Historic Flood Information for Northern California Streams From Geological and Botanical Evidence

GEOLOGICAL SURVEY PROFESSIONAL PAPER 485-E

Prepared in cooperation with the California Department of Water Resources

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By EDWARD J. HELLEY *and* VALMORE C. LaMARCHE, Jr.

VEGETATION AND HYDROLOGIC PHENOMENA

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HISTORIC FLOOD INFORMATION FOR NORTHERN CALIFORNIA STREAMS FROM GEOLOGICAL AND BOTANICAL EVIDENCE

By EDWARD J. HELLEY and VALMORE C. LAMARCHE, JR.

ABSTRACT

Severe flooding in the mountainous region of northern California has produced texturally and morphologically distinct gravel deposits. Observations of the erosion and deposition produced by the devastating floods of December 1964 allowed comparison and identification of ancient flood deposits. Age limitations have been assigned to these ancient floods at four widely scattered detailed study sites in northern California. Long-lived coniferous trees, both living and those killed by the 1964 floods, have been used to assign minimum ages to these deposits. Maximum ages have been determined on the basis of radiocarbon dating of material entrained in the same deposits. Regional extension of standard flood frequencies is not attempted. Comparison with historic records at the four detailed study sites suggests that severe floods of magnitude similar to that of December 1964 have occurred several times in the last few hundred years.

INTRODUCTION

Floods are those flows which overtop the banks of a channel and spread out across the flood plain, often causing damage and loss of life. Flood-frequency studies attempt to predict the frequency of recurrence of flood-flows. Determination of the statistical distribution of peak-discharge data is called flood-frequency analysis; the analysis attempts to determine the average interval between floods that exceed a given magnitude. The general purpose of flood-frequency analysis then, is the prediction of what is likely to happen in the future.

A knowledge of the magnitude and frequency of recurrence of floods has obvious practical applications to the proper design and location of structures such as dams, bridges, and roads. Moreover, the frequency with which certain flood plains are inundated must be considered in determining the size and strength of engineering structures or the feasibility of planning construction at all. Flood insurance and flood-plain zoning are obvious economic problems which are dependent on some knowledge of flood frequencies. Therefore, it is imperative that methods of flood-frequency analysis be sound.

STANDARD METHODS

The frequency with which floods occur and their relative magnitude are inversely related; that is, very large floods are infrequent. Smaller floods, on the other hand, usually go unnoticed and may recur as often as once every year. Severe floods usually are noticed because they affect human activities. Such floods may occur only once in 15 or even 100 years.

Several methods have been used to analyze flood events. Complete descriptions of the different methods may be found in Dalrymple (1960), Benson (1962a), and Cruff and Rantz (1965). Methods used by the U.S. Geological Survey are based on the annual peak discharge. This annual flood is the highest momentary peak discharge during any given water year (October 1–September 30) and when listed for the period of record, the resulting array is referred to as the annual flood series. Another series called the partial-duration series is sometimes used and is based upon a list of floods above a given base discharge. From either of these two series a recurrence interval may be calculated. Accordingly, it should be noted that a flood having a recurrence interval of 2 years, when computed from the annual series, has one chance in two or a 50-percent chance of occurring in any given year. A 100-year flood on the other hand has only a 1-percent chance of occurring in any one year. Naturally it follows that the size of the flood population (number of years of record) becomes very important in calculating the recurrence interval. Because most flood records are for a period of less than 40 years (Cruff and Rantz, 1965, p. 2), the chance for the available sample to be skewed or affected by an extreme event is very great. In an attempt to offset this bias, Federal agencies adopted a uniform technique for determining floodflow frequencies (Water Resources Council, 1967). In December 1967 the council agreed that the state of the art had not developed to the point where complete standardization was feasible. They did, however, recommend the log-Pearson type III distribution (Water Resources Council, 1967, p. 6). Detailed descriptions of this method were given by Foster (1924) and by the Inter-Agency Committee on Water Resources (1966). Basically the Pearson method is more flexible and definitive than other methods because the distribution of the array of flood peaks is defined not only by the mean and standard deviation but also by the coefficient of skew of the array. An excellent example of the case of the log-Pearson type III method as applied to north coastal basins in California is given by Cruff and Rantz (1965, p. 13). However, as useful as the skewness might be in improving the statistical analysis, it may be misleading unless the sample from which the skew is computed is large. It would appear then that we can do little about sampling error, unless as suggested by Cruff and Rantz (1965, p. 47), we can use historical data to extend the base period for which a given flood frequency is attempted.

The application of historical data is aptly demonstrated by Benson (1962b) with reference to long histories from colonial New England. Research of personal diaries, church records, will records, newspapers, and town histories allowed extension of an existing base period of flooding from 50 to 300 years (Benson, 1962b, p. 6). Unfortunately many regions of the United States do not have long historical records, and this is particularly true of the region with which this report is concerned. North coastal California does, however, contain some extremely long-lived nonhuman inhabitants. These are its coniferous trees, especially the coastal redwoods, which have been witness to natural processes for many centuries.

EXTENSION OF FLOOD RECORDS BY GEOLOGICAL AND BOTANICAL EVIDENCE

Several kinds of observations may be useful in making inferences about the magnitude and recurrence interval of floods that can be used to supplement or extend existing gaging-station or historical data. These observations can be divided into two general classes. First, it may be possible to state the minimum time interval that must have elapsed since the last occurrence of a flood of a certain large magnitude. Second, in certain cases, physical evidence of specific flood events can be identified and dated and may permit estimates of peak stage or discharge.

A number of studies have been carried out in which estimates were made of the probable recurrence interval of recent large and devastating floods. Jahns (1947) studied the distribution and texture of flood deposits on terraces above the Connecticut River in Massachusetts. He concluded that there was no evidence of the occurrence of a flood equaling or exceeding that of 1936 during at least the previous several hundred years. Mansfield (1938) found that older flood deposits along the Ohio River could be readily identified, and he tentatively concluded that the flood of 1937 exceeded any in the recent geologic record. The recurrence interval of cloudburst floods in the Appalachians (Hack and Goodlett, 1960) was estimated as more than 100 years, on the basis of the maximum age of trees growing on alluvial fans that typically formed at the mouths of small tributary streams during past floods. The rare occurrence of such events was also shown by the total destruction during a major flood of older trees that had grown to maturity on the flood plains of larger streams. Stewart and LaMarche (1967) concluded that floods as large as that of December 1964 were infrequent on Coffee Creek in northern California, because this event destroyed flood-plain forests containing many trees over 200 years old, and caused deep erosion of previously undisturbed deposits as old as 1,700 years.

Past floods can be identified and dated only if some interpretable record has been left. Sigafoos (1964) showed how botanical evidence could be used to date floods in the Potomac River valley. The burial, overturning, breakage, and scarring of deciduous trees located on the flood plain provided a record of major floods that could be deciphered by careful study. Dates of flood scars on trees provided the basis for an estimation of flood frequency in another study (Harrison and Reid, 1967).

