PALEOHYDROLOGIC BOUNDS AND THE FREQUENCY OF EXTREME FLOODS ON THE SANTA YNEZ RIVER, CALIFORNIA

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ABSTRACT

Many rivers in the western U.S. are flanked by a stair-step series of terrace surfaces. These terrace surfaces are abandoned flood plains that range in age from several hundred to tens of thousands of years. The soils and stratigraphy under these surfaces record the time interval since the last major flood inundation. The deposits under these surfaces are stream-transported flood plain sediment that is highly-erodible, and thereby reliably records substantial inundation. Preserved, non-inundated surfaces of known age form conservative limits for the paleostage of past large floods. These paleostage limits can be input into a step-backwater model to estimate the maximum discharge that would not significantly inundate, and therefore significantly modify, a particular geomorphic surface. This maximum discharge, together with the age of the surface, forms a conservative limiting bound on peak discharge over a long time period. These bounds are not actual floods, but instead they are limits on flood magnitude over a measured time interval. In this way, these bounds represent stages and discharges that have not been exceeded since the geomorphic surface stabilized.

Following the framework introduced by Stedinger and Cohn (1986), this type of flood record spanning hundreds to thousands of years can be input into flood-frequency calculations. These long-term paleohydrologic bounds accurately portray the ability of a specific basin or region to produce extreme floods and significantly narrow the confidence intervals around predicted flood magnitudes at long return periods. Including paleohydrologic bounds in the flood frequency calculations indicates that the flood frequency curve has a fundamentally different trend at long return periods. That is, extrapolating only from the record of annual peak discharge estimates leads to return periods for large floods that are orders of magnitude shorter than if the paleohydrologic bounds are included. In the case of the Santa Ynez River at Bradbury Dam, this means that a discharge of spillway capacity (160,000 cfs) has a calculated return period of more than 6,000,000 years when paleohydrologic bounds are included in the frequency analysis, as compared with a calculated return period of less than 2000 years when flood frequency is calculated based on the record of annual peak discharge estimates.

For dam safety, the critical issue is not the accurate estimation of a complete record of floods well within the operating range of the structure, but rather the frequency of floods that could challenge the operational capacity of the structure. The key issues are the precision of the frequency estimate of such large floods, and the probability that the operational capacity of the dam will not be exceeded. Floods near the magnitude of the paleohydrologic bounds are direct indicators of the likelihood of large floods that might compromise dam safety. The results of paleoflood studies in California, Oregon, and Utah demonstrate that discharges with calculated annual probabilities of 1 in 10,000 are in the range of five to 20 percent of the hypothetical Probable Maximum Flood (PMF).

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INTRODUCTION

A study conducted for Bradbury Dam on the Santa Ynez River, Santa Barbara County, California demonstrates the utility of incorporating paleohydrologic bounds in flood-frequency calculations. Bradbury Dam impounds 200,000 acre-feet of water in the mountainous upper 417 square miles of the Santa Ynez River basin (Figure 1). The majority of the drainage basin is in the Los Padres National Forest and is generally undeveloped. There are two dams upstream, Gibraltar and Juncal, with much smaller storage capacities of 15,000 and 7000 acre-feet, respectively (Figure 1). Bradbury Dam is a 3350-ft-long, 280-ft-high embankment constructed between 1950 and1953. The spillway capacity is about 160,000 cfs.

The calculated Probable Maximum Flood (PMF) with a peak discharge of 460,900 cfs would overtop Bradbury Dam (USBR, 1995). There is adequate time to evacuate the downstream population at risk in advance of an overtopping induced failure (USBR,1994). However, economic damages would be extreme. Therefore, a decision to structurally modify the dam to prevent an overtopping failure is based on an analysis of economic risk. A critical component of this analysis is the probability of the flood that causes overtopping failure. The extrapolated recurrence for the PMF, between the upper and lower 90 percent confidence limits, based on 41 years of annual peak discharge records, extends from less than 100 years up to 1,000,000 years (USBR, 1993). The large uncertainty in the projected return period of the PMF results in a very large range of justifiable expenditures for hydrologic dam safety modifications. The goal of this study is to provide additional information, beyond the historic record, for decision-making on hydrologic dam safety issues affecting Bradbury Dam, and thereby reduce the range of uncertainty in the frequency estimates of extreme floods on the Santa Ynez River.

PALEOHYDROLOGIC BOUNDS

The objective of the Santa Ynez River paleoflood study is to identify and assign ages to geomorphic surfaces adjacent to the river that serve as limits for the paleostage of large floods. These paleostage limits can then be input into a step-backwater model to calculate the maximum discharge that would not significantly inundate, and therefore significantly modify, a particular geomorphic surface. This maximum discharge, together with the age of the surface, forms a conservative limiting bound on flood discharge through time for use in flood-frequency analysis. These bounds are not actual floods, but instead they are limits on flood magnitude over a measured time interval. In this way, these bounds represent stages and discharges that have not been exceeded since the geomorphic surface stabilized.

Paleoflood hydrology includes the study of the geomorphic and stratigraphic record of past floods (e.g., Baker, 1989; Jarrett, 1991a). This record is a direct, long-term measure of the ability of a river to produce large floods and may often be at least 10 to 100 times longer than the conventional record of annual peak discharge estimates. Paleohydrologic techniques offer a way to lengthen a short-term data record and, therefore, to reduce the uncertainty in hydrologic analysis (Jarrett, 1991a). Obviously, this allows for a higher degree of assurance when making dam safety decisions regarding floods with long return periods. Paleoflood studies allow a long-term perspective that can put exceptional annual peak discharge estimates in context and assist in reconciliation of conflicting historical records.

Most conventional estimates of the frequency of large floods are based on extrapolation from short periods of measurement, sometimes with the addition of historic information. Most magnitude estimates for extreme floods are made by extrapolation of the flood-frequency curve to a given return period or annual probability, or by hypothetically maximizing rainfall-runoff models. Frequency estimates for maximized rainfall-runoff models are either arbitrarily assigned or are based on extrapolating the flood-frequency curve to the calculated discharge. No matter how many of these short-term records are statistically combined, they can never accurately characterize the probability of very infrequent floods because estimates of statistical

