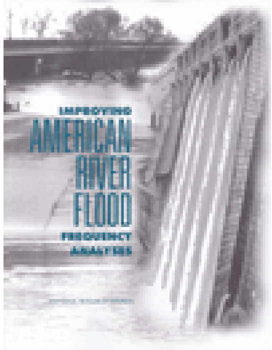

Improving American River Flood Frequency Analyses

Committee on American River Flood Frequencies, National Research Council

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Improving American River Flood Frequency Analyses

Committee on American River Flood Frequencies
Water Science and Technology Board
Commission on Geosciences, Environment, and Resources
National Research Council

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Preface

This report is the result of an intensive eight-month study effort by the Committee on American River Flood Frequencies, a group of experts organized to assist the U.S. Army Corps of Engineers (USACE) by providing an independent scientific assessment of flood frequency relationships for the American River at Sacramento, California. The study was designed and the committee formed under the auspices of the Water Science and Technology Board (WSTB) of the National Research Council (NRC). It extends the work of the former WSTB Committee on Flood Control Alternatives in the American River Basin (whose findings were published in 1995) and aims to achieve better estimation of flood frequency relationships for the American River in light of a major flood in January 1997 and other technical considerations. In its review, the committee considered issues such as the following that were specified by the USACE as technically controversial in the agreement enabling support for the study:

- applicability of (the federally-prescribed) Bulletin 17-B based statistical approach;
- appropriateness of skew factor development;
- potential censoring of water year 1977 data, considering validity of Bulletin 17-B criteria;
- updated river basin probable maximum flood, and its supportive relationship to the selected flow frequency curve;
- methodologies to 'bend over' the less frequent portion of the flow frequency curve to reflect the American River basin's realistic maximum flow productivity;
- applicability of paleoflood methodologies to this flow frequency analysis; and
- climatologic/meteorologic/hydrologic trends and American River basin parameters that may influence the American River flow frequency curve.

This report's findings are based on a review of relevant technical literature, extensive flood frequency analyses by the committee, and deliberations among committee members.

The committee consisted of 10 volunteer experts in hydrologic and geophysical statistics, hydrologic engineering, geomorphology, hydroclimatology, climatology, and economics (see Appendix A). The committee incorporated input, when appropriate, from a wide range of stakeholders and USACE personnel concerned about flood risk management for Sacramento and environmental quality of the American River and its tributaries. Much of this interaction with interested parties occurred at a committee-hosted workshop and meeting in Sacramento on July 12-15, 1998. At that workshop, the committee gathered input, deliberated on the issues, outlined this report, and took on work assignments. Following the meeting, the committee members made calculations and drafted and refined this report, which represents a consensus of our multidisciplinary committee.

The first chapter of this report provides a brief overview of the historical and ongoing development of flood control measures on the American River, associated technical issues, and policy implications. Chapter 2 provides a description of the data types that can be used in estimating flood exceedance probabilities for the American River. Chapter 3 presents and discusses the committee's flood frequency estimates for the American River. Chapter 4 reviews the meteorology of floods associated with the hydrologic cycle of the American River. Lastly, Chapter 5 provides a summary of the committee's findings and recommendations for the improvement of flood frequency analyses for the American River. The committee expects that its report will be helpful in planning for flood risk reduction in Sacramento, but so many general technical and policy issues presented themselves in Sacramento that, as the study progressed, we began to see our analyses as a case study with broader implications. We hope those with interests outside Sacramento will find our report useful.

Leading this project was a special pleasure. It is not often that one has the opportunity to address a problem as technically challenging and politically charged as the one assigned to our committee. To lead a group as experienced and intellectually powerful as ours was both an honor and a challenge. I am grateful for the opportunity to have led the members of this group, and I thank them for their many contributions. Our work was supported by three WSTB staff members, Ellen de Guzman, Mark Gibson, and Stephen Parker, and a consultant, Charles Rodgers of the University of Wisconsin, who were of great assistance in facilitating our work. On behalf of the committee and the Water Science and Technology Board, I also would like to express our appreciation to the fine staff of the U.S. Army Corps of Engineers with whom we interacted during this study. Our principal liaisons were Robert Childs and John Mack of the Sacramento District. Interaction with them and their colleagues at the district and at the Corps Hydrologic Engineering Center in Davis, California was critical to the success of this study. Additionally, the committee was briefed, informed, and assisted—principally at its July 1998 workshop—by numerous other individuals from other agencies and organizations familiar with the issues at hand. They are too numerous to list (more than 30) but we are indebted for the information and perspectives they provided.

The report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscripts remain confi dential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report: Joseph D. Countryman, consulting engineer, Sacramento, California; Katherine K. Hirschboeck, University of Arizona; George M. Hornberger, University of Virginia; Charles D. D. Howard, Charles Howard and Associates, Victoria, British Columbia; L. Allan James, University of South Carolina; William H. Kirby, U.S. Geological Survey, Reston, Virginia; and Rutherford H. Platt, University of Massachusetts. While these individuals provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

KENNETH W. POTTER, CHAIR
COMMITTEE ON AMERICAN RIVER FLOOD FREQUENCIES

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Executive Summary

Sacramento, California, has grown literally at the edge of the Sacramento and American Rivers and for 150 years has struggled to protect itself from periodic floods by employing structural and land management measures. Much of the population lives behind levees, and most of the city's downtown business and government area is vulnerable to flooding.