Geologic and botanical methods thus may be applicable to flood-frequency problems where local circumstances permit. The present study was undertaken in an attempt to apply such methods in northern California, an area with relatively sparse and short runoff records. Circumstances were felt to be favorable because of the recent occurrence of widespread, destructive flooding (1964) that could be used for comparison with the relative magnitude of past floods, and because the flood deposits of the smaller streams (draining less than a few hundred square miles) are morphologically and texturally distinctive. In addition, trees of several coniferous species that attain great ages are widely distributed on the flood plains of major streams, and many of the trees have not yet been completely eliminated by logging, fire, or construction activity.

DESCRIPTION OF THE AREA STUDIED

The area studied extends 300 miles north along the California coast from San Francisco Bay to the Oregon border and inland as much as 100 miles. Most of our emphasis was placed on the watersheds of the Smith, Klamath, Trinity, Mad, Van Duzen, and Eel Rivers.

The study area includes the Northern Coast Ranges, Klamath Mountains, and Southern Cascades physiographic provinces (fig. 1). All watersheds with the exception of those of the Smith and Klamath Rivers and their tributaries lie wholly within the Northern Coast Ranges province. The Northern Coast Ranges

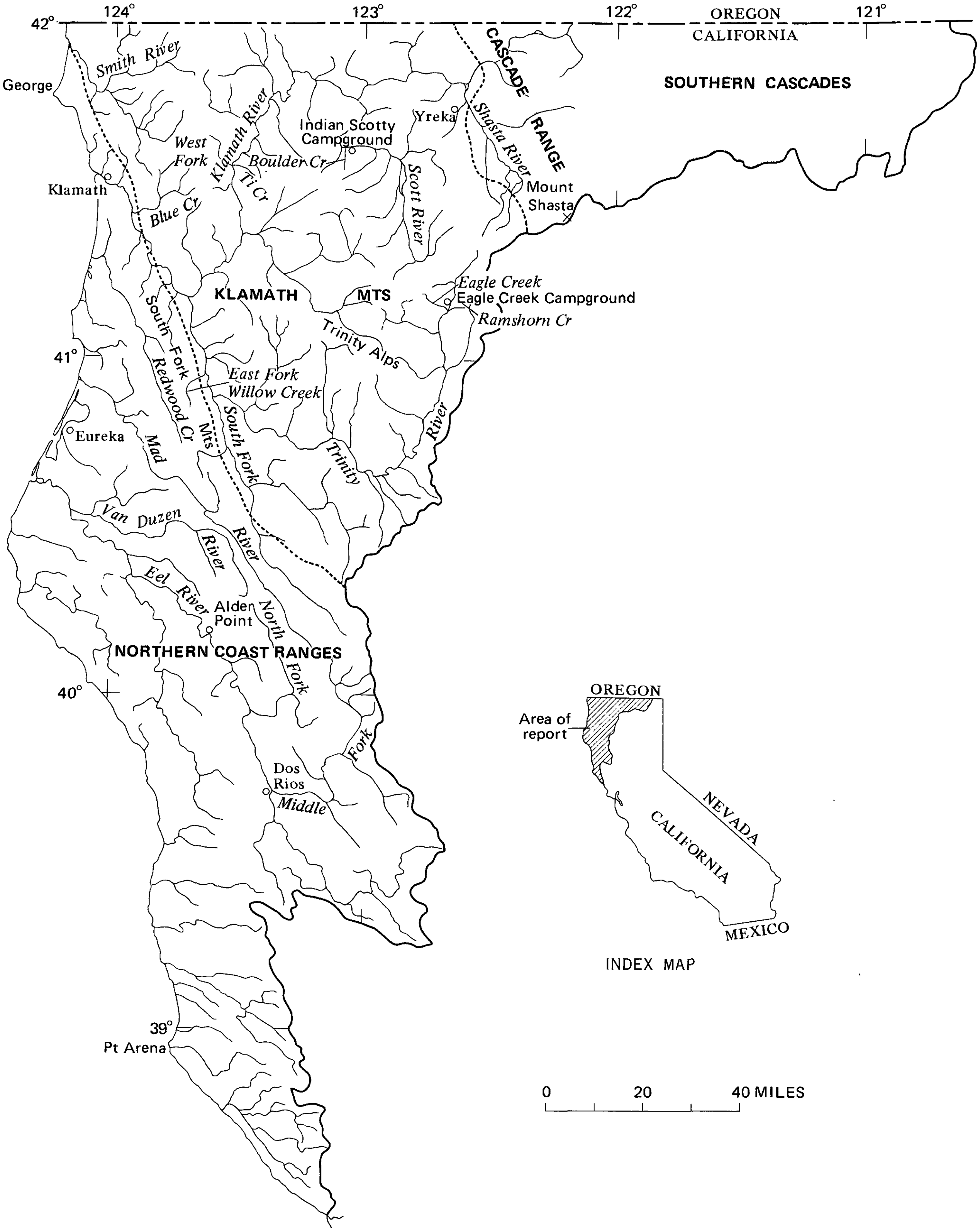


FIGURE 1.—Geomorphic provinces and major drainages of a part of northern California.

are underlain by thick sequences of sandstone and shale which have been intruded by large masses of ultramafic rocks, now largely altered to serpentine. The geologic structure is characterized by northwest-trending folds and faults which control much of the surface drainage. Stream valleys are developed along shear zones associated with major faults, producing a crude trellis drainage pattern. The combination of sheared rocks, shallow soil profile development, steep slopes, and heavy seasonal precipitation produce landslides and soil slips so common to the area.

The Klamath Mountains are rugged and somewhat inaccessible. They lie between the Northern Coast Ranges and the Southern Cascades physiographic provinces. The Klamath Mountains are underlain by highly metamorphosed volcanic and sedimentary rocks that have been intruded by granitic and ultramafic rocks. Structurally these mountains are more complex than the Northern Coast Ranges but display very well defined arcuate regional trends. The Coast Ranges province joins the Klamath Mountains province along the distinct 6,000-foot high ridgelike South Fork Mountains, which have the topographic expression of the coast ranges but are underlain by rocks similar to the Klamath Mountains.

Accordant summits and highly dissected old land surfaces are common along major watercourses in the Klamath Mountains. The modern drainage, unlike that of the coast ranges is transverse to both lithic and structural trends and is deeply incised, thus suggesting superposition.

The Cascade Range lies east of the Klamath Mountains and north of the Sierra Nevada. The Klamath River drainage heads in this plateau of effusive volcanic and pyroclastic rocks. From near the California-Oregon border the Klamath River flows in a well-defined canyon cut deeply in the volcanic rocks. Upstream from the border, however, surface drainage is poorly developed, perhaps because the highly permeable rocks allow ready infiltration of snowmelt and precipitation.

CLIMATE

The climate along the immediate coast of northern California is marked by moderate and uniform annual temperature, heavy and sometimes recurrent fog, and prevailing west to northwest winds. Inland temperatures increase and become more variable, while precipitation decreases. Temperatures inland have ranged from 0° to 110°F; however, winds become only moderate. Both temperature and precipitation are influenced greatly by elevation and local topography. Precipitation is of greater frequency and annual magnitude than anywhere else in California. Nonetheless, it is distinctly seasonal with little occurring from April through October. The seasonal distribution of precipitation is largely controlled by the presence of an anticyclonic cell (high pressure area) normally found off the California coast, especially during dry periods. The frequent and heavy winter precipitation usually occurs when this anticyclone is far south of its usual position. When this occurs warm moist tropical air masses are free to migrate eastward to the Pacific Coast.