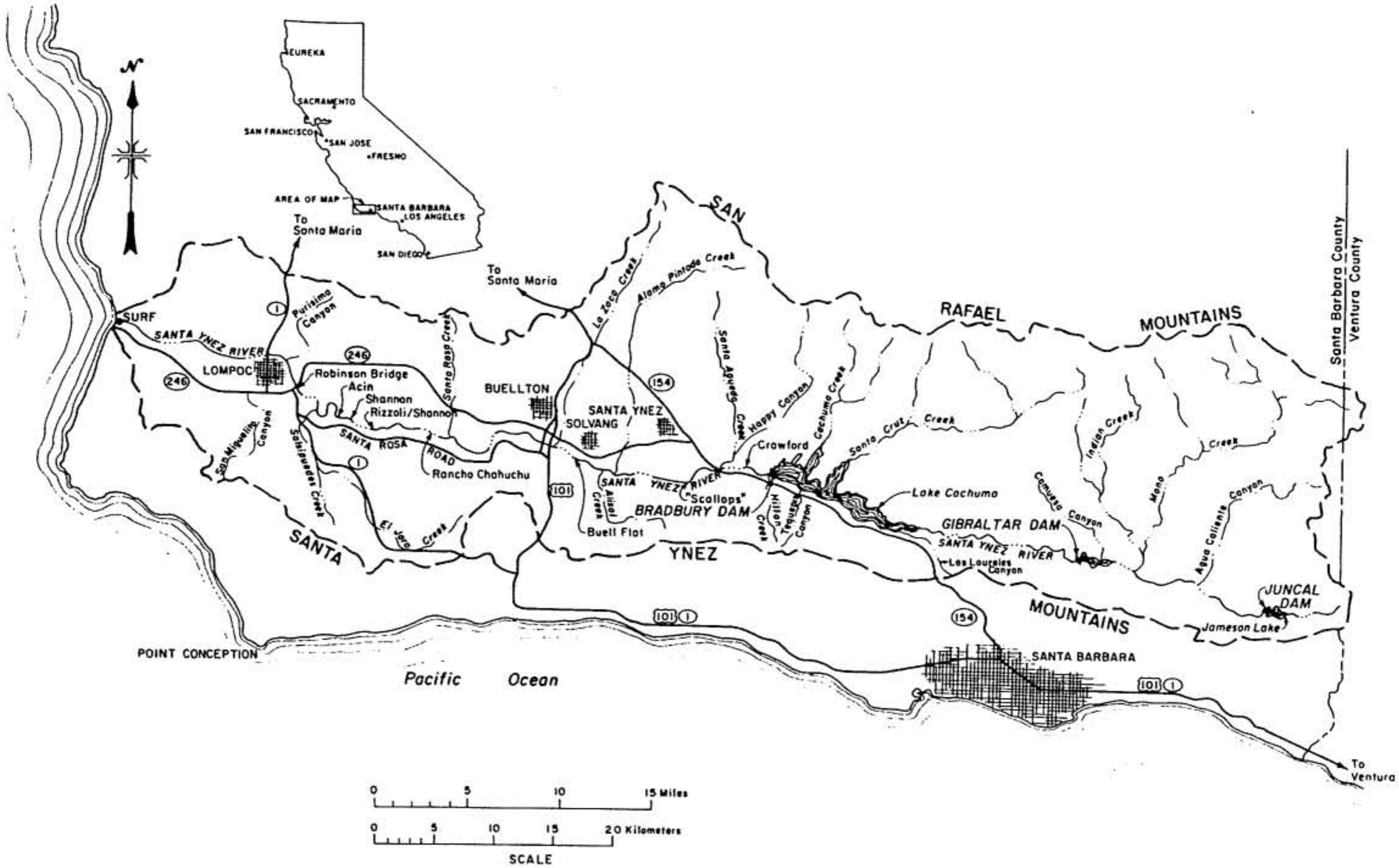

Figure 1. Location map of the Santa Ynez River and Bradbury Dam. Study locations mentioned in the text are noted along the river.

confidence are directly related to the length of record. Because each basin is unique, regionalizing or substituting space for time to compensate for short record length cannot completely substitute for the accurate characterization of the properties of a specific site or region, and may result in unwarranted confidence. If the record of annual peak discharge estimates contains an exceptionally large flood(s), this event(s) is usually assigned an unrealistically short return period, omitted from the frequency analysis, or "weighted" in some arbitrary fashion. Thus, any estimate of a flood with a recurrence greater than several hundred years that is based only on short-term record of annual peak discharge estimates or even long historic records of a few hundred years, will have a large inherent uncertainty. Paleoflood hydrology offers a means of verifying return periods that are many times longer than the length of the gage or historic records (Costa, 1978).

There is a long history of paleoflood hydrology, in a wide variety of settings throughout the world (Costa, 1986; Patton, 1987; Baker et al., 1988). One widely used technique, slackwater studies, uses fine-grained sediment that accumulates in backwater areas to construct a detailed history of past floods (e.g., Patton et al., 1979; Kochel and Baker, 1988). Early studies by Mansfield (1938) on the Ohio River and Jahns (1947) on the Connecticut River, demonstrate another approach. They recognized that historic floods had overtopped sites not previously inundated in thousands of years. Lacking evidence of recent inundation, the age of a geomorphic surface is an estimator of the minimum return period of a flood that could inundate that surface (Costa, 1978).

A paleohydrologic bound is a time interval during which a given discharge has not been exceeded. Both properties of the paleohydrologic bound, time and discharge, are independently determined from objective criteria in the field. This approach is appropriate for hazard assessment because paleohydrologic bounds provide extremely valuable information for improving estimates of the frequency of large floods, because the data are a direct description of the largest floods. It is not necessary to develop evidence of specific paleofloods to define paleohydrologic bounds, although it can be convenient for illustration.

Incorporation of long-term paleohydrologic information in flood-frequency studies does not depend on being able to reconstruct the complete record of all past floods. Statistical techniques that can incorporate paleohydrologic bounds are a useful way to take advantage of paleohydrologic information (Stedinger and Cohn, 1986). In this way, it is not important if floods of a specified recurrence are not recorded or included in the frequency analysis. What is important is that limits on flood magnitudes over time intervals can be identified. Sensitivity analyses show that the addition of only one or two paleohydrologic bounds that span a range of hundreds to thousands of years have a significant impact on the shape of the flood-frequency curve.

The field expression of paleohydrologic bounds, stable geomorphic surfaces, are flood plains that have been abandoned due to stream incision. Once abandoned, their surface characteristics change with time. Two of the most easily recognized changes involve the modification of surface morphology and the development of soil. Through time, slope processes and weathering mute the expression of surface irregularities related to fluvial erosion and deposition. Once a surface has stabilized, that is, it is no longer episodically overtopped, soils form in a predictable sequence (Birkeland, 1984).

Disruptions in soil profiles and geomorphic features, such as eroded channels, that result from significant inundation by large floods are generally easily recognized. This is why these former flood plain surfaces are reliable indicators of flood stage through time. The limits of the surface define a maximum channel width through which a maximum discharge can be modeled. The ages associated with the geomorphic surfaces that form bounds for flood magnitude are almost always minimum ages because of the problems related to dating the precise time when a particular surface was abandoned. The result is an estimate of the **maximum** discharge during the **minimum** time interval since stabilization. These estimates are made even more conservative because through time, channels may downcut and erode laterally, resulting in apparently larger cross-sections and discharges. Therefore, a study goal is to locate bedrock-floored reaches with the minimum channel capacity adjacent to stable geomorphic surfaces that place limits on paleostage through the reach.

HISTORICAL HYDROLOGY

Discharge measurements have been made on the Santa Ynez River since at least the 1880's (e.g., Wright, 1889). By combining the records of four U.S. Geological Survey gaging stations it is possible to compile an 87-year record of estimated annual peak discharges on the Santa Ynez River back to 1907 (Figure 2). This compiled record is composed of annual peak discharge estimate from the gage at Robinson Bridge near Lompoc between 1907-1934, the gage just downstream from Bradbury damsite from 1935-1952, and the adjusted sum of the gages upstream of Lake Cachuma between 1953-1993. Several questionable pre-1935 peak discharge estimates from the Robinson Bridge gaging station are re-evaluated, as discussed below, and the new estimated annual peak discharges are included in the compiled record.

Until 1906 the majority of discharge measurements were made upstream of Bradbury damsite primarily in preparation for the construction of Gibraltar Dam in 1920 and Juncal Dam in 1930. In 1906, the first gage was established about 30 miles downstream from Bradbury damsite near Lompoc at Robinson Bridge (Clapp and Martin, 1910), Santa Ynez River near Lompoc (11133500). The gage was destroyed in the flood of January 9, 1907, but was replaced in September, 1907 (Clapp and Henshaw, 1911). The gage was not maintained continuously, but estimates of annual peak discharges were made by the Corps of Engineers (1946) for the period of missing records, water years 1919 through 1925. Although it is not possible to assess the accuracy of these estimates, these peak discharge values, and other regional accounts (e.g., Troxell et al., 1942) indicate that no large floods occurred during that interval.

In 1935 a gage was placed about one-half mile downstream from Bradbury damsite, Santa Ynez River near Santa Ynez (11126000). In 1941 gaging started at the main tributary of the Santa Ynez River upstream from Bradbury damsite, Santa Cruz Creek, Santa Cruz Creek near Santa Ynez (11124500). In 1947 a gage was established just upstream from the proposed Cachuma reservoir on the Santa Ynez River below Los Laureles Canyon Creek, Santa Ynez River below Los Laureles Canyon near Santa Ynez (11123500). Storage began behind Bradbury Dam on January 7, 1953 (USBR, 1959).