A major flood in 1986 served as impetus for efforts by federal, state, and local entities to identify an acceptable and feasible set of measures to increase Sacramento's level of safety from American River floods. Numerous options were identified in 1991 by the U.S. Army Corps of Engineers (USACE) in a report known as the *American River Watershed Investigation.* Due to the controversial nature of many of the alternatives identified in that report, study participants were not able to reach consensus on any of the flood control options. In response, the Congress directed the USACE to reevaluate available flood control options and, at the same time, asked the USACE to engage the National Research Council (NRC) as an independent advisor on these difficult studies. In 1995 NRC's Committee on Flood Control Alternatives in the American River Basin issued *Flood Risk Management and the American River Basin: An Evaluation.* This report outlined an approach for improving the selection of a flood risk reduction strategy from the many available.

In March 1996, the USACE and its non-federal affiliates completed the Congressionally directed reevaluations of flood control options and submitted recommendations to Congress. In response, Congress authorized a component of the recommended plan but not an adequate plan for the reduction of flood risk for the Sacramento area. Thus, evaluations of alternatives continue. To add considerable complication to the technically and politically difficult decision process, in January 1997 the American River experienced a major flood, nearly as large as and hydrologically similar to the "flood of record" that occurred just 11 years before in 1986.

The occurrence of the 1997 flood suggests that it may be necessary to recompute flood flow frequency relationships for the American River at Sacramento. In February 1998, the USACE published a revised unregulated rain flood flow frequency analysis[1] for the American River at Fair Oaks. The analysis produced a flood frequency curve that indicates that large floods are appreciably more likely than

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[1] Unregulated rain flood flow frequency analysis is conducted on annual peak flow data that have been corrected for the effects of upstream reservoir storage. Rain flood flow is due primarily to rainfall rather than snowmelt.

previously thought. Based on the newly estimated 100-year flood discharge, the levees protecting Sacramento no longer provide protection against the 100-year flood. The revised flow frequency relationships have immediate policy implications (e.g., "decertification" of levees by the Federal Emergency Management Agency, resulting in building restrictions and higher flood insurance rates) and also reduce the estimated level of protection provided by the flood control alternatives that are currently being considered for Sacramento.

Perhaps not surprisingly, recalculation of the flow frequency relationships has proven controversial. Occurrence of the 1997 flood has also brought into question many issues of technical methodology that bear on decisions about flood risk management in Sacramento.

Shortly after their release, the results of the USACE flood frequency analysis prompted a number of questions, comments, and criticisms from representatives of local, state, and federal government agencies, public interest groups, private citizens, as well as from the Corps itself. In response, the USACE requested the assistance of the NRC to extend the work of the former Committee on Flood Control Alternatives in the American River Basin. This report is a product of NRC's Committee on American River Flood Frequencies, which was organized to assist the USACE by providing an independent scientific assessment of flood frequency relationships for the American River at Sacramento.

DATA SOURCES AND NON-STATIONARITY

A variety of data types can be used in estimating flood quantiles or exceedance probabilities for the American River. These include systematic streamflow and precipitation data, historical and paleoflood data, and regional hydrometeorological information on extreme events. Flood frequency analysis traditionally has been based on systematic streamflow or precipitation records, where use of the latter requires the application of precipitation runoff modeling.

Flood frequency analysis is commonly based on the assumption that flood flows are independent and identically distributed random variables. In reality, the probability distribution of floods can change in time (i.e., exhibit non-stationarity) as a result of local human activities, such as land use changes or reservoir operations, or regional or global climate change. As noted in NRC (1998a), there are many intrinsic modes of climatic variability at decadal to centennial time scales that may be independent of global warming effects or may confound them. Thus non-stationarity in the American River flood frequency due to climatic factors cannot be unambiguously attributed to changes in atmospheric composition over the last century. For example, there are relatively few gaged streams on watersheds that have not been affected by human activities. Unfortunately, there are also relatively few cases where human impacts on flood magnitude and frequency have been carefully documented. There is evidence of significant changes in land use and surface attributes of the American River basin over the last two centuries.

Furthermore, the assumption that floods are independent and identically distributed in time is at odds with the recognition that climate naturally varies at all scales, and that climate additionally may be responding to human activities, such as changes over the past century in atmospheric composition or in global land use patterns, which have changed the climate forcing and the hydroclimatic response on regional scales in recent decades. In this regard the committee notes that its understanding of climate variability suggests that (a) the uncertainty of flood frequency estimates is higher than that indicated by the usual statistical criteria, (b) climatic regime shifts may—slowly or abruptly—significantly affect the local flood frequency curve for protracted periods, and (c) at this time, given the limited understanding of the low frequency climate-flood connection, the traditional approach to flood frequency estimation entails a tradeoff between potential bias and variance. Bias arises from the use of long periods of record that are more likely to include time periods during which flood risk is different from that during the immediate planning period. On the other hand, longer periods of record allow the construction of risk estimators with less variance due to the larger sample with which the estimators are constructed.