Snow falls in moderate amounts at elevations above 2,000 ft, but only at elevations above 4,000 ft does snow remain on the ground for any appreciable length of time. With many mountain peaks at 6,000–7,000 ft above sea level and a few about 9,000 ft, features of past glaciation exist, but the glaciers themselves are virtually extinct.

SURFACE-WATER HYDROLOGY

Precipitation and runoff phenomena have been described in detail by Rantz (1968), Cruff and Rantz (1965), and Rantz and Thompson (1967). The descriptions given here are brief and intended only as a general outline. The reader is referred to the earlier work for more specific information.

About 75 percent of the total annual precipitation falls in the 5-month period, November–March. Most of this precipitation occurs during general storms of several days duration and relative moderate intensity. The isohyetal map (fig. 2), slightly modified from Rantz (1968) shows marked orographic control. This map was constructed from data for a 60-year base period from 1900–1959. It shows that average annual precipitation is influenced by distance from the ocean, elevation, and shape and steepness of mountain slopes in addition to the direction of slopes in relation to moisture-bearing winds. In general, precipitation increases from south to north and is much heavier on southern and western than on northern and eastern mountain slopes. The wide range in average annual precipitation is striking, decreasing from 120 in. in the northwest to a low of only 10 in. in the northeast. Precipitation has varied widely in time as well as space. For example, the precipitation station at Dos Rios in the Eel River basin (fig. 2) has a 60-year mean annual rainfall of 46.4 in. but ranged from 15.3 in. in 1924 to 85 in. in both 1956 and 1958. Obviously rainfall variability can be expected to produce variable unit runoff throughout the region.

The present topography, geology, and climate are major factors that combine to influence the dynamic runoff phenomena characteristic of the north coast. Consider the Eel River basin as a typical example. With only 2 percent of the State's land area it yields 9 percent of the State's runoff (over 5 million acre-feet annually). Average annual rainfall for this 3,000-square mile drainage basin is about 59 in.; some 35 in. or about

60 percent runs off. Most of this runoff occurs during and shortly after the late fall and winter storms. Because of the low permeability of surficial materials, base flow is poorly sustained, thus adding to the large variations in streamflow. Although suspended sediment loads have been measured in the north coastal basins

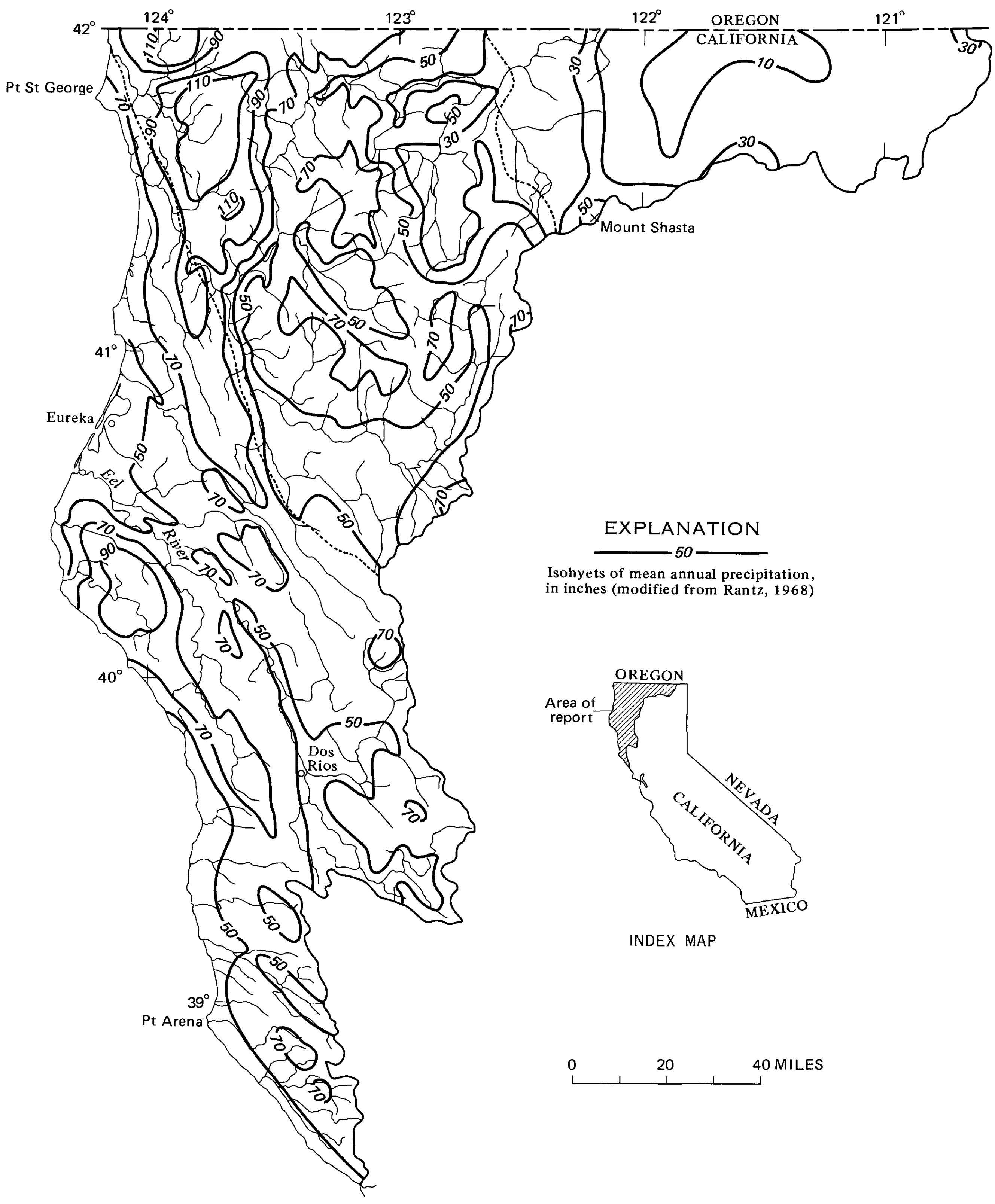


FIGURE 2.—Isohyetal map of a part of northern California.

for only slightly more than 14 years, a recent summary of the first decade of data revealed some dramatic information. Using data collected from 1957–67, a period that spanned the State's largest flood, that of December 1964, Brown and Ritter (1971) show that the Eel River discharged an average of 31,000,000 tons per year of suspended sediment. Converted to a sediment yield of 10,000 tons per square mile annually, this rate is larger than any basin for its size in North America. For example, this rate is 4 times that of the Colorado and 15 times that of the Mississippi. Most significant is the fact that most of this load was moved by high flows, which occurred on the average 10 percent of the time or less. With very few exceptions, throughout the entire Eel River basin, 50 percent or more of the total annual suspended load was carried on fewer than 6 days during the water year. It is also noteworthy that the high sediment yield of 10,000 tons per square mile per year does not include bedload or dissolved load. A minimum erosion rate extrapolated from these data is 4 feet per 1,000 years for the entire Eel River basin with various subbasins having erosion rates of up to 10 feet per 1,000 years (Brown and Ritter, 1971). The data suggest that most material is transported and hence the geomorphic work is done in a very short time. In other words, the infrequent hydrologic event is most significant in the mountainous areas of northern California. A brief description of the largest hydrologic event ever recorded in northern California follows.