Most precipitation in southern California is received from November to March, commonly as a series of frontal systems 2 or 3 days apart. Because precipitation comes from these frontal storms, the largest peak floods in southern California occur on many streams in the same year, and the flood peaks over a region usually coincide within several days or weeks (Troxell et al., 1942; Waananen, 1969; Chin et al., 1991; Hunrichs, 1991). In general, the years of the largest floods in this part of southern California are 1862, 1938, and 1969. The three largest reported peak flows on the Santa Ynez River occurred in 1907, 1914, and 1969 (Hoffman et al., 1993; Wells, 1960). The 1907 flood was reportedly larger than the next-largest peak in 1884, and several feet higher than any flood previously observed (Lompoc Record, 1907). The 1907 flood was most likely the largest flood in 45 years, since 1862 (Moore, 1948; Santa Barbara County Road Dept., 1938). With the addition of this historical data it becomes possible to extend the observed record of major floods to 132 years.

It became apparent after initial geologic reconnaissance that several peak discharges from the early part of the record of annual peak discharge estimates for the Santa Ynez River are substantially overestimated. This is particularly important because two of the three largest peaks of record are from 1907 and 1914. The fact that there is no geologic record of these events necessitated a re-evaluation of these and several other flood peaks. To resolve this issue, written accounts of these floods as well as the history of the Robinson Bridge

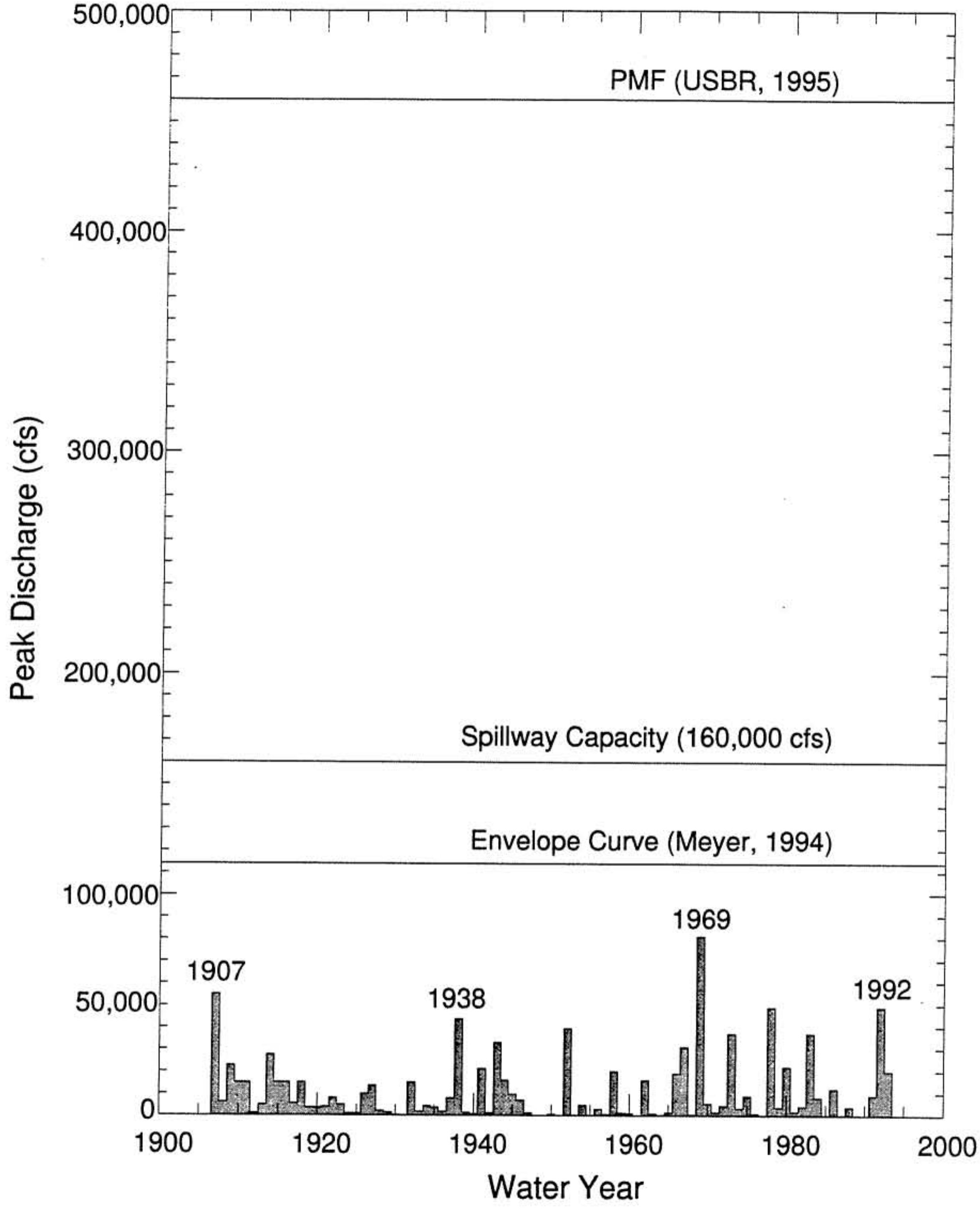

Figure 2. Compiled record of annual peak discharge estimates for the Santa Ynez River at Bradbury damsite. Also shown for comparison are an envelope curve for this part of California from Meyer (1994), the spillway capacity of Bradbury Dam, and the calculated Probable Maximum Flood.

gaging site were reviewed. To further refine discharge estimates, the flow through the reach including Robinson Bridge was modeled using HEC-2 (Hydrologic Engineering Center, 1990), a detailed topographic base from the Corps of Engineers (1970), and a cross-section of the river channel at the gage measured in 1914 (Cowles, 1914). The flow model was calibrated using the discharge and water surface of the 1969 flood (Corps of Engineers, 1970), so the resulting model discharges can be considered accurate relative to the magnitude of the peak discharge in 1969. Revised estimates of several peak discharges are presented in Table 1 as are the 1938 and 1969 peak discharges for comparison.,

Table 1. Revised Peak Discharge Estimates for the Santa Ynez River at Lompoc

Date	Previously Reported Peak Discharge (cfs)	Depth of Flow (ft)	Revised Peak Discharge (cfs)
January 9, 1907	120,000	16 to 18.5	55,000
January 25, 1914	75,000	10.6 to 13.3	27,500
February 9, 1915	41,500	4.9 to 5.8	<15,000
January 17, 1916	27,000	6.4 to 7.0	<15,000
March 3, 1938	45,000	14.4 to 16.8	45,000
January 25, 1969	80,000	21.8 to 22.2	80,000

The revision of the 1907 peak discharge estimate clearly demonstrates the overestimation of early annual peak discharge estimates on the Santa Ynez River. The 1907 discharge is currently reported as the extreme of record at 120,000 cfs (Hoffman et al., 1993). However, the original estimate made in 1907 was of a mean daily discharge of 62,000 cfs (Clapp and Martin, 1910). The current peak value of the flood was apparently derived in 1959, 53 years after the event, as part of a compilation study (Wells, 1960). At the same time, the magnitude of the 1914 flood nearly doubled from the original estimate of 41,800 cfs (Grover, 1917) to 75,000 cfs (Wells, 1960).

The current records cite a gage height of 22 feet for the 1907 discharge of 120,000 cfs (Hoffman et al., 1993). However, based on discharge rating data (Clapp and Martin, 1910), this corresponds to a flow depth of only 17 feet. Further, the Robinson Bridge in use at the time had a clearance above the river of 20 feet as stated by the Santa Barbara County Road Department (1938). The bridge did not overtop during this flood, and published eye-witness accounts state that the water was 18 inches below the bridge deck at the flood peak (Lompoc Record, 1907). That corresponds to a flow depth of 18.5 feet. Photographs obtained from the Lompoc Historical Society corroborate these flow depth estimates. A photo taken in 1907 at high water shows about a 2-3 foot wave on the upstream side of the bridge, indicating the actual flow depth may have been more on the order of 16 feet. Photos taken within days after the flood document a flood depth of 16 to 17 feet based on the height of debris stacked against the bridge piers.