FLOOD FREQUENCY ANALYSIS

Effective planning and design of flood risk management projects require accurate estimates of flood risk. Such estimates allow a quantitative balancing of flood control efforts and the resultant benefits, and also enhance the credibility of floodplain development restrictions. They allow determination of the flows associated with specified exceedance probabilities, as well as the expected benefits associated with alternative flood risk management proposals. These considerations are critical for the American River, where billions of dollars of property are at risk due to flooding.

Fitting a continuous mathematical distribution to data sets yields a compact and smoothed representation of the flood frequency distribution revealed by the available data, and a systematic procedure for extrapolation to flood discharges larger than those historically observed. Whereas the American River flood record at Fair Oaks is almost 100 years in length, there is a goal of providing flood protection for at least the flood that has a chance of 1 in 200 of being exceeded in any year. This requires extrapolation beyond the data, as well as smoothing the empirical frequency curve to obtain a more consistent and reliable estimate of the 100-year flood.

A variety of distribution functions and estimation methods are available for estimating a flood frequency distribution. The guidelines for frequency analysis presented in Bulletin 17-B were established to provide consistency in the federal flood risk management process. In estimating a flood frequency distribution for the American River, the committee believed it was desirable to follow the spirit of these guidelines, although not necessarily the exact letter. The committee based its estimation on the log-Pearson type III distribution, as specified in Bulletin 17-B. With only a traditional systematic gaged record, the report employs the conventional log-space method of moments, as recommended by Bulletin 17-B. When additional historical flood information is included or some peaks are censored, the Expected Moments Algorithm (EMA) is used as the generalization of the conventional log space method of moments method. The EMA (Cohn, Lane, and Baier, 1997), developed well after the publication of Bulletin 17-B, makes more effective use of historical and paleoflood information than does the weighted-moments method recommended in Bulletin 17-B for use with historical information.

The committee explored alternative estimates of the flood frequency distributions for the American River using various combinations of systematic, historical, and paleoflood data and selected a recommended distribution, shown in Table ES.1 and Figure ES.1.

The recommended distribution is based on the systematic record of three-day rain flood flows estimated by the USACE from the U.S. Geological Survey flow record for Fair Oaks, and upon the historical record for 1848-1904 which included an estimated large three-day flow associated with the 1862 historic flood. Based on several independent analyses conducted by the committee and the USACE, the committee concludes that the three-day rain flood record is an accurate representation of the magnitude of the flood flows over the period of record, and that the observed increase in the frequency of large floods since 1950 is not an artifact of the method by which flood peaks were computed. The committee's estimate of the three-day flow associated with the 1862 flood is based on a regression model developed by the committee. In its frequency analysis the committee assumes that this flow was the largest three-day flow in the historical period from 1848 to 1904.

The recommended frequency distribution assumes a log-skew of -0.1. This skew is based on a weighted average of a regional skew (-0.1) and the sample skew (-0.06). The committee estimated the regional skew by averaging the sample log-skew of three-day flow series from seven rivers on the west slope of the central Sierra Nevada. Sensitivity analysis using the committee's recommended approach indicates that censoring below various flows with exceedance probabilities ranging from about 0.94 to 0.31 does not significantly affect the estimated distribution.

In developing its recommended flood frequency distribution, the committee chose not to use the paleoflood information to compute a frequency curve for the American River. When the paleoflood data are used in conjunction with the systematic and historical data in an estimation framework consistent with the spirit of Bulletin 17-B, the resulting log-Pearson type III distribution provides a poor fit to the systematic data (Figure 3.3). While it might be possible to improve the fit by using a method outside the framework of Bulletin 17-B (e.g., censoring the systematic data at a very high threshold), the committee chose not to take this approach for several reasons. First, the committee was committed to following the spirit of Bulletin 17-B. Second, the committee was uneasy about using the paleoflood data because of questions about climatic variability during the 3,500-year period represented by this information. In particular, given present understanding of global climate variations during the past 10,000 years, the committee questions whether it is prudent to assume that flood magnitudes during this period are independent and identically distributed.

While the committee's preferred estimate of the frequency distribution of three-day rain flood flows on the American River is consistent with the systematic and historic data, the committee cautions against extrapolating much beyond these data. Frequency analysis of basin average precipitation data (as well as the paleoflood information) indicates that the upper tail of the "true" distribution flattens for very large flows.