THE FLOODS OF DECEMBER 1964

METEOROLOGY

The following description of the meteorology responsible for the floods of December 1964 is a condensation of the work of Rantz and Moore (1965). Heavy rainfall began on December 18, 1964, caused by a storm system which approached the California coast at more northerly latitudes than usual. The storm of December 18–20 brought snow and lower temperatures to higher altitudes and latitudes of the region. This early cold storm set dangerous antecedent conditions by freezing soil moisture and storing additional storm runoff in snowpack. After December 20 succeeding storm tracks moved progressively southward in response to a deteriorating high pressure system over the Pacific. Concurrently, an outbreak of cold arctic air moved farther south out of the Gulf of Alaska and only intensified the tropical storm systems as they approached the coastal areas of northern California. These new storms (after Dec. 20) struck the coast at nearly right angles to the orientation of the mountain ranges thus producing high rainfalls. Higher temperatures associated with the new tropical storms raised the freezing level to altitudes as high as 10,000 ft and caused high precipitation, all in the form of rain even at the highest altitudes. Rates in excess of 8 in. in 24 hours were common throughout the north coast although there was wide regional variation. Precipitation totals for the 5-day period December 19–24 exceeded 20 in. in many places but ranged from a low of 10 to a high of more than 30 in., with the highest values recorded in the mountainous regions of northern California. During the period after December 24 a surge of rising pressure effectively blocked the storm track by moving into the area northeast of Hawaii. The pressure cut off the flow of warm moist air to the west coast but allowed colder arctic air to move southward and cause heavy snow and hail down to very low altitudes. This very effectively reduced further flooding hazards but seriously hampered rescue work in the area.

RUNOFF

With favorable antecedent conditions, high soil moisture, and a thick snowpack, the warm torrential rain of December 19–23 quickly brought north coast streams to the bankfull stage. Exactly 9 years earlier, most of these same streams had flooded to cause a then unprecedented disaster. However, the floods of December 1964 were generally more intense; in many areas of both northern California and Oregon peak stages not only exceeded those of 1955 but were equal to or greater than those that occurred during the almost-legendary floods of 1861–62 (Rantz, 1968). The floods of December 1964 were directly resonsible for the loss of 47 lives and caused damage that totaled almost one-half billion dollars.

The Eel River is a prime example of the response of north coastal streams to the heavy precipitation and consequent runoff. On December 18, 1964, the Eel River at Scotia was discharging a meager 4,600 cfs (cubic feet per second) but peaked only 5 days later at a record 752,000 cfs. The Klamath, Trinity, and Smith Rivers, and other streams also peaked at record-setting stages and rates of flows. At Alderpoint, on the main stem of the Eel, the river rose 90 feet above its normal low-water level. For a 3-day period beginning December 22, 1964, the Eel River discharged 116 million tons of suspended sediment. Only 94 million tons were discharged in the previous 8 years (Brown and Ritter, 1971). Unit runoff for the storm of December 19–23 was as variable as the widespread heavy precipitation. Runoff ranged from a low of about 20 cfs/sq mi (cubic feet per second per square mile) on the Shasta River near Yreka to over 580 cfs/sq mi in parts of the Eel River basin. Although the storm of December 19–23, 1964, was intense over large areas of the Western States, the runoff was not uniform owing to many factors. Erosion was most severe in the eastern sections of the Eel River basin where North and Middle Forks were fed by high unit runoff from steep west-facing slopes. These slopes, saturated by antecedent precipitation and somewhat unstable even under normal rainy conditions, were badly eroded by landslides, slumps, and gullying, especially in areas of sparse vegetal cover.

Over reaches several miles long streambed elevations rose 6–8 feet (Hickey, 1969). These streambed changes reflect large quantities of sediment placed in the stream from bank erosion and landslides. At most sites studied by Hickey (1969) the changes were positive; that is, streambed elevations rose. This effect will probably continue in a downstream direction in succeeding years. Although only qualitative information can be inferred from Hickey's (1969) study it is certain that large quantities of bed material were moved. The quantitative information regarding sediment transported is that of Brown and Ritter (1971) and refers only to suspended load. Their study showed that 51 percent of the total suspended sediment discharged by the Eel River in the 10 years from 1957 to 1967 was transported during a scant 30-day period. Studies in progress on the Middle Fork of the Eel River suggest that the bedload component of the total sediment transported varies between 10 and 40 percent. Obviously the effect of a rare hydrologic event such as the floods of December 1964 have long-term implications beyond the immediate loss of life and property. Channels have changed geometry and location within valleys, and the capacity to transport both water and sediment are altered perhaps for many years to come. Flood records must be extended to give man a better perspective of floods and flood-plain use.

EXTENSION OF FLOOD RECORDS IN NORTHERN CALIFORNIA

METHODS

Some of the geological and botanical methods used elsewhere were found to be of limited applicability in this study. The stratigraphic approach of Jahns (1947) and Mansfield (1938) is more appropriate for large streams with broad flood plains, where thin layers of relatively fine-grained flood deposits may be laid down over large areas. In the steep, narrow canyons of mountain streams in northern California the flood deposits tend to be coarse, thick, and local in distribution. Deep lateral and vertical erosion during major floods frequently destroys older flood deposits, so that a regular succession of beds representing a sequence of past floods is rarely found. However, such depositional records do exist locally in the study region. For example, at the mouth of Bull Creek, above the junction of the South Fork and the main stem of the Eel river, backwater conditions exist during major floods that result in the deposition of thin silt-clay beds. Fifteen such flood-deposited layers totaling 30 feet in thickness have been recognized (Zinke, 1968).

Detailed investigation of flood damage to individual trees, as described by Sigafoos (1964), was not attempted in this study. We observed few examples of scarring or breakage as the result of the 1964 or earlier flooding, and saw no instances of survival of overturned or buried trees. The coniferous trees in the study regime seem less suitable for this kind of investigation than are the deciduous flood-plain species of other regions.

TREE-RING DATING OF FLOOD DEPOSITS

The minimum age of a flood-plain deposit can be estimated from the age of the oldest tree that is growing on the deposit. The age of a living tree is determined by counting the annual rings in a sample taken with an increment borer. The main source of uncertainty is the need to estimate the number of years that were required for height growth of the tree to the level at which the sample was taken, normally about 3 ft. We have allowed 5 years for height growth in all such age determinations in this work. The actual age of the deposit is necessarily at least somewhat greater than the date of establishment of the oldest tree, because considerable time may have elapsed between deposition and the establishment of tree seedlings on the new surface. In all of our study localities, we found that seedlings of at least some local coniferous species were abundantly established on 1964 flood deposits by the summer of 1969—a lapse of no more than 5 years. In a more detailed investigation, Sigafos and Hendricks (1969) also found an average time interval of 5 years between surface stabilization and tree-seedling establishment on glacial moraines and outwash deposits on Mount Rainier, in the State of Washington. Therefore, in estimating the minimum age of a flood deposit, at least 5 years should be added to the age of the oldest tree on the deposit. However, a deposit may be much older than age data from trees would indicate, because many generations of trees may have lived and died on the surface in the time interval between the date of deposition and the present.