For comparison, the 1969 flood had a flow depth of about 22 feet and an estimated discharge of 80,000 cfs as measured at the gage on the current Robinson Bridge and at the spillway on Bradbury Dam. Additionally, the cross-section measured in 1914 shows the width of the main channel to be on the order of 370 feet at the old bridge location upstream (Cowles, 1914). At the current bridge location the channel cross-section is 447 feet. So not only was the flow 4 to 6 feet shallower in 1907, but also the majority of the flow cross-section was more than 70 feet narrower than in 1969. These conditions are physically impossible for a flood with an estimated magnitude 50% larger than the 1969 flood. HEC-2 results show that a flood of about 120,000 cfs would have overtopped the old bridge by 4.5 feet, or would have to have been supercritical for the water surface to be below the bridge deck. Both of these conditions did not occur.

SANTA YNEZ RIVER TERRACES

The longitudinal profile of the Santa Ynez River, from Bradbury Dam to Lompoc, is controlled by prominent bedrock outcrops. The river is bordered by terraces that range in age from historic to several hundred thousand years. For the most part, the terraces are relatively thin veneers of sediment overlying bedrock. A typical exposure of the younger terraces often consists of a few feet of gravel overlain by a few feet of fine-grained sediment.

Latest Pleistocene and Holocene terrace surfaces along the Santa Ynez River between Bradbury Dam and Lompoc constrain the age of last inundation. Correlating and delineating the extent of these terrace surfaces provides useful bounds for flood frequency. Five major terrace groups, fp1, fp2, t1, t2, and t3, are delineated based on soil development, surface morphology, sedimentology, relative stratigraphic position, and elevation above river level (Figure 3). These were mapped using 1928 aerial photographs in an attempt to minimize the cultural impacts. Fourteen stratigraphic locales were described in detail and seventeen radiocarbon ages obtained to characterize these surfaces. Correlation to regionally developed soil chronosequences outside the Santa Ynez River basin, principally from the Ventura basin to the south, provides additional age control (Rockwell et al., 1982.

The fp1 surfaces are historic and within a few feet of the river bed. These surfaces are frequently inundated by moderate discharges in the Santa Ynez River. The next highest surface, fp2, is 10-20 feet above the river bed and is as old as about 700 years. Soils formed on these surfaces are weakly developed with thin A/C - horizon profiles and the surface morphology of bars and channels is slightly muted.).

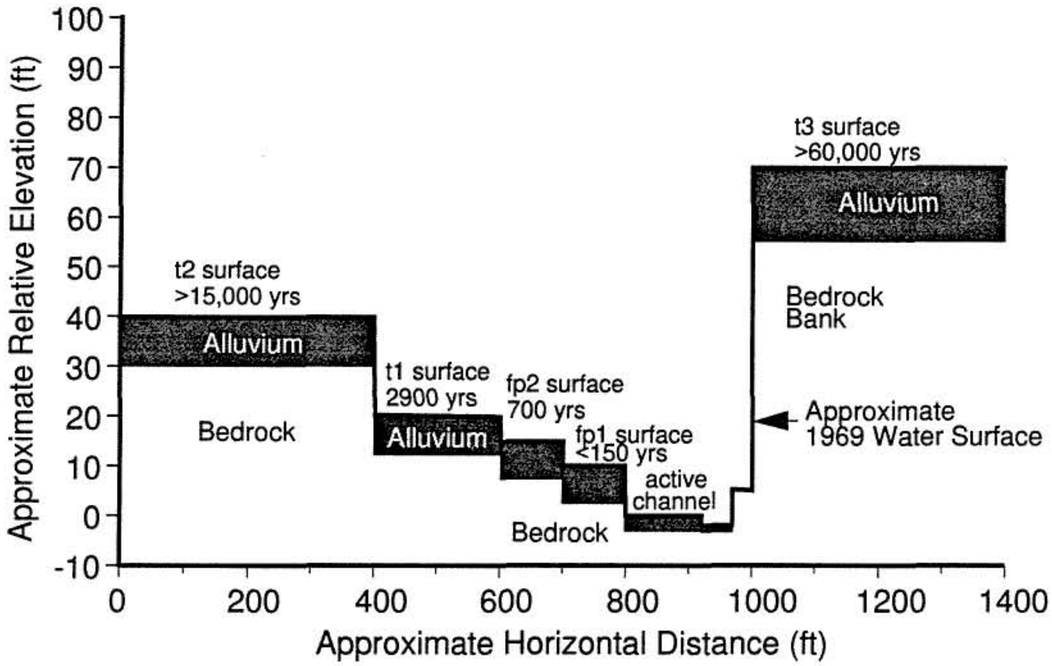

Figure 3. Idealized cross section of the Santa Ynez River with stratigraphic relationships and ages of terrace surfaces.

The t1 surfaces, with estimated ages of 2000 to 5000 years, are generally about 20-25 feet above the river bed. These surfaces have smooth surface morphology, and only in very local areas have tributary drainages constructed small alluvial fans on these surfaces. Soils are mostly thin A/C - horizon profiles, but are substantially thicker than on fp2 surfaces. The t2 and t3 groups include extensive surfaces of Pleistocene age (older than 10,000 years) that are more than 25 feet above the river bed, with distinct surface morphologies and soils. The t1, fp2, fp1 surfaces, and active river channel are nested inside and below these older surfaces (Figure 3).

The fp2 and t1 surfaces form bounds for paleostage since the time of last major inundation. Discharge estimates are developed for these paleohydrologic bounds using the HEC-2 step-backwater model (Hydrologic Engineering Center, 1990) for two detailed study reaches, Crawford and Rizzoli-Shannon, where paleostage indicators and stratigraphic deposits are well-preserved (Figure 1). Both reaches are bedrock floored, which eliminates channel scour as a factor in the discharge estimates. High-water marks from flows of known discharge in 1969 and 1993 provide a basis for calibrating the flow models in the study reaches.

The best estimate for time and discharge associated with the fp2 paleohydrologic bound is 700 years and 70,000 cfs. For the t1 paleohydrologic bound, the best estimate is 2900 years and 90,000 cfs. For the frequency analysis, a range of values for both age and discharge are input. These ranges incorporate the analytical and stratigraphic uncertainties in the age estimates, as well as the uncertainties associated with the discharges derived from the step-backwater model. The striking difference in the length of the record of annual peak discharge estimates, historic records, and paleohydrologic bounds and the relative influence of record length on flood frequency calculations is discussed below.

THE 1969 FLOOD

In January 1969, the Santa Ynez River experienced the largest flood in historic time. The estimated maximum spillway release from Bradbury Dam was about 80,000 cfs. Frequency analyses using only the record of annual peak discharge estimates typically consider this event to have a return period of 100 years or less (e.g. USBR, 1993). Paleohydrologic bounds based on the non-inundation of terrace surfaces form a basis for estimating a more realistic return period for this event.

The 1969 flood had profound effects on the Santa Ynez River. The flood waters overtopped almost all areas of the 700-year-old fp2 surface leaving dramatic evidence of erosion and deposition. Water depths on the order of one foot devastated previously stable surfaces and removed all the fine-grained deposits down to gravel, demonstrating the reliability of these surfaces as paleostage indicators (Figure 4). In other reaches, several feet of sediment were deposited on fp2 soils (Figure 5). Flood deposits are easily distinguished by the inclusion of 1960's artifacts such as Coca-Cola cans, irrigation pipe, and cars. The effects of the flood are also readily apparent from comparisons of pre- and post-flood aerial photographs (Figures 6 and 7). In many areas, there was dramatic straightening of the Santa Ynez River channel, with new channels cut through previously stable, 700-year-old surfaces (Figure 6C)

Aerial photography taken within days of the flood peak documents the high-water marks of the 1969 flood. The t1 surfaces were not overtopped, and lines of floated debris are only locally present along margins of the t1 surfaces. Bracketing of the 1969 flood between the fp2 and t1 paleohydrologic bounds indicates that the spillway release of 80,000 cfs was the largest flood in about 700 years and that there has been no flood even slightly larger in at least 2900 years.