TABLE ES.1 Summary of Three-Day Flood Quantile Estimates for the American River at Fair Oaks Using the Expected Moments Algorithm (EMA)[a]

Data and Assumptions:	
Systematic Observations:	1905 - 1997
Historical Period:	1848 - 1904
Historical Flood	1862; 147,000 cfs[b]
Upper Bound for Remainder of Historical Period:	147,000 cfs[b]
Paleoflood Observations:	not included
Estimated Distribution Moments:	
Log(10) Mean:	4.3329
Log(10) Std. Deviation:	0.4149
Log(10) Skewness Coefficient:	-0.1000
Estimated Three-Day-Mean Flood Quantiles and 90% Confidence Limits[c]:	
$Q_{10}(P_{exceed} = 0.10)$	72,500 cfs (60,000 cfs; 88,000 cfs)
$Q_{20}(P_{exceed} = 0.05)$	101,000 cfs (81,000 cfs; 126,000 cfs)
$Q_{50}(P_{exceed} = 0.02)$	145,000 cfs (109,000 cfs; 192,000 cfs)
$Q_{100}(P_{exceed} = 0.01)$	185,000 cfs (131,000 cfs; 257,000 cfs)
$Q_{200}(P_{exceed} = 0.005)$	230,000 cfs (154,000 cfs; 338,000 cfs)
Associated Recurrence Interval of PMF:	
USBR 1996 (401,000 cfs)	1,500 years
USACE 1997 (485,000 cfs)	3,400 years

[a] Flood quantile estimates are based on rain floods only.

[b] Corresponds to estimated 1862 three-day mean Q.

[c] Based on the LP III using a log skew of -0.1 to the systematic record and the historical record from 1848 that included the historical 1862 flood.

The committee did not have time to develop a recommendation regarding extrapolation of the frequency distribution beyond the flow with an annual exceedance probability of 1 in 200. This is clearly an area in need of analysis. One complicating factor is the observed post-1950 increase in large floods. This increase may reflect structural changes in the flood generation process wrought by human activity (e.g., atmospheric composition changes or global land use changes) or by natural factors that have always been present.

IMPLICATIONS FOR FLOODPLAIN CERTIFICATION

Based on the USACE 1998 100-year flood estimate, the Federal Emergency Management Agency (FEMA) issued new floodplain maps for Sacramento. As result of these new maps, most of the floodprone areas of Sacramento were classified as being in the so-called AR zone (area of special flood risk). Generally, this designation would have resulted in building restrictions and higher flood insurance rates. In this case, FEMA waived the increases in flood insurance rates, but enforced