In some of our study localities, stumps of recently cut trees were also used to obtain minimum age estimates for flood deposits (fig. 3). In some cases, cutting followed the 1964 flood and was designed to salvage trees that had been damaged or killed by flood deposition. Although the condition of the cut surface gives a clue as to time elapsed since cutting, we relied primarily on local information for general or specific dates of cutting activity. The use of stumps introduced an additional uncertainty into the age estimates—that is, the uncertainty in the time that has elapsed since cutting.

FIGURE 3.—Ring-counted and radiocarbon-dated stumps used to date flood deposits along Blue Creek near Klamath, Calif.

RADIOCARBON DATING

The radiocarbon method was used to estimate ages in the few cases in which datable material could be found in flood deposits. There are a number of possible sources of uncertainty in radiocarbon age determinations. However, there are only two major sources in the dating of wood used in this study. The first is the counting error, or statistical uncertainty in the measurement of the carbon-14 content of the sample. This uncertainty is conventionally expressed as a range of plus and minus one standard deviation (one sigma) of the stated age. On the average, two-thirds of a large number of repeated observations on the same sample would be expected to give dates in the range from the stated age minus one sigma to the stated age plus one sigma. Sigma ranges from 60 to 100 years in the determinations that we obtained from a commercial radiocarbon laboratory.

A second source of error or uncertainty may be more important than the counting error in radiocarbon dates from certain time periods. This is the discrepancy between radiocarbon (C^{14}) age and true age that is due to past fluctuations of the concentration of C^{14} in the atmosphere (Stuiver and Suess, 1966). For example, wood that was formed during a period when atmospheric C^{14} concentration was much higher than normal will yield an anomalously "young" date. Conversely, a date that is too "old" will be obtained from wood formed during a period of relatively low atmospheric C^{14} content. During intervals of rapid atmospheric C^{14} fluctuation such as the past 500 years, a sample with a given C^{14} content may represent any of several possible time periods.

It is possible to correct an apparent C^{14} age to get a better estimate of the true sample age. A large number of selected comparative C^{14} and "true" dates have recently been published, based on radiocarbon analysis of wood samples that have been accurately dated by dendrochronological methods (Damon and others, 1970; Ralph and Michael, 1970). In our work, an estimate of the true sample age was made by comparing the one-sigma radiocarbon age range of our sample with the one-sigma range of wood samples of true known age (calibration sample). The most probable true age of our sample is assumed to be the true age of the calibration sample with an overlapping one-sigma radiocarbon age range. In most cases, more than one calibration sample has a radiocarbon age range that overlaps our sample age. This results in a large uncertainty in the true age of our samples.

Despite the abundance of logs and organic debris in the 1964 flood deposits, such material was rarely seen in exposures of older flood deposits. We were able to find and sample buried logs and natural stumps in only a few of our study localities.

DESCRIPTION OF SITES WITH GOOD EVIDENCE FOR PAST FLOODS

Field studies began during the summer of 1968 with reconnaissance automobile trips along all major drainages of the north coast. The necessity of covering large land areas in a short time precluded foot traverses, and boat traverses were impossible during low water discharges. Therefore, it is possible that many potential sites with good prehistoric flood evidence may have been overlooked. Although we observed many dead trees and buried stumps, all of which could be related to the flood of December 1964, not all were long-lived species and many more were killed because of human activities. For example, backwater conditions generated by narrow culverts caused severe upstream aggradation that normally would not have occurred. This aggradation buried many trees in as much as 30 feet of alluvium; although spectacular, these sites were discounted as being unnatural (fig. 4).

FIGURE 4.—Douglas-fir tree killed by burial in flood debris during 1964 flooding as a result of backwater effects caused by a culvert on Ti Creek at the Klamath River.

The location of sites are shown in figure 5 where evidence of prehistoric flooding has been found. Unfortunately not all sites provide evidence for both maximum and minimum recurrence interval. Any one site rarely offered both types of age-control data. Figure 5 shows that widespread botanical evidence does exist and this evidence is a potentially useful tool in placing age constraints on the potential frequency of occurrence of modern natural processes. Only four sites will be discussed in detail to show the techniques utilized in placing some time limitations on ancient floods. These four sites are Blue Creek near Klamath (pl. 1*A*, *B*, *C*), Scott River at Indian Scotty Campground (pl. 1*D*), Trinity River at Eagle Creek Campground (pl. 1*E*), and the East Fork of Willow Creek (pl. 1*F*). Large-scale topographic maps were especially made of these four sites from low altitude aerial photographs. The detailed maps allowed contact geologic mapping at a scale of 1 inch equals 100 feet. Contour intervals are 5 ft on the Blue Creek, Scott River, and Trinity River maps and 2 ft on the Willow Creek map.

BLUE CREEK NEAR KLAMATH

DESCRIPTION

The valley of Blue Creek contains at least three gravel units older than the flood deposits of 1964. The highest level deposit, older gravel 3, is a deeply weathered gravel located east of the creek near the southern end of the study area (pl. 1*A*). The gravel rests on bedrock about 25 feet above the present channel and is about 65 ft thick. A much lower gravel deposit, older gravel 2, underlies extensive terraces bordering the stream. The terrace surface is about 20 ft above the channel, and the coarse, obscurely bedded and poorly sorted gravel is about 20 ft thick. A small gravel deposit with a surface at about the same relative height is located in the West Fork of Blue Creek, 1,000 ft upstream from the confluence with Blue Creek (pl. 1*B*). The lowest pre-1964 deposit, older gravel 1, that could be identified is a gravel bar that was overtopped by the 1964 flood and is partly buried in 1964 deposits (pl. 1*A*).

AGE DATA

The oldest fluvial deposit along Blue Creek is the small patch of older gravel 3 resting on bedrock east of the stream. Based on its topographic position, small extent, and degree of weathering, it probably is of Tertiary or Pleistocene age. It is probably unrelated to more recent flood events.