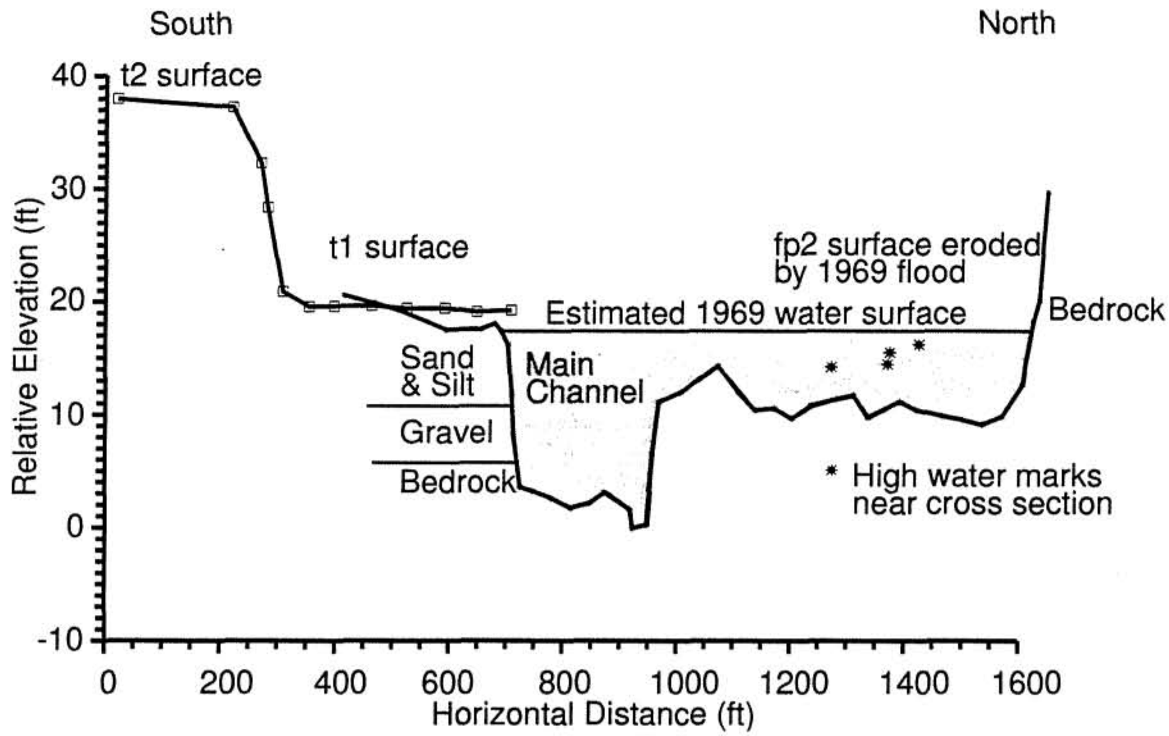

Figure 4. Cross section of the Santa Ynez River at the downstream end of the Crawford study reach. Shallow inundation of the former fp2 surface resulted in severe erosion. The 1969 water surface was up to the margin of t1.

FREQUENCY ANALYSIS

The goal of this analysis is to calculate the annual probability of a peak discharge exceeding the spillway capacity of Bradbury Dam. A second goal is to quantify the statistical value of incorporating historical and paleoflood data into peak discharge frequency analysis. The maximum likelihood (MLH) method of Stedinger and Cohn (1986) and Stedinger et al. (1988) is modified and incorporated into a Bayesian approach (Tarantola, 1987). The likelihood functions modified from Stedinger and Cohn (1986) provide a formalism to statistically combine information from the record of annual peak discharge estimates, historical, and paleohydrologic bounds. Although Stedinger et al. (1988) provide a robust approach to estimate the MLH parametric distribution, their uncertainty calculations assume the parameters are perfectly known and only incorporate sampling errors. The Bayesian approach explicitly allows both the parameter and data uncertainties to be incorporated into risk and confidence interval estimates of peak discharge frequency. The availability of high-speed workstations makes it possible to estimate peak discharge frequency probabilities using systematic parameter-space searches, and to calculate parameter and peak discharge frequency likelihoods and confidence intervals by direct numerical integration.

The discharge and age data are characterized by uncertainty distributions into two groups. First, the estimated annual peak discharge uncertainties are parameterized by Gaussian frequency distributions. For estimated annual peak discharges less than 5000 cfs, two standard error estimates of 10% are used; for those greater than 5000 cfs, two standard error uncertainties of 25% are used, based on Hoffman et al. (1993). Second, values in a range, with a potentially variable likelihood within a range, describe the uncertainties for historical peak discharges and paleohydrologic bounds. The Log Pearson III (LP3) frequency function is used to describe peak discharge frequency.

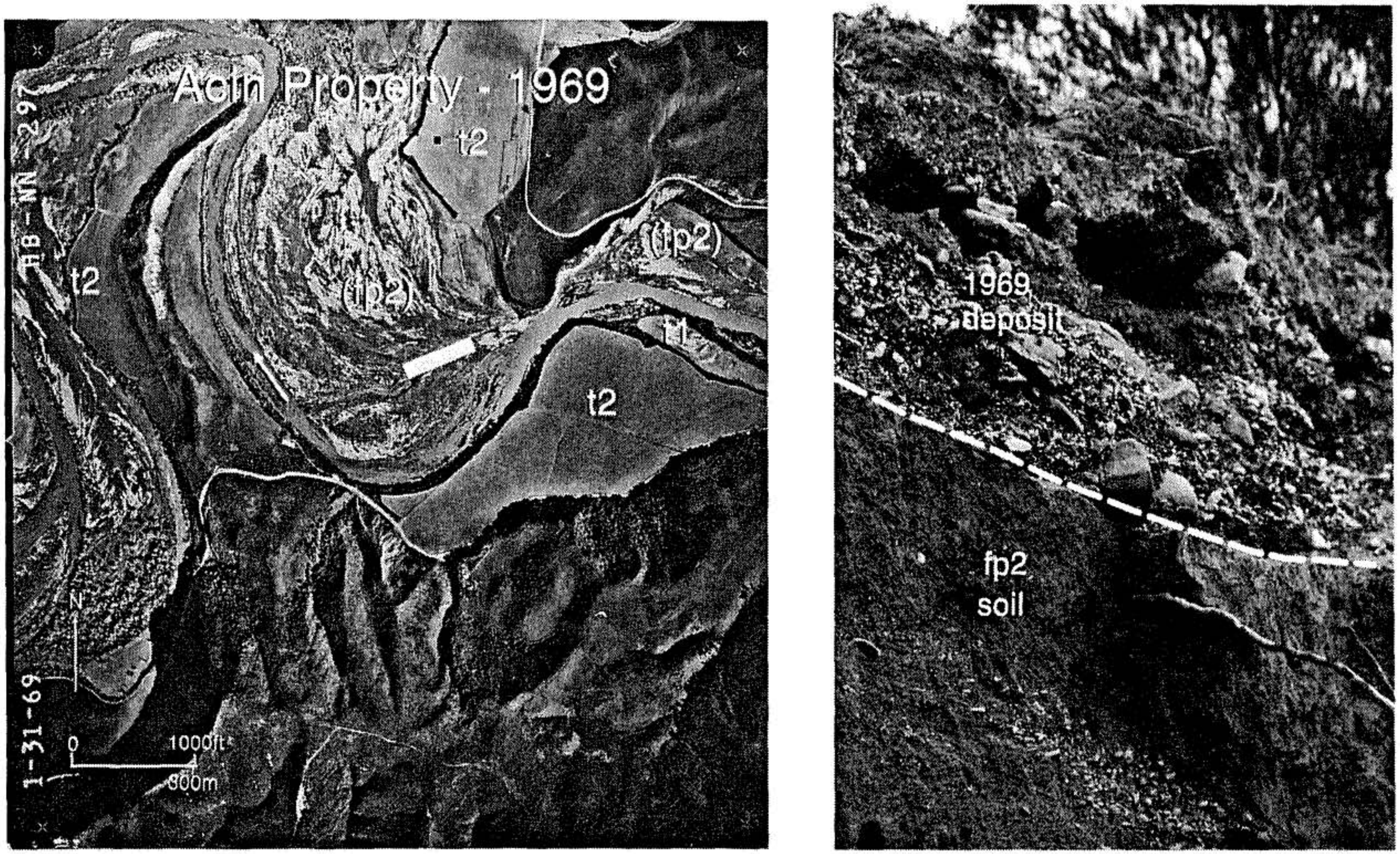

Figure 5. Geomorphic and stratigraphic record of a large flood. On the left, aerial photograph of the Acin Property taken six days after the January 1969 flood peak. (fp2) denotes former stable fp2 surface. Where fp2 surfaces were overtopped there is a clear record of erosion and deposition. The rectangle is the location of the stratigraphic study site where the photo on the right was taken. On the right, photograph taken in 1993 that shows about two feet of gravelly deposits from the 1969 flood that overlie finer-grained, 700-year-old fp2 soil and sediment.