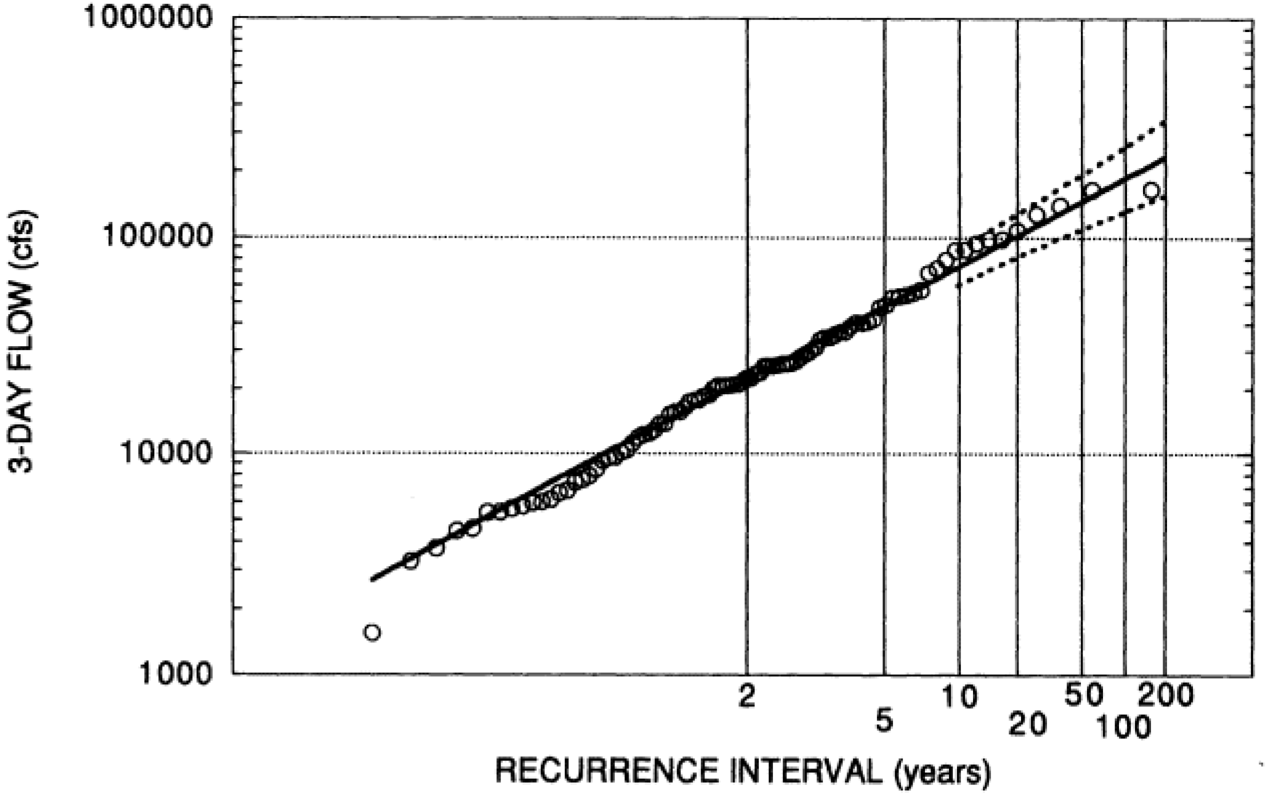

Figure ES.1
Recommended estimated flood frequency distribution for annual maximum unregulated three-day rain flood flows, American River at Fair Oaks. Also shown are the flow data and approximate 90% confidence limits. Plotting position is from Cunnane (1978).

the building restrictions.

If adopted, the 100-year flood estimate recommended by this committee may result in removal of some floodprone areas of Sacramento from the AR zone.[2] This would result in suspension of the building restrictions. It would also likely reduce the political pressure to achieve a solution to the acute flooding threat facing Sacramento.

If our 100-year flood estimate does indeed imply that floodprone areas of Sacramento along the American River levees are not in the 100-year floodplain, it will be by the thinnest of margins. But because the uncertainties in this estimate are so large, the evidence that these areas are not in the 100-year floodplain would be far from compelling. In fact, there is about equal evidence that these areas belong or do not belong in the 100-year regulatory floodplain. The worst consequence of falsely designating such floodprone areas to be in the regulatory floodplain would be the requirement of building restrictions that in the future may prove to be unnecessary. The worst consequence of falsely designating such floodprone areas to be out of the regulatory floodplain would be a prolonged delay in solving acute flood problems, a delay that could have catastrophic results. Given the gross inequality of these two consequences, the committee strongly recommends that authorities carefully consider the situation and the large uncertainties in the estimated 100-year floods, and attempt to develop a flood risk management strategy that addresses the significant risk of flooding in Sacramento.

RESEARCH NEEDS

Flood frequency analysis has been practiced for nearly a century and has seen significant developments in both technological and sociopolitical contexts. Despite the progress that has been made, much remains to be learned. But this improved understanding may present policy issues to be resolved if and when new knowledge and methods are proposed to be incorporated into nationwide guidelines, such as Bulletin 17-B. In particular, it will raise questions as to whether previously completed flood frequency analyses need to be revised, and whether such revisions should significantly change the boundaries of regulatory floodways and floodplains.

To address issues such as these will require both scientific study and informed public debate. But, as was pointed out by the NRC Committee on Flood Risk Management in the American River Basin (NRC, 1995), needs for future research and issue resolution should not be used as an excuse for not taking action now. While that committee's comment was directed specifically to the American River situation, the present committee believes that the ongoing needs and opportunities being experienced by Sacramento suggest that the time is ripe to begin

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[2] The 100-year flood estimate recommended in this report is for unregulated maximum average three-day rain flood discharges at Fair Oaks. Floodplain designation in Sacramento is based on the 100-year regulated annual maximum instantaneous discharge in Sacramento. Determination of the latter requires modeling of the hydrology and hydraulics of the river and associated flood-mitigation systems.

The committee recommends the establishment of a new interagency effort for flood risk assessment and management. The impetus for such action is clear: rising property damages and loss of life; 30 years of experience with the National Flood Insurance Program; aging federal policy and technical guidance; improvements in scientific methods of computing and modeling; emergence of understanding of paleohydrologic and climate variability issues; and a growing data base and availability of information. Virtually all these issues have arisen in the Sacramento case, and can be expected to arise in others as well.

The committee proposes that this interagency effort should emphasize research focused on coordinated and cooperative flood risk reduction, including meteorologic, hydrologic, hydraulic, and policy and socio-economic aspects of flood management. In Chapter 5, a number of specific issues that should be addressed in the recommended interagency effort are discussed.

1

Sacramento and the Struggle to Manage Flood Risk

SETTLING IN THE FLOODPLAIN

Sacramento, California, was settled literally on the banks of the Sacramento and American Rivers (see Figure 1.1) shortly after gold was discovered upstream at nearby Sutter's Mill in 1848. It has been plagued by frequent floods ever since. The problem of understanding and coping with flood risk was faced early (the first flood to inundate Sacramento occurred in January 1850) and often by the original settlers and continues today as a major scientifically underpinned public policy issue. It has subsequently been determined that the town of Sacramento was built in the middle of what was essentially an inland sea that local Native Americans warned appeared almost annually (Kelley, 1989). Presently, more than 400,000 people and $40 billion worth of property are vulnerable to flooding, including most of the city's downtown business and government areas, including the state capitol.

