipitation and temperature, and rainfall totals for periods ranging in length from 5 minutes to 60 days.

The physical basis for regional extrapolation is the large-scale nature of the region's precipitation processes. An example of the spatially homogeneous nature of these processes is presented in Figure 4. The 5-year running averages show nearly identical trends across the region. Correlation coefficients between the high-quality record at Eureka and the stations noted in Figure 1, on a water year basis, generally range between 0.8 and 0.9. Additional examples of regional similarity can be found in Janda and others (1975).

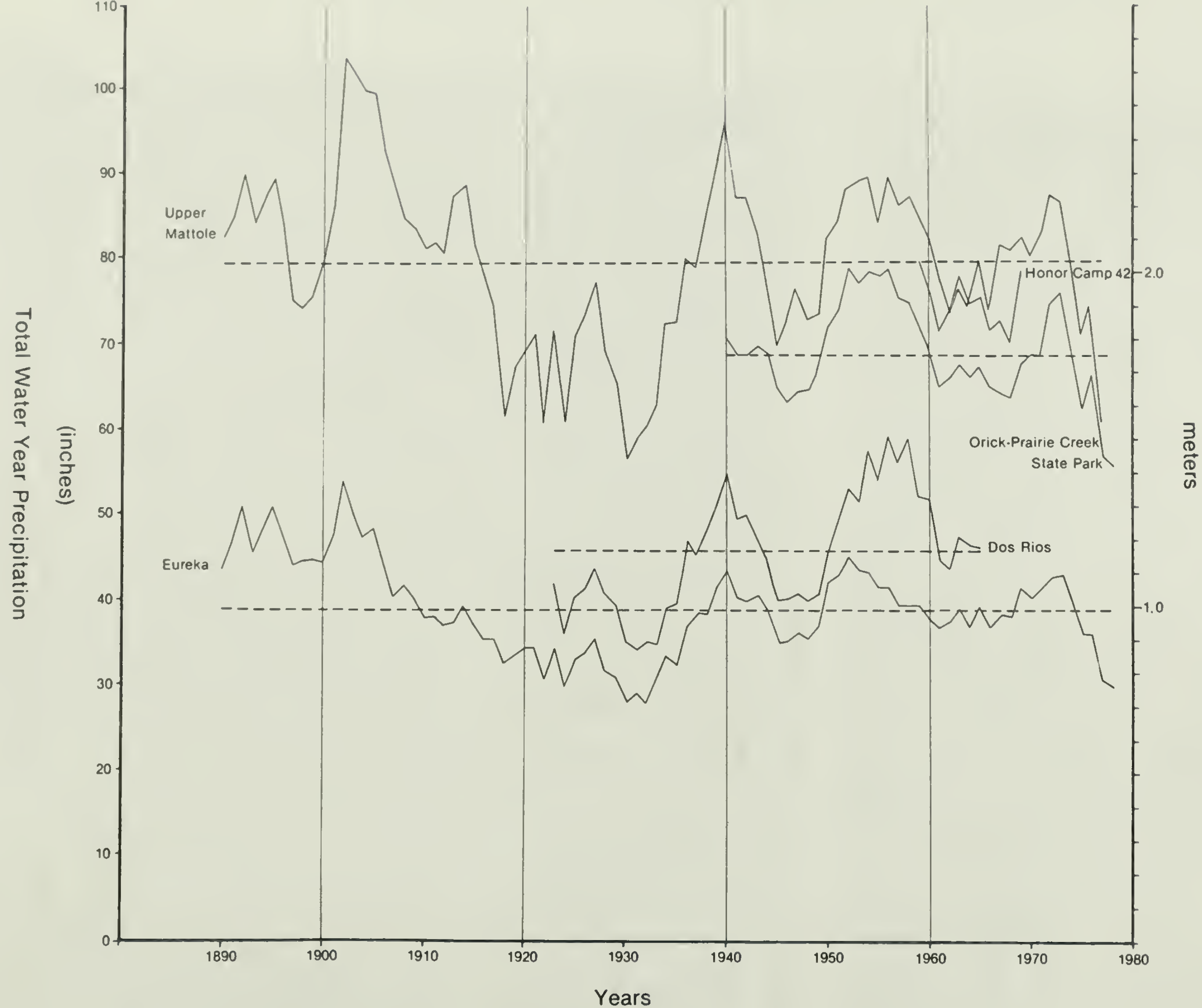


Figure 4. Total water-year precipitation, 5-year moving averages. Horizontal lines are station means. See Figure 1 for station locations. These moving averages show the spatially homogeneous nature of northwestern California precipitation. Station elevations range from near sea level at Eureka to about 570 meters at Honor Camp 42.

Two characteristics of northcoast storms provide the basis for extrapolating geomorphic evidence between northcoast watersheds. First, the summertime dominance of high pressure, and the resulting absence of summer storms of any importance, means that only the winter Pacific storm systems are hydrologically important. Thus the geomorphic evidence of earlier flooding can be assumed to have resulted from winter storms. Second, the diameter of large west coast storms is on the order of 1400-1600 km (Roden, 1966), which is over 40 times the size of the northcoast region. Such storms are likely to affect the whole area at once, thereby accounting for the synchronous behavior shown in Figure 4. Estimating the size of the high-intensity precipitation cores in high-magnitude events provides additional support. Isohyethal maps of the 1953 and 1964 storms (Hughes and Roe, 1953; Harden and others, 1978; California Department of Water Resources, 1965; Posey, 1965) indicate that between 300 and over 650 km of coastline were severely affected during the course of the storms. The inland extent appears to vary from about 80 to more than 320 km. The evidence for the occurrence of a major storm in one part of this region, particularly a low-latitude storm, strongly implies occurrence of that same storm in another.

C. Eel River - Redwood Creek Comparison

The Eel River (drainage area = 8063 km^2) lies about 65 km south of Redwood Creek (Figure 1). The Eel River has a high-quality discharge record that began in 1911 at Scotia. Early historical records and pre-settlement geomorphic data also are available for this watershed. In order to establish the hydrologic similarity of these basins, I will examine the relationship between runoff characteristics of Redwood Creek and the Eel.