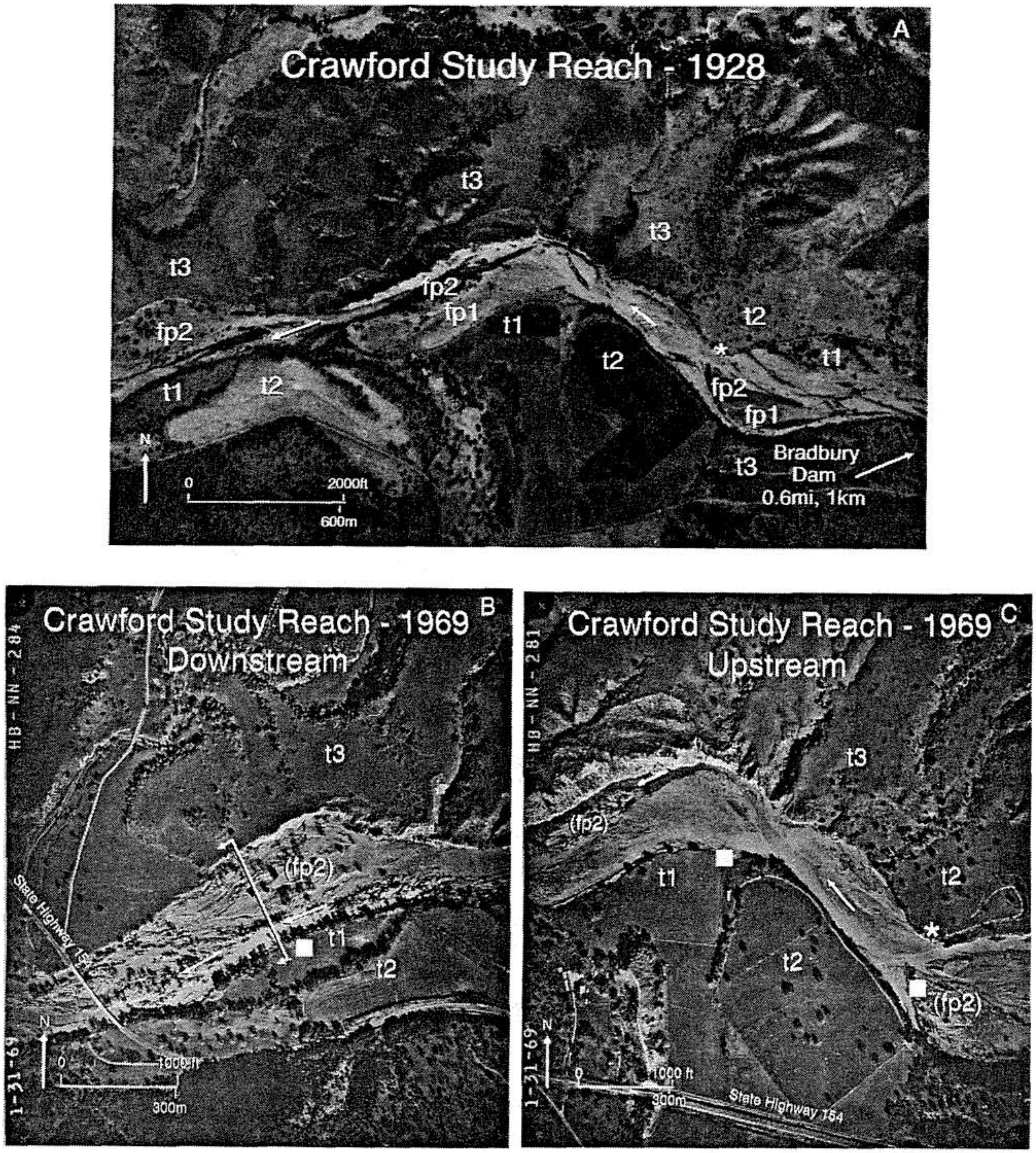

Figure 6. Aerial photographs of the Crawford study reach. A) In 1928 there are large areas of stable, 700-year-old fp2 surfaces. B) and C) were taken six days after the peak of the January 1969 flood. (fp2) denotes former stable fp2 surfaces. Squares are 1993 test pit locations. B) Downstream portion of study reach. Note overtopped, eroded fp2 surface compared with unmodified t1 surface. Line with arrows shows the location of the cross-section in Figure 4. C) Upstream portion of study reach with modified fp2 surfaces. Compare the post-flood channel width at star to the channel width in 1928.