The extensive terrace gravel, older gravel 2, can be assigned a minimum age of 100 years, based on estimated dates of establishment of the largest trees grow-

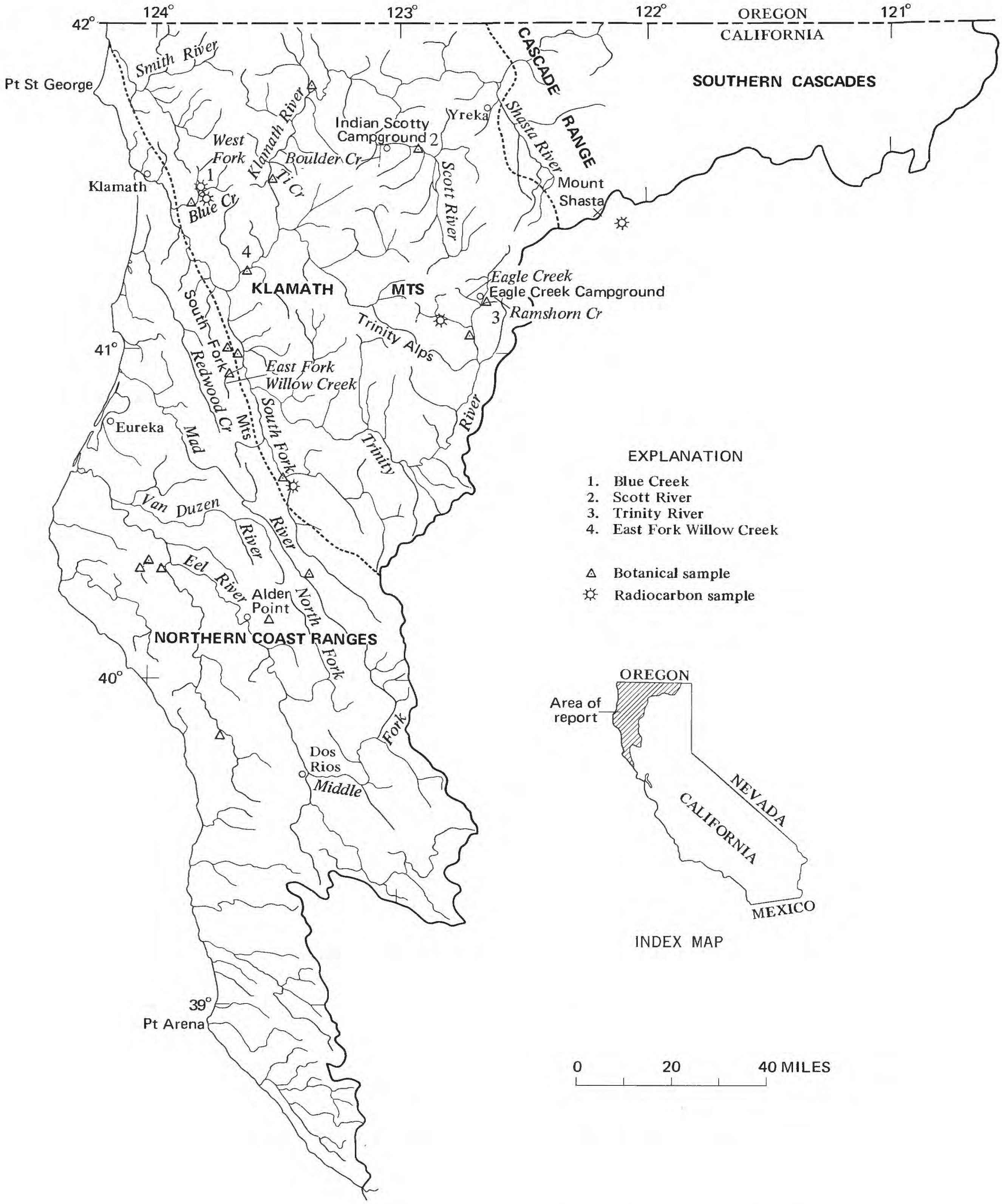


FIGURE 5.—Sites where evidence of prehistoric flooding has been found in northern California.

ing on the terrace surface (pl. 1*A*, *B*). A maximum age for this deposit can be assigned on the basis of radiocarbon and dendrochronological dating of included logs and buried trees. The approximate date of death of the buried trees can also be estimated from study of growth fluctuations in a nearby living tree.

Radiocarbon age determinations were obtained for wood samples from the stumps of a buried tree (BC 11) and from two logs (69–146 and BC 1) included in the terrace gravel along Blue Creek (pl. 1*A*, *B*). The resulting ages were between the mid-1500's and the present. (Years given are A.D.) The older gravel 2, therefore, probably was deposited between 1545 and 1870. The radiocarbon date of the stump (69–145) in the gravel deposit on West Fork, Blue Creek gives a date of death between 1600 and the present. Thus, this deposit seems to be correlative with the terrace gravel along the main stream.

Tree-ring dating methods were also used to obtain an age estimate for the terrace gravel. Four of the buried redwood stumps (BC 9, 10, 11, 13) were sampled using a power increment borer. A large living redwood (BC 21) on the hillslope immediately adjacent to the buried stand of trees was also cored. Study of the annual ring patterns showed that the growth records of three of the stumps could be matched by cross-dating techniques (pl. 1*C*). The same ring patterns appear near the inside of the core from the living tree. Therefore, it is possible to assign approximate calendar dates to the annual growth rings in the stumps. These dates are approximate because certain annual rings may not be present along the sampled radius of the living tree. Such locally absent rings present a well-known dendrochronologic problem in old coastal redwoods (Fritz, 1940).

Despite the uncertainty in the tree-ring dates, the time of death of the buried redwood stand probably can be estimated more accurately from this evidence than is possible using the radiocarbon method. The tree-ring dates for the outermost annual ring in each of the three dated stumps ranges from about 1660 to about 1705. These are only minimum estimates of the dates of death of the trees, because fire and decay have removed three or more inches of wood (primarily sapwood) from the outside of the stumps. This estimate is based on the thickness of the zone of decayed wood that lies between the bark and the sound wood at the base of the stumps. Three inches of wood corresponds to 100 to 150 years of growth in these stumps. Therefore, this must be added to the dates of the outermost rings in the sound wood, giving estimated dates of death sometime after 1800.

Another line of tree-ring evidence suggests that the trees in the redwood stand in the valley of Blue Creek died between 1860 and 1870. The annual rings in the living redwood (BC 21) show an abrupt tenfold increase in average thickness beginning about 1870. This growth "release" is similar to that observed in trees when neighboring trees are removed by fire, windstorm, logging operations, or other causes. This growth release probably followed the death of the trees in the buried stand in the valley of Blue Creek. Thus, the buried trees probably died in the 1860's as a result of burial to a depth of 20 feet by the terrace-gravel deposits.

Three separate lines of evidence suggest that the deposition of older gravel 2 occurred probably between 1860 and 1870. Major flooding on north coast streams is known to have occurred during the winter of 1861–62. Deposition of the gravel probably took place during one or more floods on Blue Creek during the 1861–62 season. Our previously published estimate (Helley and LaMarche, 1968) of the date of the gravel as 1,500±100 years is thus considerably in error. One source of this error was our use of an uncorrected radiocarbon date of 1,100±100 years that actually corresponds to a tree date between 1200 and 1300. The second source of error was our failure to take into consideration the 100 to 150 years of annual growth that is missing from the outside of the buried stump. The dendrochronologic and radiocarbon data are summarized in tables 1 and 2.