RISK REDUCTION EFFORTS

Since its founding, the city has struggled to protect itself from periodic floods by employing structural and land management measures. In a meeting of citizens it was decided to build Sacramento's first levee immediately following the January 1850 flood (Kelley, 1989). At present, much of the population lives behind levees along the two rivers (see Figure 1.2). Local and federal land use criteria govern the development that occurs in floodprone areas. In addition to Folsom Dam, completed in 1956, several small privately owned reservoirs upstream of the American River act to attenuate the flood runoff peaks issuing from headwaters.

A major flood in 1986 served as impetus for efforts by federal, state, and local entities to identify an acceptable and feasible set of measures to increase Sacramento's level of safety from American River floods. Numerous options were identified in 1991 by the U.S. Army Corps of Engineers (USACE) in a report known as the *American River Watershed Investigation* (USACE, 1991). Due to the controversial nature of many of the alternatives identified in that report, study participants were not able to reach consensus on any of the flood control options, including the construction of a dry dam (with no permanent storage of water) at Auburn, which was ultimately recommended by the USACE. In response, Congress directed the USACE to reevaluate available flood control options and, at the same time, asked the USACE to engage the National Research Council as an independent advisor on these difficult studies.

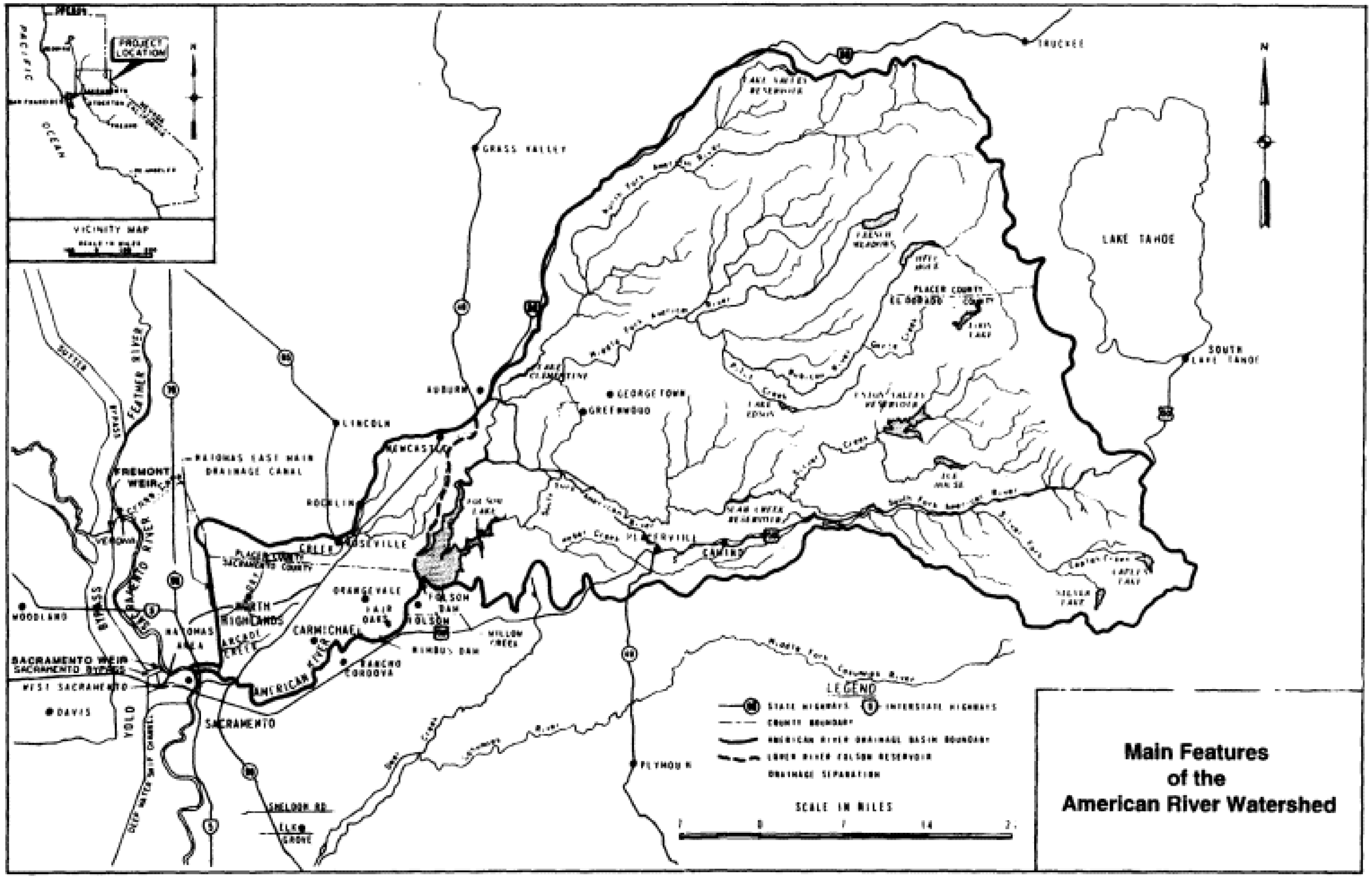

Figure 1.1
Main features of the American River watershed. SOURCE: Sacramento District, USACE, 1991.