Figure 5 shows normalized peak discharges for the Eel River at Scotia and Redwood Creek at Orick for the common period 1954-1980. All reported peaks have been plotted. The base discharges below which peaks are not published are 2,040 cms (72,000 cfs) on the Eel and 255 cms (9,000 cfs) on Redwood Creek. These correspond to about the 1.03 and 1.01 year events respectively (Log-Pearson III values for the period 1954-1980, excluding 1977). For each year the normalized peaks (Qpeak/Qbase) are graphed from left to right in order of their occurrence. The major events of 1955 and 1964 showed up on both streams. Smaller events, such as those of 1972 on Redwood Creek and 1974 on the Eel, were likely only to be significant in one watershed. However, the discrepancies evened out over time, and each stream experienced seven peaks greater than a normalized magnitude of 4.0. The average magnitude of the Eel peaks was 2.09 times the base discharge, while those of Redwood Creek were 2.00 times the base. For over half the number of peaks on both streams (56 times), a peak on one stream occurred within 1 day of a peak on the other; that is, the same storm caused significant peaks in both watersheds. During these storms the peaks on the Eel were larger than those in Redwood Creek (2.52 and 2.09 times their base discharges respectively). The coefficient of variation of Redwood Creek's yearly peak discharges was 0.45, compared to the Eel River value of 0.46. Both values are for the logarithmic transforms, excluding 1977. A regression of the number of yearly peaks on Redwood Creek

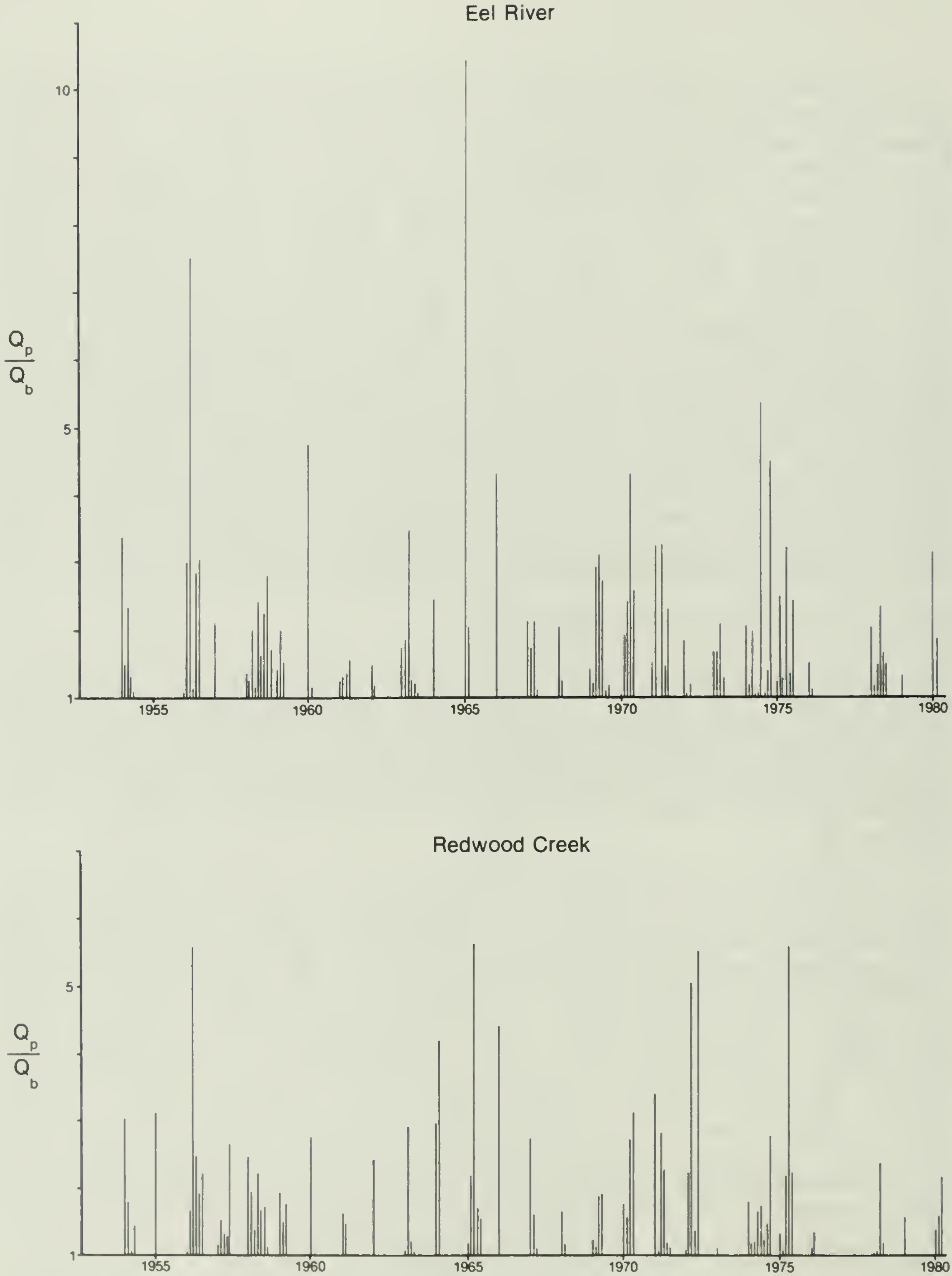


Figure 5. Normalized peak discharge records, 1954 - 1980; Redwood Creek at Orick and Eel River at Scotia. Q_p = peak discharge. Q_b = base discharge; peaks smaller than Q_b are not reported. Q_b for the Eel River = 2,039 cms (72,000 cfs) with a RI = 1.03 yr. Q_b for Redwood Creek = 255 cms (9,000 cfs) with a RI = 1.01 yr. All recurrence intervals derived from 1954 - 1980 data, excluding 1977.

versus the number on the Eel yielded a correlation coefficient of 0.77. Both the 1955 and 1964 storms were larger in the Eel than they were in Redwood Creek.

The correspondence of peak flow behavior extends to other measures as well. For both streams, the number of peaks in a given year is highly correlated with the total annual discharge. Annual discharges for the two streams also related well to each other and to the trends and magnitudes of the regional precipitation totals. For example, regressing Redwood Creek's yearly discharge totals against Eureka's yearly precipitation yielded a correlation coefficient of 0.87. The analogous value for the Eel was 0.81. The complete set of regression equations describing the discharge relationships is listed in Table 6. These equations are not taken in a predictive sense, but rather as general indicators of the correspondence of each stream's behavior and response to regional precipitation patterns.

The conclusion is that despite the disparity in size, the Eel's discharge can serve as a general surrogate for that of Redwood Creek. Specifically, averaged over a period of years, the number of large peaks will be about the same, and they will be about the same size (when normalized). The same storm events (normalized) may be slightly larger in the Eel than in Redwood Creek. There will also be a strong correspondence between the total annual discharges. All quantities will mirror closely the trends and magnitudes of the regional precipitation. In particular, years receiving large amounts of precipitation will tend to experience higher numbers of peak discharge events. It should be noted, however, that while in general more precipitation results in more peaks, annual totals in themselves are not reliable indicators of the occurrence of major storms. Large storms are a consequence of a specific set of meteorological conditions that are related to annually averaged conditions only in a general way. For example, precipitation during water year 1965, the year of the December 1964 storm, was only slightly above average. Lastly, a high-magnitude event such as the storm of December 1964 will usually generate severe discharge events in both watersheds.