TABLE 1.—*Radiocarbon and dendrochronologic data for trees sampled at Blue Creek*

	Radiocarbon laboratory number	Species	Apparent C^{14} date of sample, years A.D.	Number of annual rings to outside ring	Apparent C^{14} date of outermost ring, years A.D.
		Buried stumps			
BC 11	I–2572	Redwood	1100±100	460	1560±100
69–145	I–4728	Douglas-fir	>1765	95	>1860
		Logs included in deposit			
BC 1A	I–4151	White fir	1680±60	141	1821±60
BC 1B2	I–4341	White fir	>1765	30	>1795
69–146	I–4729	Douglas-fir	1655±90	195	1850±90

TABLE 2.—*Corrected radiocarbon-based dates for trees sampled at Blue Creek*

Specimen number	Probable outside date, A.D.	Condition of specimen
	Buried stumps	
BC 11	1560–1710	Sapwood missing.
69–145	1610–present	Sapwod partly preserved.
	Logs	
BC 1		Sapwod partly preserved.
1A	1591–present	
1B2	1545–present	
69–146	1645–present	Sapwood and bark preserved.

SCOTT RIVER AT INDIAN SCOTTY CAMPGROUND

DESCRIPTION

Two well-preserved gravel deposits are exposed along the left bank of the Scott River in the northeast quarter of the Scott Bar 15-minute quadrangle just east of its confluence with Boulder Creek. Few older gravel deposits are preserved along the Scott River and those described here are in a protected bend in an otherwise steep canyon.

The left bank of the Scott River at this site is underlain by two gravel units older than the 1964 flood deposits (pl. 1*D*). The highest deposit, older gravel 2, up to 40 feet above the present river bed, is the thickest and most extensive. It extends 600 feet along the river and is as much as 250 feet wide. This deposit is about 25 feet thick, very coarse, poorly sorted, and covers a bedrock surface. Its flat to slightly undulating surface has only traces of old channels preserved.

Another gravel deposit, older gravel 1, is found lower and closer to the channel. It, too, underlies the left bank, but is thinner and less extensively preserved as a thin layer about 10 ft above the river bed. This deposit is only slightly more than 5 ft thick. One small patch of this gravel is found as an island in the channel about 500 ft downstream. The gravel deposited by the floods of 1964 covers older gravel 1, and has, in part, eroded the lower section of older gravel 1. Streamflow measurements at the U.S. Geological Survey's gaging station located approximately 5 miles upstream indicated peak stages of a little more than 25 ft during the December 1964 floods. Although no stage information was available at Indian Scotty Campground, valley shape considerations would necessitate that the older gravel 1 was inundated by the 1964 floods.

AGE DATA

The oldest gravel (older gravel 2) can be assigned a minimum age of 445 years based on ring counts on the largest stump preserved on the surface. "Release" effects shown in living trees adjacent to the stump were used to establish the date of cutting. These counts suggest a depositional date before 1525.

Both stump counts and increment cores were taken on older gravel 1. The oldest core taken was from a tree on the island in the channel downstream, and it appears to be 80 years older than stump and increment core counts upstream. Although no textural or morphological difference was detected between upstream and downstream deposits of older gravel 1, a chance does exist that two events may be recorded in the younger of the gravels. The date of deposition of the younger gravel at the downstream site is earlier than 1610. At the upstream site the oldest date appears to be 1690. Since the upstream site is in a narrower channel, where both water velocities and stages would be higher during floodflows, it may simply have been more difficult to establish growth at the upstream site.

No samples suitable for radiocarbon dates could be found in the two older gravel deposits. From existing gaging-station records it would appear that the historic floods of 1861 and 1955 were equal in magnitude, and both were probably less severe than the December 1964 floods. The December 1964 floods would be equal to or slightly less severe than those responsible for the deposition of older gravel 1. No estimate can be made for the flood responsible for older gravel 2; however, owing to the very coarse texture, thickness, and extent of the deposit, it is highly probable that the flood was of greater magnitude than the floods of older gravel 1.

TRINITY RIVER AT EAGLE CREEK CAMPGROUND

DESCRIPTION

Trinity River at Eagle Creek Campground (pl. 1*E*), along the eastern edge of the Trinity Alps part of the Klamath Mountains Province, has been the location of repeated gravel deposition. Here the valley of the Trinity River is wide, flat, and situated just downstream from a very narrow, steep-walled, straight, and hence, highly competent channel. In addition to the abrupt change in channel geometry, two tributaries enter the Trinity River in this wide valley, enhancing the potential for sediment deposition and preservation.

At least three older gravel units are easily recognized here (pl. 1*E*). The oldest of these units, older gravel 3, covers the largest area. It extends from the head of the valley, where it forms the banks of the Trinity River, downstream for approximately 1,200 ft. It is as much as 15 ft thick and consists of poorly sorted boulder gravel with most clasts displaying thin weathering rinds. The surface is subdued but broad swalelike channels and low levees are discernible. The next-youngest gravel, older gravel 2, is incised and lies nested with older gravel 3 (fig. 6). It is not as extensive and only slightly more than 5 ft thick. The younger gravel has been slightly modified by both erosion and deposition caused by the floods of 1964. Debris from the 1964 flood covers much of the surface of older gravel 2, especially at the confluence of the Trinity River with Eagle Creek (pl. 1*E*). The surface morphology is distinct, showing well-preserved flood channels and levees which are especially analogous to those seen on deposits of the 1964 flood on the East Fork of Willow Creek (fig. 7) and those described on Coffee Creek by Stewart and LaMarche (1967).

A small, but distinctly older gravel unit, older gravel 1, is incised in older gravel 2 but found preserved only near the mouth of Ramshorn Creek (pl. 1*E*). This unit is recognized as a separate gravel because it is incised in older gravel 2, because it has fresher surface morphology than the older deposits, and because of the

FIGURE 6.—Prehistoric flood channel between older gravel 3 (left) and older gravel 2 (right). View is upstream of the right bank of the Trinity River Eagle Creek.