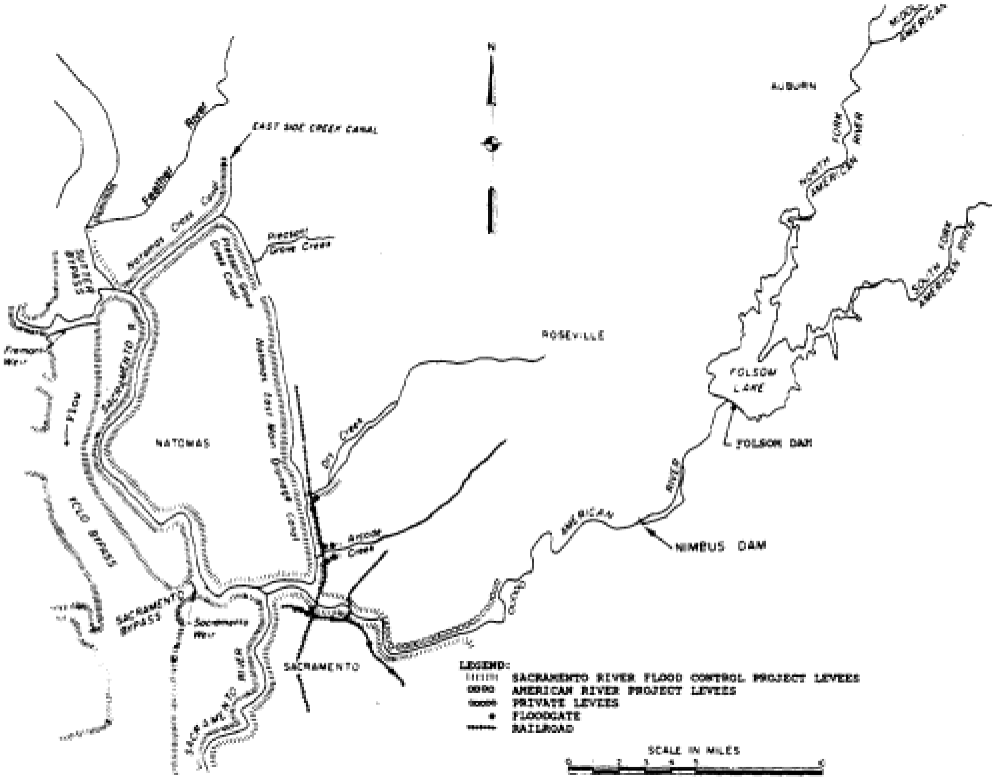

Figure 1.2
Existing flood control features of the American River watershed. SOURCE: Sacramento District, USACE, 1991.

Thus, for about 18 months in 1993-1995, a WSTB-formed committee was engaged in a study relevant to American River flooding and risk reduction. In 1995, the committee issued *Flood Risk Management and the American River Basin: An Evaluation* (NRC, 1995), a report that outlined an approach for improving the selection of a flood risk reduction strategy from the many available. The report contains a variety of recommendations covering improved operations of existing dams in the upstream basins, the integrity and hydraulic capacity of existing levees, statistical analysis of the historic flood record, better hydrologic monitoring in the basin, ecological analysis of alternatives, risk management analysis and water resources planning approaches, and research needs.

CURRENT PLANNING EFFORTS AND CONTROVERSIES

In March 1996, the USACE and its non-federal affiliates completed the Congressionally directed reevaluations of flood control options and submitted recommendations to Congress. In response, Congress authorized a component of the recommended plan but not an adequate plan for the reduction of flood risk for the

Sacramento area. Evaluations of alternatives continue. At the time this report was being prepared, two major flood control approaches are under serious consideration. One option is for the construction of a $1 billion, 500-foot-high flood retention ("dry") dam upstream at Auburn. Funding for similar plans has been repeatedly rejected at the federal level for decades, largely due to high costs and environmental issues. Alternatively, a "stepped release" option seeks to raise and reinforce levees downstream from the Auburn site and to increase the outflow capacity of the existing Folsom Dam. To add considerable complication to the technically and politically difficult decision process, in January 1997 the American River experienced a major flood, nearly as large as and hydrologically similar to the "flood of record" that occurred just 11 years before in 1986.

Flood Flow Frequency Relationships

The occurrence of the 1997 flood suggested that it may be necessary to recompute flood flow frequency relationships for the American River at Sacramento. This second major flood in the past 11 years of 93 years of hydrologic history has significant implications for the flood risk management decision process. Simply put, climatic and hydrologic conditions may be changing so that larger, more damaging events would be expected to occur more frequently. If this is the case, residual flood risks—under present or future conditions—would likely be greater than previously thought.