D. Pre-1950 Regional Discharge Record

Harden and others (1978) have used newspaper accounts and precipitation records to outline the area's flood history back to 1861. Their conclusions have been supplemented here by other observations and are presented in Table 7. River locations are noted in Figure 6. The record shows that during the late 19th century, northwestern California experienced flooding that was at least as severe, if not more severe, than that experienced recently. Seven major storms occurred. The two largest, those of December 1861 and February 1890, were both comparable in magnitude to the storm of December 1964. That of December 1861 was probably larger (Harden and others, 1978).

After 1890, regional flooding was much less important. However, the first part of this interval, from 1890 to 1915, was much different from the 35-year period that followed. As noted in Figure 4, rainfall totals during the earlier period were well above the average, and in the case

TABLE 6

Summary of Discharge Regressions: Redwood Creek at Orick and Eel River at Scotia.
All relations are for the period 1954 - 1980 unless noted otherwise.

	Redwood Creek	Eel River
Number of peaks above the discharge base vs. total annual discharge	$\#Q_p = 7.41 \times 10^{-7} (Q_{annual}) - 2.32$ n = 27 r = .89	$\#Q_p = 8.0 \times 10^{-7} (Q_{annual}) - 1.11$ n = 27 r = .855 1912 - 1980 $\#Q_p = 8.18 \times 10^{7} (Q_{annual}) - 1.28$ n = 27 r = .880
Total annual discharge vs. Eureka precipitation total	$Q_t = 28{,}400$ (Eureka) - 312,000 n = 27 r = .868	$Q_t = 296{,}000$ (Eureka) - 5,274,000 n = 27 r = .813 1911 - 1980 $Q_t = 253{,}000$ (Eureka) - 3,995,000 n = 70 r = .828
Number of peaks greater than base discharge on Redwood Creek vs. number on the Eel		$\#Q_{RC} = .62 (\#Q_{Eel}) + 1.10$ n = 26 r = .77
Total annual discharge on Redwood Creek vs. annual discharge on the Eel (acre-feet)		$Q_{RC} = 0.075 (Q_{Eel}) + 319.900$ n = 27 r = .834

TABLE 7

Major North Coast Floods, 1852 - 1950

Storm Date	Comments
December 1852	Peaks lower than those in 1861-62, but of outstanding magnitude.
December 1861 - January 1862	Four distinct peaks during this interval. Peaks on the Eel higher than those of the 20th century. Stages in the upper part of Redwood Creek may have been higher than during the storm of December, 1864. (Personal communication, James Chezem, 1981).
January 1867	Floods on Redwood Creek may have been as high as 1861-62.
March 1879	Eel almost as high as the earlier events. Major flooding on the Mad River.
January 1881	Klamath and Trinity Rivers highest since 1861.
January - February 1888	Apparently concentrated in the lower Eel.
February 1890	Mad River higher than in 1861-62. Rainfall comparable to December 1864.
March 1907 February 1915 February 1927 February 1927 December 1937	Widespread and locally severe flooding, but peaks were generally lower than the post-1950 floods.

Data sources:

Harden and others (1978)

McGlashen and Briggs (1939)

Hofmann and Rantz (1963)

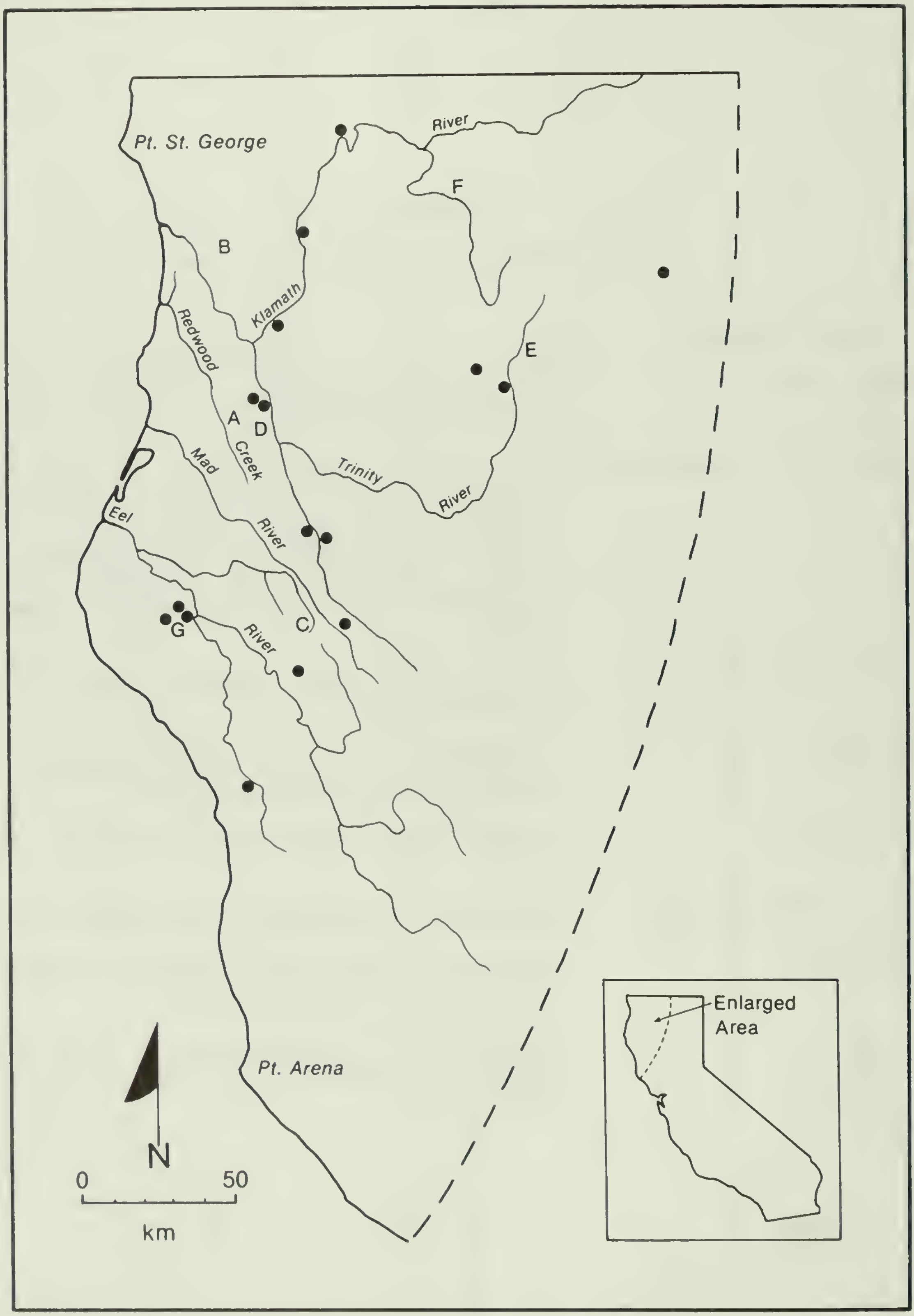


Figure 6. Sites where geomorphic evidence of prehistoric flooding has been found in northern California. The letters A-G refer to dated deposits discussed in Table 8. The black circles indicate undated deposits noted by Helley and LaMarche (1973).