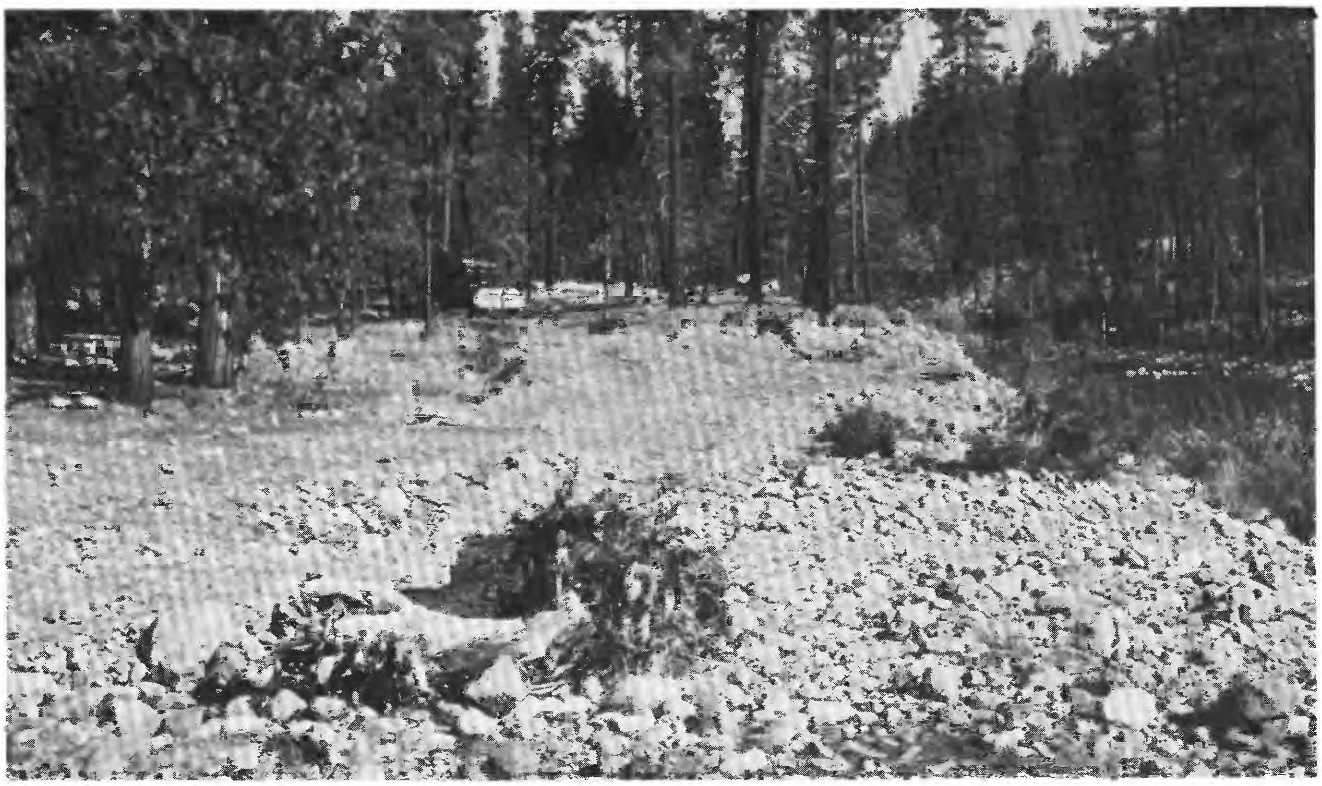
tree-ring evidence. This unit was partially modified by erosion during the 1964 flood. Data from gaging-station records collected approximately 4 miles downstream from Eagle Creek indicate that the floods of 1964 had a peak stage of just above 12 feet. Extrapolation upstream would suggest that probably all of older gravel 1 and larger areas of older gravel 2 were inundated.

AGE DATA

Ponderosa pine and incense-cedar stumps here were counted. Dates of cutting were obtained from a nearby Forest Service field office. The oldest dendrochronological sample is found on older gravel 3, yielding an estimated date of establishment of about 1500. However, this is only 40 years older than a stump count on older gravel 2. This suggests that the oldest gravel unit, older gravel 3, may be much older than any living tree in the area. Older gravel 1 is at least as old as 1735 but only one stump count was used to determine this and, of course, probably is the result of an event on Ramshorn Creek. No vestige of the floods of 1861 or 1955 was observed, probably because the floods of 1964 were larger, and completely obliterated any evidence.

Observations of deposits laid down by the floods of December 1964 and reports by Stewart and LaMarche (1967) of eyewitness accounts may allow estimates of the relative water discharges which deposited each of the older gravel units. At least a comparison between older gravel 1 and older gravel 2 and sediments deposited by the flood of December 1964 should be attempted. Several assumptions are necessary. First, and perhaps the least acceptable, is that the average depth of flow during the floods was at least as great as the relief shown by the boulder levees. At most places this is only 5 ft. Second, that the width of the gravel deposits, as shown on the geologic maps, represents the width of the channel during the flood; this of course assumes only one channel. Using the floodmarks and distribution of 1964 gravel it is possible that older gravel 2 was deposited by an event about 50 percent larger than 1964 and older gravel 3 was deposited by an event about twice as large as 1964. Using discharge data computed at a site 4 miles downstream from the Eagle Creek site, the 1964 flood peak was about 21,000 cfs (cubic feet per second), the flood for older gravel 2 would have been about 30,000 cfs, and that for older gravel 3 about 40,000 cfs.

A



B

FIGURE 7.—Surface morphology. *A*, Gravel levee on right bank of the East Fork Willow Creek deposited by the flood of December 1964. *B*, Gravel levee on the right bank of the Trinity River at Eagle Creek deposited by a flood at least as old as 1540. Note asymmetry of topography.

EAST FORK WILLOW CREEK

DESCRIPTION

The East Fork of Willow Creek, just upstream from its confluence with Willow Creek, has been the site of extensive aggradation due to the 1964 flood (fig. 5). Although only 1,200 ft of the stream has been mapped, the 1964 flood debris appears as a continuous blanket from the mouth of the East Fork upstream for more than one-half mile (pl. 1*F*). Here only two small patches of pre-1964 gravel units could be found, but old partially buried stumps apparently rooted beneath the 1964 debris provided an unusual site for dating the pre-1964 gravel. The older gravel was not eroded nor was 1964 flood gravel deposited on it; hence its morphology was preserved, and it was identified as an older gravel levee. Both older gravel deposits are similar in texture and morphology to the 1964 deposits and differ only in having more accumulated organic matter on their surfaces.

AGE DATA

Two living Douglas-fir trees, unscathed by the 1964 flood, were found on the upstream site while only stumps were found on the downstream site. Ring counts of increment cores on the living trees allow minimum date of deposition of the upstream gravel, older gravel 1, to be at least 1749 (pl. 1*F*). The downstream gravel, older gravel 1, was dated by ring counts on stumps which we ascertained were logged after the December 1964 flood. The estimated date of deposition is at least 1590. Since the age of deposition of the two older gravel deposits differ by about 160 years, it may be concluded that two events prior to 1964 are represented by these older gravel deposits. The probability also exists that no trees were established on the upstream older gravel deposit in 1590 and that only one older flood event is responsible for both deposits. The interesting fact in terms of flood frequency, however, is the elevation to which the older gravel deposits and those of 1964 extend. The field evidence suggests that both flood events probably had similar stages and since the channel is straight and confined in bedrock, the discharges probably were similar. An event similar in magnitude to the flood of December 1964 occurred around 1600 and probably another around 1750. No evidence of the large floods of 1861 or 1955 were found, probably because the flood of 1964 was larger.

SUMMARY AND CONCLUSIONS

The concepts and techniques described here will have great utility for onsite determination of flood frequency, flood stage, and possible discharge, and should not be ignored when considering flood-plain zoning and possible development.

Age determinations from standing trees certainly have more validity than those from stumps. However, we found little difficulty in establishing the date of cutting by either "release" effects in adjacent trees or actual oral confirmation of cutting.

Any regional comparison of previous flood histories in northern California probably would be premature because of the lack of more detailed local data and because of the extreme variability in unit runoff during large floods such as demonstrated during the 1964 floods. A good example is the preservation of the 1861 flood deposits along Blue Creek while no evidence of this large flood was observed at the other three detailed study localities. It does seem evident, however, that the largest flood event in the recorded history of northern California, that of December 1964, was exceeded by an earlier flood that occurred about 1600 and that floods of the 1964 magnitude have occurred in the more recent past.

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