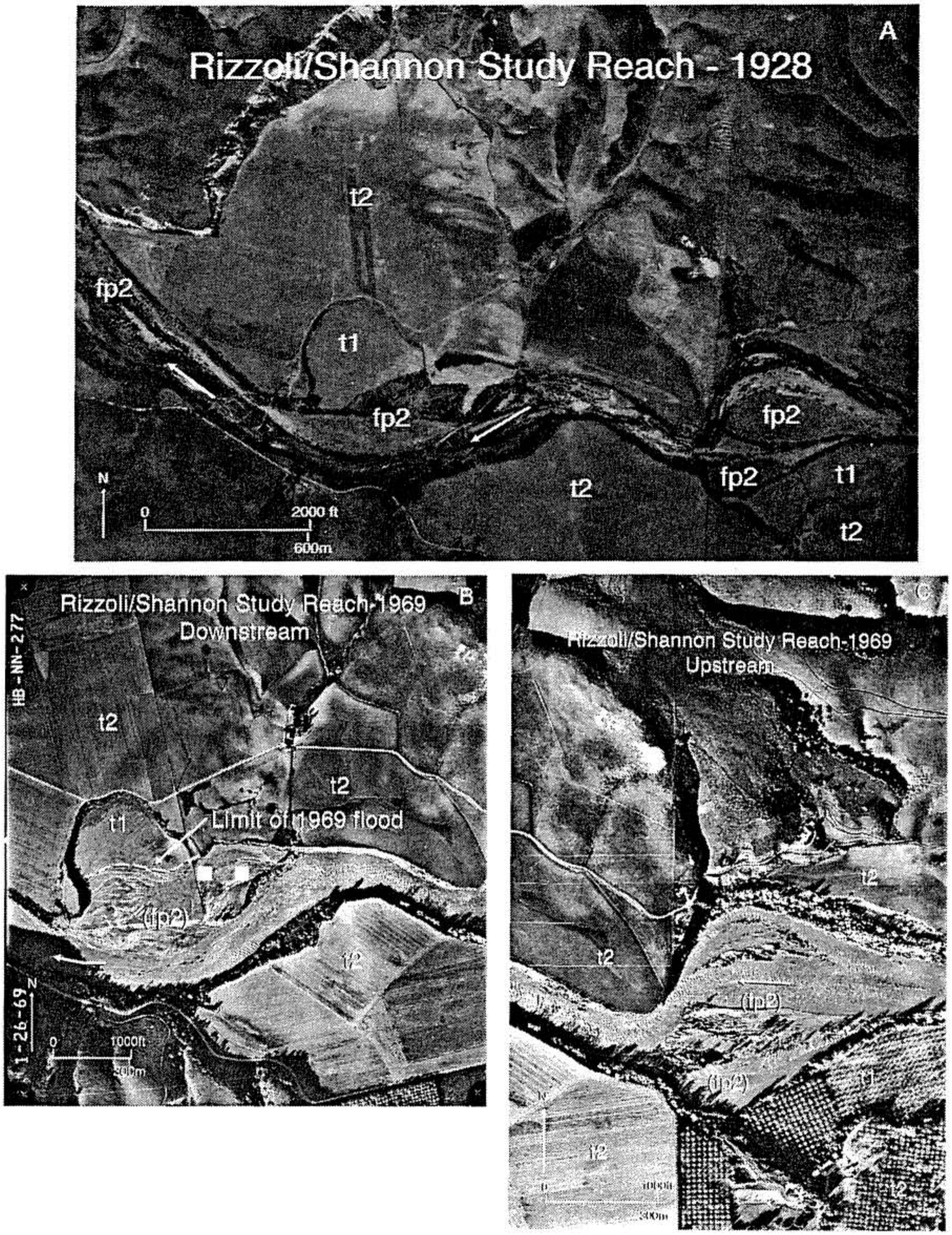

Figure 7. Aerial photographs of the Rizzoli/Shannon study reach. A) In 1928 there are large areas of stable, 700-year-old fp2 surfaces. Note the contrasting, smoother morphology of adjacent t1 surfaces. B) and C) were taken the day after the peak of the January 1969 flood. (fp2) denotes former stable fp2 surfaces. Squares are 1993 test pit locations. B) Downstream portion of study reach with overtopped fp2 surfaces. C) Upstream portion of study reach. Note large channel cut through former fp2 surface.

The Bayesian frequency analyses were repeated three times using 150^3 LP3 parameter-space grids. The first trial only used the readily available (57 year) record of annual peak discharge estimates (Figures 2 and 8). The second trial combined the compiled record of annual peak discharge estimates (87 years) and historic bound (45 years). Finally, all types of data were combined: the record of annual peak discharge estimates, the historical bound, and the paleohydrologic bounds (2900 years). The resulting differences in the estimated mean annual probabilities of spillway capacity exceedance (Table 2) and the peak discharge frequency upper 97.5 percentile (Figure 9) are quite striking. The paleohydrologic bounds place the 1969 peak discharge in its proper context (plotting position) as a rare event (Figure 9). The paleohydrologic bounds provide the capability to estimate peak discharge frequency in the 1,000 to 10,000 year return period range with substantially smaller uncertainties than the record of annual peak discharge estimates or combined annual peak discharge estimates/historic data sets. If only record of annual peak discharge estimates was available, the inescapable conclusion would have been that a discharge exceeding spillway capacity is likely to occur within a 10,000 year period (Figure 9). However, adding the paleohydrologic bounds to the Bayesian analysis shows that the probability of a discharge exceeding spillway capacity is essentially zero for return periods of 10,000 years or less.

Table 2. Mean Annual Probability and Return Period of Discharges Exceeding Spillway Capacity (160,000 cfs) at Bradbury Dam

Data Set	Mean Annual Probability	Return Period (years)
Gage	5.74×10^{-4}	1740
Historic + Gage	1.43×10^{-4}	7000
Paleoflood + Historic + Gage	1.57×10^{-7}	>6,000,000

PALEOHYDROLOGIC BOUNDS AND THE CALCULATED PROBABLE MAXIMUM FLOOD

The Probable Maximum Flood (PMF) has been used as a standard for hydrologic analyses in dam safety for several decades (NRC, 1985). As originally defined, the PMF has no return period. However, this definition is not practical for dam safety decisions based on risk. As a practical matter, the PMF has often been arbitrarily assigned a return period of 10,000 to 1,000,000 years at the upper and lower confidence limits for flood frequency analysis (e.g., NRC, 1985).

Paleoflood studies are a basis for testing whether the calculated PMF and the associated extrapolated return period are realistic. Because the fluvial geomorphology and stratigraphy of flood plains adjacent to streams are recorders of the most extreme floods, paleoflood records should contain extreme floods that are a large percentage of the PMF, if such floods are physically possible. The shorter the estimated return period assigned to the PMF, the more likely it becomes that such large floods should be included in paleoflood records that are thousands of years in length. Considering the number of drainage basins present in an area the size of the western U.S., if there actually have been floods comparable to the hypothetical PMF, the numerous multi-thousand-year paleoflood records present along western rivers are likely to record multiple PMF-scale floods.

The paleohydrologic bounds from the Santa Ynez River are only a small percentage of the calculated PMF for Bradbury Dam. Data from other Reclamation paleoflood studies in the western U.S. shows a similar relationship to calculated PMF estimates (Table 3). It is clear that in a variety of hydrometeorological