of Eureka, they remained at those levels with a consistency that has not been attained since. Although major floods were infrequent, the relationships outlined in Table 6 imply that numerous smaller peaks must have occurred. As examples, the floods of 1904 raised stages in the Scott and Shasta Rivers, on the northeast edge of the area, to the highest levels since 1861. For the Eel River at Scotia, the 9,950 cms (351,000 cfs) peak of February 2, 1915 is the third largest gaged discharge on record (McGlashen and Briggs, 1939; Hofmann and Rantz, 1963). Thus it would appear that the period 1890-1915 was, in general, conducive to storminess, though not to the regional extent or intensities experienced earlier. However, after 1915 the record changes dramatically. As shown in Figure 4, precipitation dropped to levels well below the average, and stayed there until the late 1930's. Peak discharges followed suit. For example, the period from 1917 to 1935 on the Eel was one of uniformly small and infrequent flood events. Four of these years experienced no peaks larger than the 2,040 cms (72,000 cfs) cut-off point.

It is suggested here that this record constitutes additional confirmation of the region's sensitivity to large-scale changes in atmospheric circulation, and specifically to the early 20th century switch from meridional to zonal flow documented in Table 3. The classification analysis of Blasing and Fritts (1976) provides additional information. Fifteen of the 25 winters between 1890 and 1915 were classified as being dominated by Type 3 circulation. During the 25-year period between 1915 and 1940 there were only four winters of this type. All the observed hydrologic differences between the two intervals, lowered precipitation, fewer and smaller storms, as well as the continued lack of widespread flooding, are consistent with these changes. One can therefore say that the impacts of increasing zonality began to dominate the region's climate somewhere between 1910 and 1920, and that 1915 is as good a year as any to mark the change from one type of circulation to the other.

V. PRE-1950 GEOMORPHIC RECORD

The regional geomorphic record is summarized in Table 8. The sediments comprising this record were deposited in one of three ways. The first mode of deposition is flood-deposited gravel bars. The deposits on the East Fork of Willow Creek are of this type (Helley and LaMarche, 1973). Secondly, some of the sediments, such as those in the West Fork of the Van Duzen (Kelsey, 1977), are remnants of aggradation waves. Third, landsliding may have initiated a debris torrent whose material was deposited immediately downstream as alluvial fill. The Bald Mountain deposits are a good example (Kelsey, 1977).

TABLE 8

Geomorphic evidence of past storm events.

Location	River Basin	Latest Possible Depositional Date #	Map Symbol Used In Figure 6	Source* of Data
Redwood Creek	----	About 1874	A	3
Blue Creek	Klamath	1871	B	1
Bald Mountain Creek	Eel	1861	C	2
West Fork Van Duzen River	Eel	1819	C	2
East Fork Willow Creek	Trinity	1749	D	1
Trinity River at Eagle Creek	Trinity	1735	E	1
Red Lassic Creek	Eel	1645	C	2
Coffee Pot Creek	Eel	1632	C	2
Scott River	Klamath	1610	F	1
East Fork Willow Creek	Trinity	1590	D	1
Scott River	Klamath	1525	F	1
Bull Creek	Eel	At least 5 events between 950 and 1964	G	4
Red Lassic Creek	Eel	900 - 1000 B.P.	C	2
Bull Creek	Eel	9540 ± 120 B.P. 9500 ± 120 B.P. 9450 ± 120 B.P.	G	5

Dates from sources 1-3 are probable values based on the age of the oldest tree growing on the unit.

Events in source 4 are inferred from floodplain stratigraphy. The lower limiting date is a ^{14}C on charcoal.

Dates from source 5 are ^{14}C dates of buried Douglas Fir trunks.

* 1. Helley and LaMarche (1973)
2. Kelsey (1977)
3. Janda and others (1975)
4. Zinke (1981)
5. Stone and Vasey (1968)

Each type of deposit is interpreted differently. Gravel bars directly imply the size of the runoff event. Helley and LaMarche (1973) used the East Fork of Willow Creek bars to infer that both of those events (1590 and 1735) were about the same size as the December 1964 storm (about 4.37 cms/km^2 or 400 cfs/mi^2). Aggradation waves imply a large, usually widespread influx of sediment that overwhelms the capacity of the channel system to support it. Such an event may result either from a single storm, or from a series of closely spaced storms that concentrated locally large sediment influxes downstream. The wave of aggradation presently moving through the northcoast river system is a perfect example of this mechanism. The third type, debris torrent deposits, imply that rainfall intensities at that particular spot were high enough to cause large-scale landsliding.

Not all major storms leave geomorphic evidence. That of 1861, for example, left only scattered deposits, in spite of being the largest runoff event observed in the past 130 years (Kelsey, 1977; Harden and others, 1978). Additionally, field experience indicates that nearly all of the geomorphic evidence likely to represent the post-1950 storms was deposited between 1964 and 1975. Thus 200 or 300 years from now, only one event will be inferred, when in fact there were six.

VI. CLIMATOLOGICAL IMPLICATIONS OF GEOMORPHIC RECORD

The geomorphic record has been interpreted to imply the occurrence of two major pre-settlement events. These were assigned general dates of 1590 and 1735 (Kelsey, 1977; Helley and LaMarche, 1973). Both were at least as large as the storm of December 1964. That of 1590 is interpreted as being larger (Helley and LaMarche, 1973). These events, along with those of 1819, 1632, and 1645, are briefly re-examined. Discussion of the events preceding 1590 is a separate problem, and will not be attempted here.

The 1819 deposits are interpreted by Kelsey (1977) as resulting from an event that could have occurred any time from the latest part of the 18th century to a few years prior to 1829. The winter type classifications support this dating, as the winters of 1819-1829 were almost entirely composed of the high potential circulation patterns. Supporting, though limited, historical data from other parts of northern California are also available. Indians in the Sacramento River Valley recalled floods of exceptional magnitude during the winter of 1825-26. That winter journals, letters, and newspaper accounts of settlers also describe severe flooding. Reports from the San Francisco Bay area state that storms in January and February of 1819 caused flooding that changed the courses of many streams (McGlashen and Briggs, 1939). It is concluded that the dating of the 1819 event is correct. The possibility also exists that the storm or storms that caused it were the result of a decadally persistent set of circulation patterns analogous to those occurring after 1950. The character of the hemispheric circulation patterns dominant at that time supports this conclusion. That is, the period between 1788-90 and 1830-40 has been determined by Lamb (1969) to have been one of notably low zonality. Thus large-scale conditions also favored the occurrence of major storms.

The winter type analysis was also applied to other intervals. The 1861, 1867, 1890, and 1937 storms all occurred during high potential winters. Half of the winters between 1860 and 1890 displayed the high potential correlation structure. The period 1860-1890 is therefore considered analogous to the post-1950 period (see also discussions in Harden and others, 1978). The period of 1730-1750 was also examined. During that period the high potential correlation structure occurred 14 times. The 1740's were also noted by Lamb (1969) as being a period of prominent blocking in the North Atlantic. It is therefore concluded that the event dating for this interval is correct. The existence of another decadally-persistent episode of high-potential winters is also suggested. It is considered likely that the two deposits noted in Table 8 can imply the occurrence of two events as easily as they can one.

Kelsey (1977) correlated the deposits of 1632 and 1645 with the event of 1590. It is suggested here that they may represent a separate interval of enhanced storminess. Support for this suggestion comes from the dendrochronological work of Curry (1969), who found the early to mid-1600's in the Sierra Nevada to have experienced precipitation that was markedly above average.

VII. SUMMARY OF THE REGIONAL DISCHARGE RECORD

The events of the past 25 years were preceded by a similar set of storms in the 19th century. These storms were at least as severe as the recent ones. Thirteen major storms have occurred since 1850. Four of these were exceptionally severe and the largest was probably that of December 1861. There was one exceptionally dry spell lasting from about 1915 to 1935.

The past existence of decadally-persistent circulation patterns conducive to the occurrence of major storms is implied by all three types of evidence examined here: historical records, geomorphic evidence, and climatological analyses. One such interval between 1860 and 1890 was directly observed. There is strong support for the existence of at least two other such intervals, those of the 1820's and from 1730 to 1750. Another high-potential interval is suggested by the dating of events in 1632 and 1645. Because the interval of 1580-1610 was one of the severest phases of the European Little Ice Age (Lamb, 1969), it is considered a likely possibility that the event of 1590 represents still another.

VIII. IMPLICATIONS FOR REDWOOD CREEK

The general conclusion regarding Redwood Creek's pre-1950 discharge record is that it closely follows the regional trend. All of the considerations mentioned earlier, the large size of the major storms, the Creek's sensitivity to regional precipitation trends, and the demonstrated concurrence with the Eel's discharge record, all point to the fact that while the details might be different, all of the storms discussed here had their counterparts in Redwood Creek.

The most specific conclusions can be reached about the 1590, 1749, and 1861 events. The first two events have been studied in the East Fork of Willow Creek (Helley and LaMarche, 1973). This stream is located immediately adjacent to, and east of, Redwood Creek (Site D, Figure 6). The discharges implied to have occurred there are about the same size as those of the December 1964 storm, around 4.37 cms/km^2, or 400 cfs/mi^2. At the time of the 1964 storm, it had been at least 300 years since the last geomorphically significant depositional event in upper Redwood Creek (Janda and others, 1975). However, given the proximity of Redwood Creek to the East Fork of Willow Creek, it is considered likely that both events had occurred in Redwood Creek during that interval. Their magnitudes are implied to have been similar to the 1964 storm. Discharges during the storm of December 1861, at least in the upper third of the watershed, equalled and probably exceeded those of December 1964.

IX. STATISTICAL CONSIDERATIONS OF THE FLOOD HISTORY OF REDWOOD CREEK

A. High-Magnitude Storms

I will first discuss the recurrence interval estimates for the 1964 storm. In a long-term sense, the size of that storm was not unusual. There have been a minimum of five such storms in the past 400 years (1964, 1890, 1861, 1735, and 1590), and at least two of them were larger. This yields a minimum storm frequency of one every 80 years. However, given the imperfections in the geomorphic record, and the fact that this evidence probably records storm periods and not storm events, it is considered likely that the pre-1861 storms were associated with others that have remained unrecorded. For example, Zinke (1981) estimates a minimum of 10 major depositional events at Bull Creek in the past 600 years, or one every 60 years. This initial estimate of 80 years is therefore revised downward using the more complete post-1850 record as it is outlined in Tables 1 and 7.

The basis of the revision is that the post-1850 record appears to be a reasonable first approximation of Little Ice Age climate. It contains two periods conducive to the occurrence of major storms, and one period of storm absence. It contains a reasonable sampling of the winter types. For example, between 1700 and 1960 the high potential correlation structure occurred about 43 percent of the time. Between 1850 and 1960 this frequency was about 48 percent. The 1950's and 1960's have been characterized as being the closest approximation of Little Ice Age climate experienced in this century (Lamb, 1969; Sanchez and Kutzbach, 1974). These considerations, along with those of climatic persistence, and the generally increased Little Ice Age storminess and meridionality outlined earlier, lead to an estimated long-term storm recurrence interval of 45-50 years. This applies to storms greater than or equal to that of December 1964, both in terms of intensity and regional size.

Since 1850 there have been at least four, and probably five, storms of magnitudes greater than or equal to that of December 1955 (the possible fifth is 1852). The same considerations regarding the post-1850 record, the regional discharge record, and the Little Ice Age meridionality also apply here. The post-1850 record is also used to generate the estimate. The estimated recurrence interval of the 1955 storm is placed at 25-30 years.

There have been 13 regional storms in the past 130 years. This yields an average of one storm every 10 years. As a first approximation, this recurrence interval is taken to apply to storms greater than or equal to the magnitude of that of March 1972 (Table 1).

As a matter of perspective, it is convenient to view occurrence probabilities as functions of the prevailing climatic state; that is, as conditional probabilities (probability being the reciprocal of the recurrence interval). The averages derived above describe the average climatic state as it has existed since the onset of the Little Ice Age (the past 600 years). During high-potential winters the probabilities will be higher. During zonal periods, or periods of meridional drought, they will be lower. While the average occurrence probability associated with the March 1972 storm is probably about 0.10, during a highly meridional period like the 1950's and 1960's it is considerably higher. One could speculate, judging from the post-1600 record, that as much as 30 to 40 percent of the Little Ice Age may have experienced these higher levels of risk.