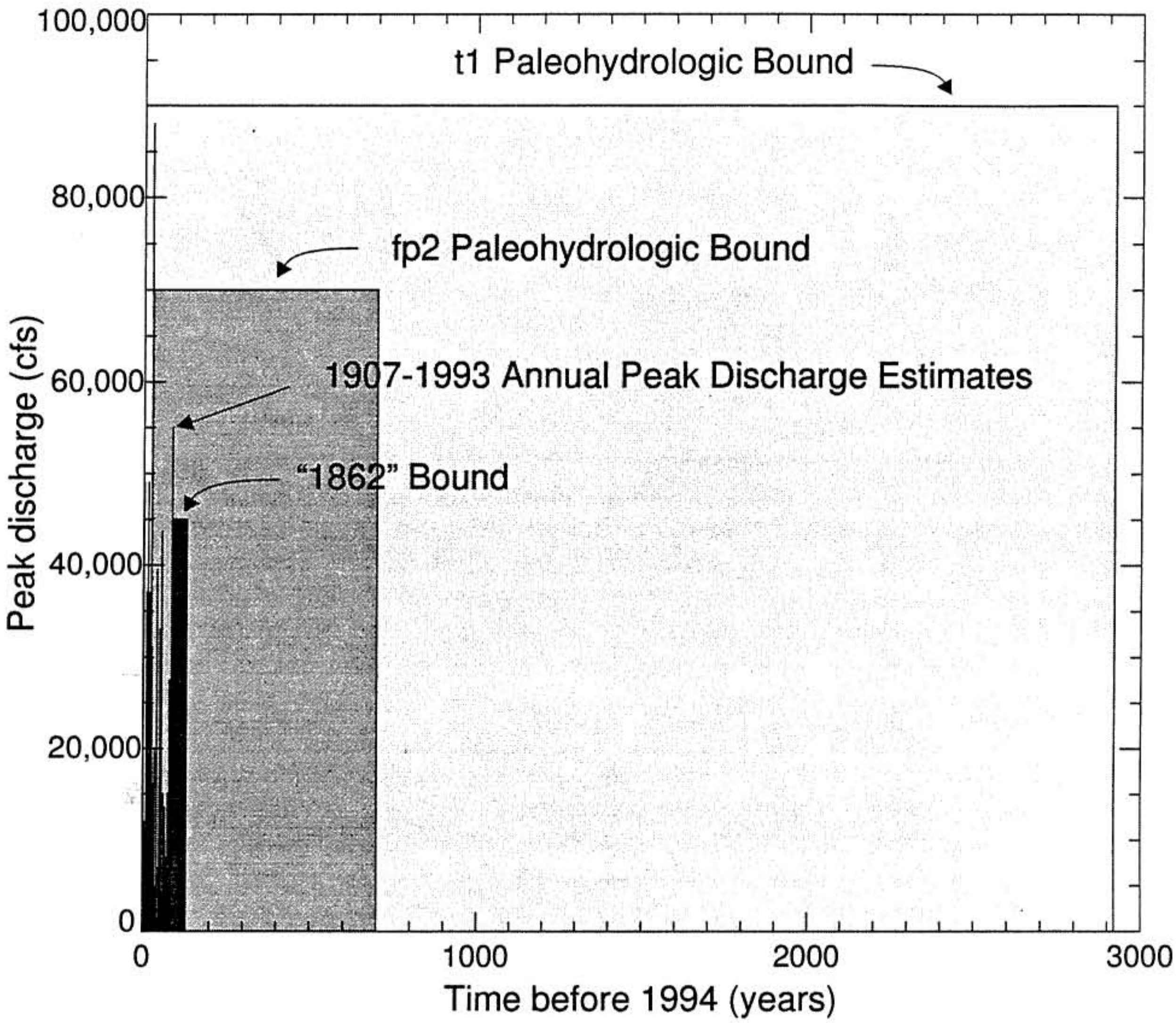

Figure 8. Comparative time spanned by paleohydrologic and historic peak discharge bounds, and compiled record of annual peak discharges. Light-shaded area is the maximum likelihood (MLH) t1 paleohydrologic bound (90,000 cfs and 2920 years); intermediate-shaded area is the MLH fp2 paleohydrologic bound (70,000 cfs and 700 years); dark-shaded bar is the MLH historic peak discharge bound (45,000 cfs and 45 years (1862-1907)). Estimated annual peak discharges are shown as narrow lines at left.

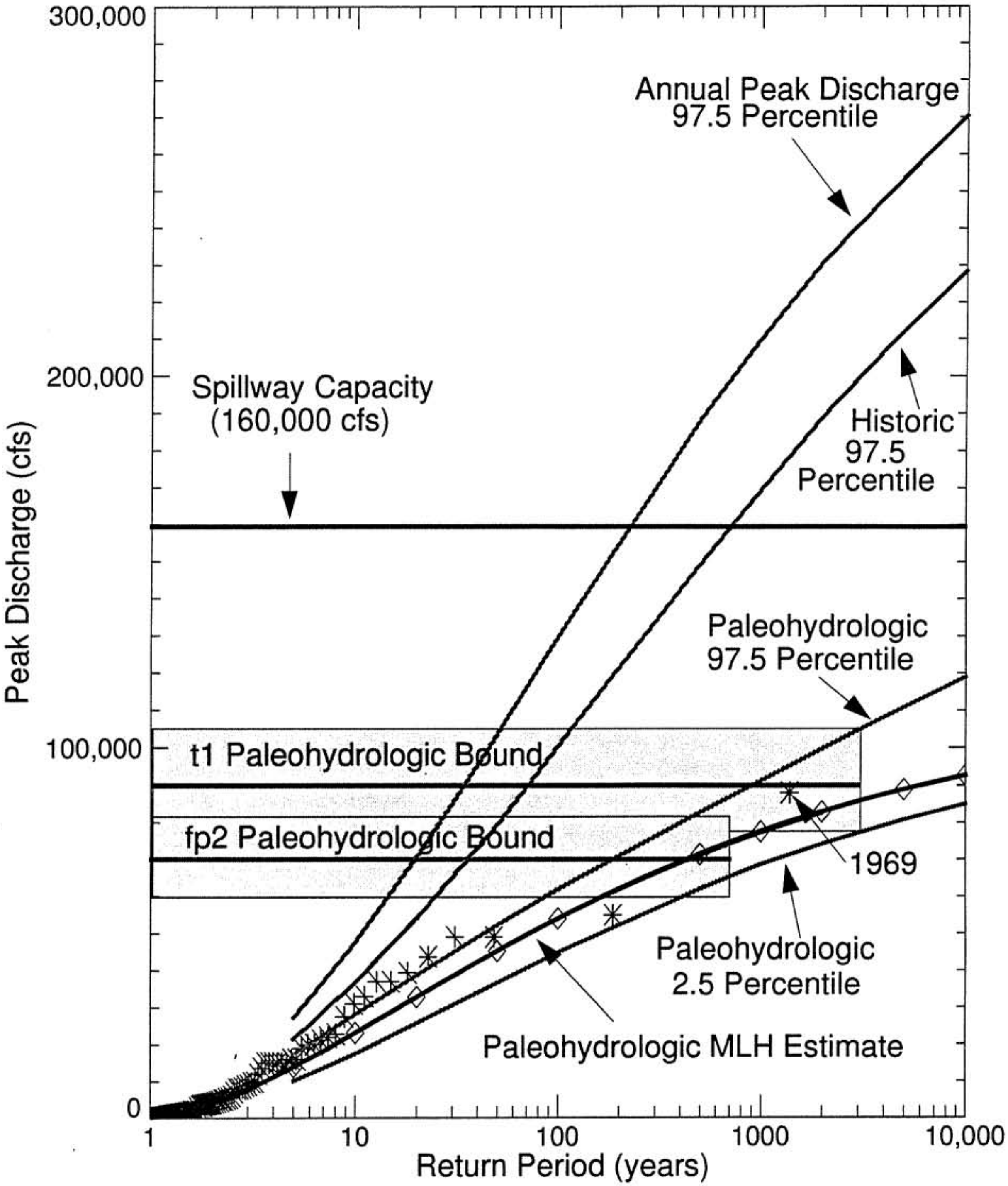

Figure 9. Paleohydrologic discharge MLH LP3 estimate (solid curve) with MLH observed discharges (stars). Probability regions were calculated for all data sets at the points denoted by the diamonds for return periods between 5 and 10,000 years. Upper and lower percentile limits are shown as dashed lines. Only the paleohydrologic lower 2.5 percentile limit is plotted; the other 2.5 percentile limits are similar. The shaded regions are the paleohydrologic bound ranges and MLH time durations as labeled with the interior lines denoting the MLH paleohydrologic bound values. The 1969 peak discharge is plotted just below the MLH t1 paleohydrologic bound, with a return period of 1390 years.

settings, the paleoflood record does not validate floods as extreme as the PMF nor does the paleoflood data validate estimates of PMF return period in the range of 10,000 to 1,000,000 years. Rather, the paleoflood data imply a potential upper limit for flood magnitude that is substantially smaller than implied by PMF calculations. The data in Table 3 indicate that in the western United States, peak discharges with an extrapolated return period of 10,000 years may be as little as five to twenty per cent of the calculated PMF. These results have substantial impact when incorporated into dam safety decisions or criteria based on risk.

CONCLUSION

The most reliable way to obtain probability estimates of extreme floods, i.e., floods with return periods of thousands of years, is to study the geomorphologic and stratigraphic record of extreme floods. Paleoflood hydrology is an event-based method for extending the length of the flood record in order to make realistic estimates of the probability of extreme floods. For guiding hydrologic dam safety decisions, comparable levels of confidence cannot be obtained from analysis of short-term records of annual peak discharge estimates and historic information alone. Compared to conventional frequency analyses, incorporation of paleoflood data provides high assurance that the spillway capacity of Bradbury Dam will not be exceeded even at long return periods, and dramatically reduces the spread in the peak discharge confidence limits (Figure 9). For Bradbury Dam, inclusion of paleoflood information provides justification in the dam safety decision-making process for eliminating consideration of a hydrologic modification costing tens of millions of dollars.

Table 3. Comparison of Paleohydrologic Bounds from Selected Western U.S. Sites with Calculated PMF Values

Location	Drainage Basin Area (km^2)	Paleohydrologic Bound		Estimated 10,000 year paleoflood discharge (m^3/s)	Probable Maximum Flood peak discharge (m^3/s)	10,000 year Paleoflood as percentage of PMF
		Time Interval (years)	Discharge (m^3/s)			
Santa Ynez River, CA[1]	1080	2900	2550	2690	13,060	21%
Ochoco Creek, OR[2]	764	10,000 to 15,000	285	285	4785	6%
Crooked River, OR[3]	6825	8000 to 10,000	<1100	1100	7225	15%
South Fork Ogden River, UT	210	400 2500	70 115	<215	3075	7%

Data References: 1) Ostenaa et al., 1994; 2) Ostenaa and Levish, 1996; 3) Levish and Ostenaa, study in progress.

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