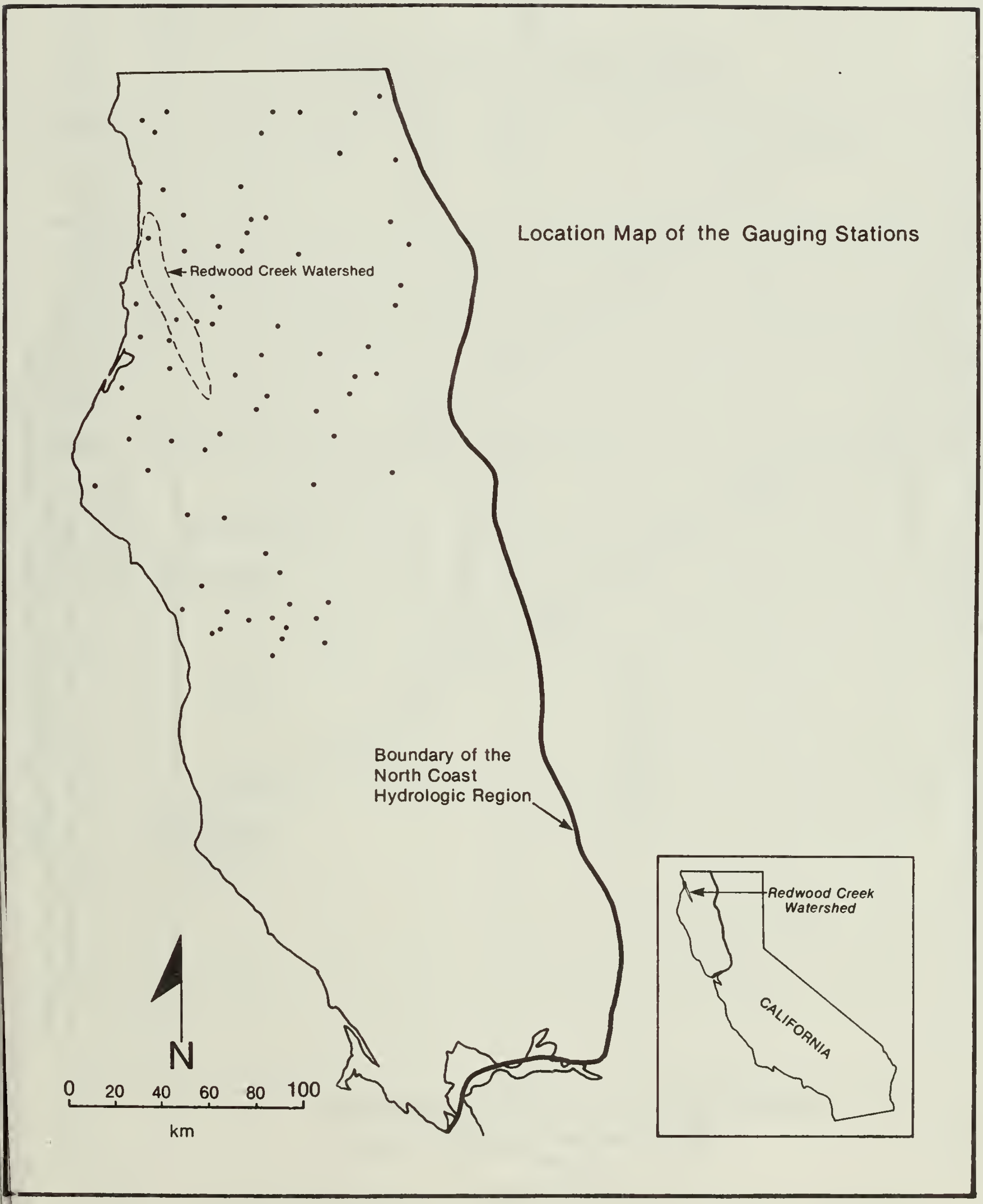
B. Redwood Creek Flood Magnitudes

The highest peak discharge recorded in Redwood Creek at Orick is 1,430 cms (50,500 cfs), or 1.97 cms/km^2 (180 cfs/mi^2). However, peak discharges in Redwood Creek have been far below the regional maximums, based on an analysis of those northcoast drainage basins shown in Figure 7. Peak discharges at 75 stations for the storm of December 22, 1964 (Figure 8) show that 14 of the 23 streams with areas between 259 km^2 and 1,036 km^2 experienced peaks greater than the 1.97 cms/km^2 (180 cfs/mi^2) recorded at Orick. Ten had discharges in excess of 3.28 cms/km^2 (300 cfs/mi^2). In smaller watersheds even higher peak discharges occurred. For example, in Panther Creek near Denney (D.A. = 14.8 km^2), the peak was 27.00 cms/km^2 (2,470 cfs/mi^2).

The highly elongated nature of the Redwood Creek watershed may prevent peaks at Orick from reaching the extremes shown in the 259-1,036 km^2 range of Figure 8 (for example, see discussions in Black, 1972). Because no hydrologic model incorporating Redwood Creek's morphology presently exists, no attempt will be made to estimate an upper limit to discharges at Orick. However, no such morphological constraints exist for its tributaries. Any of the unit discharges noted in Figure 8 are considered realistic discharge possibilites for Redwood Creek tributary basins.

C. Redwood Creek Flood Frequencies

The Redwood Creek and Eel River frequency curves are shown in Figure 9. Curves A-C are Log-Pearson III curves fitted using observed parameters. Curve D is a long-term estimate generated using assumed parameters and also assuming a Log-Pearson III distribution. In all of the analyses except Curve D, the 1977 peak discharge was ignored. The year 1977 was one of severe drought and the peak discharge on the Eel was only 164 cms (5,790 cfs). This peak discharge was 5.65 standard deviations below the mean (log values), and an order of magnitude smaller than the second smallest peak (1,172 cms or 41,000 cfs in 1929). Redwood Creek's peak in 1977 was only 94 cms or 3,310 cfs (4.4 standard deviations below the mean). The climatic conditions these discharges represent are those of storm absence, not of storm occurrence. In addition, the log-Pearson III analysis is very sensitive to sample skew. The addition of the Eel's 1977 discharge to the long-term record changes the skew from -0.04 to -1.38. This seriously affects the discharge values at the upper end of the curve. Because it represents a set of circumstances that are mutually exclusive to those considered in this study, and thereby distorting the statistical analyses, 1977 was excluded from consideration.



igure 7. Location map of gauging stations used in Figure 8, total number of gauging stations is 75.

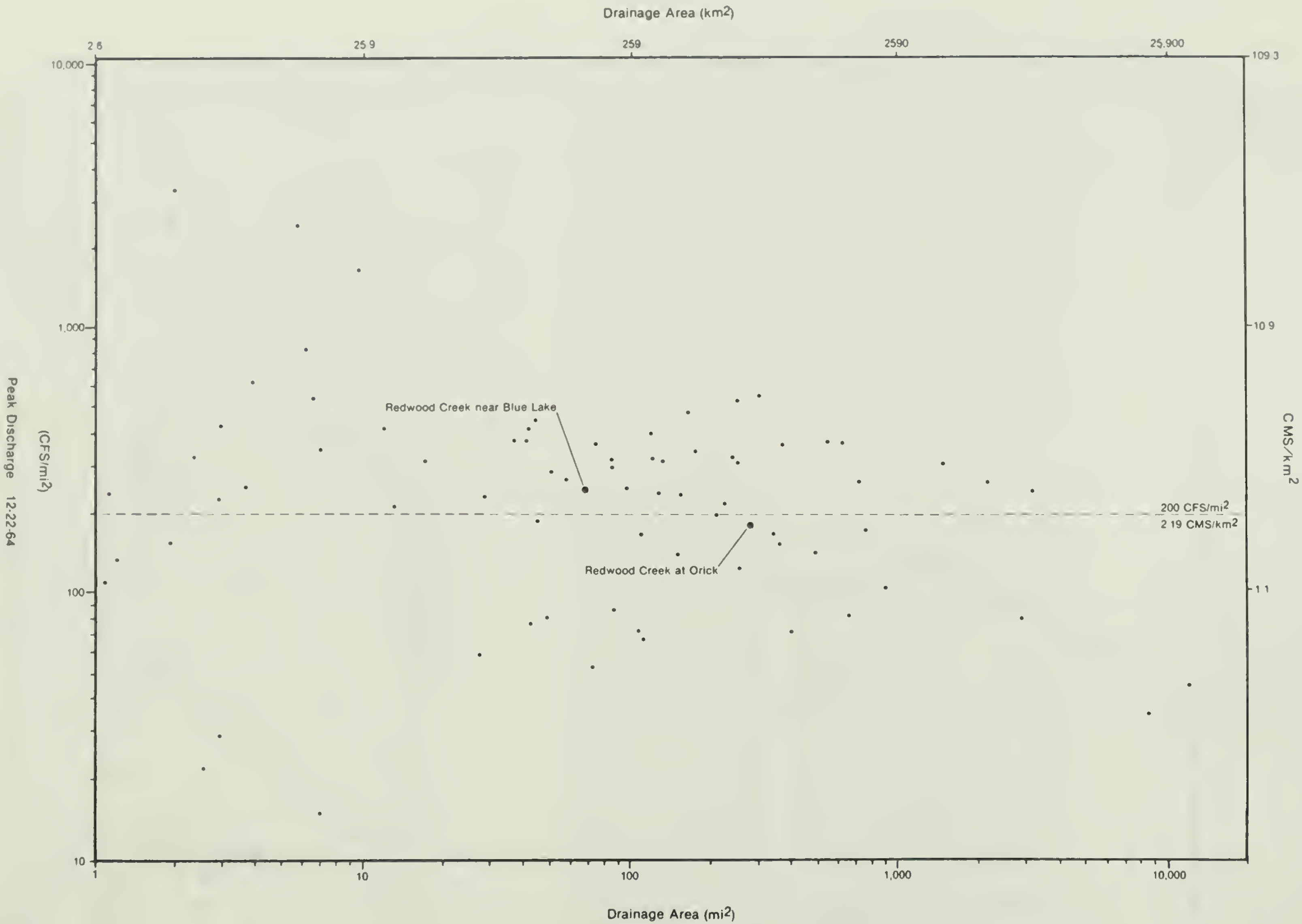


Figure 8. Peak discharges of northwestern California streams during the December 1964 storm. See Figure 7 for gaging station locations. Discharge data from Waananen and Crippen, 1977.

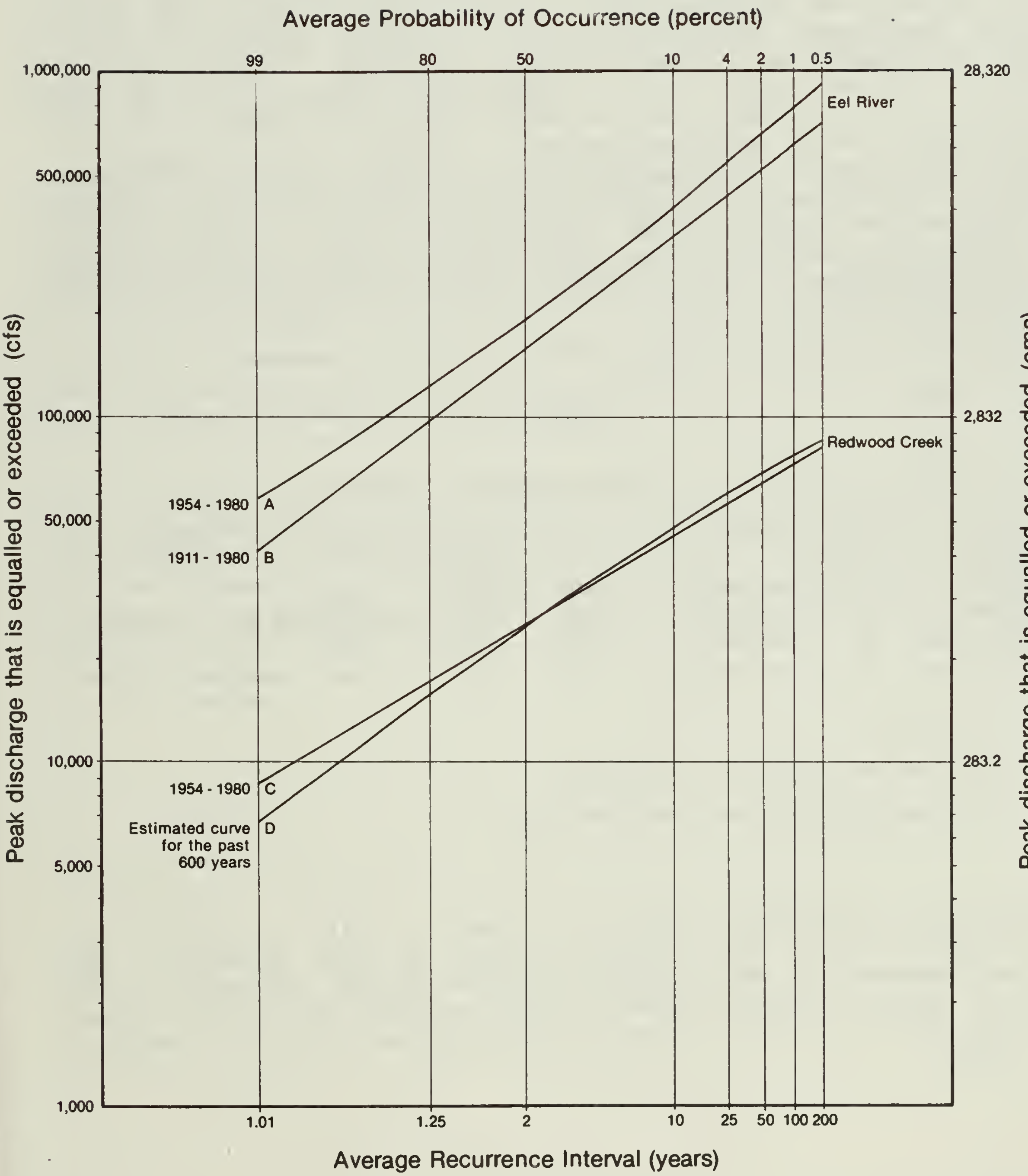


Figure 9. Log-Pearson Type III flood frequency curves for Redwood Creek at Orick and Eel River at Scotia. No data in 1916 for Curve B. Parameters for Curve D estimated, see text. All curves except D exclude consideration of 1977. See Table 9 for more detailed information.

The fourth curve, D, is a qualitative estimate of Redwood Creek's flood frequency curve for the past 600 years. The derivation of this curve uses climatic data discussed above. The similarity of the 1950's and 1960's to the Little Ice Age conditions was noted earlier. The 1970's continued to be years of extremes, often comparable to those of 100-200 years ago (Lamb, 1982b). Thus the 1954-80 curve in Figure 8 (C) was taken as the starting point for the analysis. Further considerations incorporated into Curve D include the higher frequency of Little Ice Age drought, and its more frequent storminess. Redwood Creek is also considered capable of sustaining peaks greater than 1,430 cms (50,500 cfs), though with an upper constraint imposed by its morphology. As an additional guide to choosing long-term parameters, the 1954-80 record was re-analyzed using a hypothetical 1964 discharge peak of 1,982 cms (70,000 cfs). The parameters finally adopted to generate the long-term curve are listed in Table 9. They reflect long-term assumptions of about the same mean annual discharge, higher flow variability, and a more negative skew than was recorded during the post-1954 interval.

TABLE 9

Parameters of the curves in Figure 9.

Stream	Curve	Interval	Mean	Deviation	Skew	Remarks
Eel River	A	1954-1980	5.290	0.243	0.216	
Eel River	B	1911-1980	5.201	0.254	-0.035	No data for 1916.
Redwood Creek	C	1954-1980	4.401	0.200	0.002	
Redwood Creek	D	Last 600 years	4.390	0.230	-0.200	Parameters estimated; see text.

Curves A - C derived using standard techniques.

All curves except D exclude consideration of 1977.

The long-term recurrence interval for peaks of 1,416 cms (50,000 cfs) or larger at Orick is estimated to be about 12 years (Figure 9). The close agreement of this estimate with the 10 year estimate for the return period of major regional storms indicates that most of these storms can be expected to generate discharges of about this magnitude or larger.

X. IMPLICATIONS FOR RESOURCE MANAGEMENT IN NORTHWESTERN CALIFORNIA

The anomalous nature of the early to mid 20th century climate has biased climatological statistics throughout western North America (Fritts and others, 1971; Blasing and Fritts, 1976). Therefore, one should be very cautious when interpreting statistics that are heavily influenced by observations made during this interval. As an example, one could anticipate that the 70 year parameters of the Eel River at Scotia for Curve B, Figure 9, are less representative of their actual long-term values than are the 26 year parameters of Curve A.

The current large-scale climatic conditions resemble those of the mid-to late-19th century (Wahl, 1968; Wahl and Lawson, 1970; Eichenlaub, 1971). Recent West Coast and California precipitation patterns are also similar to those of the mid- to late-19th century (McGuirk, 1982; Granger, 1979). These conditions can be expected to remain in place until at least the end of the century (Granger, 1981; National Defense University, 1978). Precipitation extremes similar to those of the late-19th century have been forecast for California (Granger, 1981). Therefore, the average values derived above for the various storm recurrence intervals, and for the flood frequency estimates, can be conservatively viewed as lower bounds for the currently prevailing probabilities.

The occurrence in the next 20 years of another storm equal in magnitude to that of December 1964 must be considered a realistic possibility. If one does occur, all of the flood intensities noted in Figure 8 can be expected to occur somewhere in northwestern California. Resource management implementations should be designed considering that they will probably have to withstand such climatic extremes at least once in their lifetimes.

XI. OVERALL SUMMARY

Twentieth century streamflow characteristics in northwestern California reflect the effects of two major climatological changes. The first was a switch from meridional to zonal flow that occurred around 1915. The result was fewer and smaller storms, and correspondingly fewer and smaller peak discharges. The second was a switch back to meridional conditions around 1950. This increased the frequency and magnitude of both large storms and large floods. The fact that both sets of conditions persisted for many years is not unusual. They were a result of the tendency for the atmosphere to adopt decadally-persistent circulation patterns.

The following average recurrence intervals are suggested to hold for high-magnitude storms in northwestern California.

Storms ≧ that of March 1972	10 years
Storms ≧ that of December 1955	25 - 30 years
Storms ≧ that of December 1964	45 - 50 years

Storms of these magnitudes are a normal and permanent part of the area's climate.

Because of the anomalous nature of the early to mid-twentieth century climate, the 1954-80 statistics for Redwood Creek are closer to the long-term values than might be suspected on the basis of its frequent flooding and short record length. This perspective is summarized in Figure 9. Curve D in that figure represents the estimated long-term (600 year) occurrence probabilities. During certain periods these probabilities will be higher and during others they will be lower. A discharge of 1,416 cms (50,000 cfs) or greater at Orick is suggested as occurring every 10-12 years.

The current climatic state is conducive to precipitation extremes. It is likely this state, or one like it, will remain in place until at least the end of the century. Any decision that incorporates hydrologic variables should consider the probabilities expressed here as realistic lower limits to the currently prevailing values. The possibility that a storm the size of that of December 1964 will occur within the next 20 years cannot be discounted.

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SEDIMENT BUDGET PROJECT

In 1978, the National Park Service initiated a study project to formulate a sediment budget for the Redwood Creek basin. This investigation documents and quantifies sediment source areas in the watershed, changes in sediment storage in tributary and mainstem stream channels, and sediment transport out of the basin. Results are presented in a series of Technical Reports and Data Releases, and condensed versions will be published in scientific journals.

NOTICE

This document contains information of a preliminary nature, and was prepared primarily on an interim basis. This information may be revised or updated prior to publication in a forthcoming U.S. Geological Survey Professional Paper.