Perhaps not surprisingly, recalculation of the flow frequency relationships has proven controversial. Occurrence of the 1997 flood has brought into question many issues of technical methodology (e.g., consideration of the paleoflood record, hydrometeorological non-stationarity, the validity of prescribed statistical approaches, and consideration of deterministic precipitation runoff modeling) that should be considered before further assessment of flood risk and consideration of alternatives for risk management can effectively proceed. Revised flood flow frequency relationships form the underpinnings of all future planning and must be realistic and professionally defensible in order to avoid controversy, to the maximum extent possible, and minimize uncertainties and errors in the decision process.

Hydrologic Risk and Uncertainty Analysis

The timing of the 1997 flood coincides with new thinking and methods in the field of hydrologic risk and uncertainty assessment. In 1994, the USACE adopted new risk and uncertainty analysis procedures for project evaluation that explicitly include uncertainties of hydrology, hydraulics, and economics of project planning. The primary advance in these new methods is that uncertainty is quantified and incorporated in project analysis (NRC, 1995). The U.S. Congress also recently commissioned a study of the USACE's risk-based analysis, which is just underway and is being carried out by a new committee organized by the WSTB. The WSTB 1995 American River study, the 1997 floods, and the concurrent WSTB study on risk-based analysis all suggest that a case study on updating flow frequency and other hydrologic/hydraulic parameters in the American River basin is particularly timely.

TECHNICAL ISSUES AND POLICY IMPLICATIONS

In February 1998, the USACE published a revised unregulated rain flood flow frequency analysis for the American River at Fair Oaks (USACE, 1998).[1] This revision was the first since 1986, and was motivated by the occurrences in 1986 and 1997 of two major floods on the American River. As expected, the analysis produced a flood frequency curve that indicates that large floods are appreciably more likely than previously thought. Based on the newly estimated 100-year flood discharge, the levees protecting Sacramento would no longer provide protection against the 100-year flood according to criteria[2] set by the Federal Emergency Management Agency—the effect of this essentially being "decertification" of the existing levees to provide 100-year protection and new requirements for the purchase of flood insurance. The revised flow frequency relationships also reduce the estimated level of protection of the flood control alternatives that are currently being considered for Sacramento.

USACE Approach

In calculating the revised flood frequency analysis, the USACE used daily flow data collected at the Fair Oaks gage (USGS #11446500) that were adjusted for the impact of upstream reservoirs.[3] The adjustment consisted of adding the gaged mean daily flows to the daily change in storage at Folsom Lake and the lagged daily change in storage of the most significant reservoirs in the upper American River basin (the latter accounting for about 90% of all storage in the upper basin). The change in storage for the upstream reservoirs was lagged by one day to account for travel time. For each year of record, the maximum rain-event flows for 1-, 3-, 5-, 7-, 10-, 15-, and 30-day durations were extracted (USACE, 1998). Spring snowmelt events were excluded to avoid mixing populations.

Analyses

In conducting flood frequency analysis on each of the maximum flow series, the USACE was guided by Bulletin 17-B (IACWD, 1982). The mean, standard deviation, and coefficient of skewness of the logarithm of the flow series were computed from the flow series. (The 15-day and 30-day flows for 1977 were identified as outliers; but in order to avoid having the frequency curves cross, the flows were not censored.) For the 1-day, 3-day, and 5-day series, the skews used were weighted averages of the sample and regional skews; for the remaining durations, sample skews were used directly. The regional skews were based on the skew map given in Plate 1 of Bulletin 17-B, and weighting was based on the mean square errors

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[1] Unregulated rain flood flow frequency analysis is conducted on annual peak flow data that have been corrected for the effects of reservoir storage and are associated with events that are primarily due to rainfall rather than snowmelt.

[2] 44 CFR 65 of the Code of Federal Regulations.

[3] Daily rather than instantaneous flows are critical to flood management decision on the American River because of the significant volume of upstream flood storage at Folsom Dam.

of the sample and regional skews, as suggested in Bulletin 17-B. No historical data were used in the analysis, reportedly because it did not appear that use of historical data would affect the results. Finally, the expected probability adjustment was applied to the estimated distributions. The three-day flow values computed by the USACE (1998) were 215,000 cubic feet per second (cfs) for the 100-year flood and 278,000 cfs for the 200-year flood at the Fair Oaks gage. For perspective, estimates of the three-day flow values for the 1986 and 1997 floods at Fair Oaks are 166,000 cfs and 164,250 cfs, respectively.

Reactions to USACE Analysis

The methods and results of the USACE flood frequency analysis have prompted several questions, comments, and criticisms from representatives of local, state, and federal government agencies, public interest groups, private citizens, as well as from the Corps itself These concerns were conveyed to the committee both orally and in writing over the course of this study. In addition, the committee identified other issues of concern. Below is a list of the issues that the committee recognized as potentially critical, and that are addressed in this report:

- accuracy of the adjusted daily flows used in the flood frequency analysis;
- failure of the USACE analysis to incorporate historical data or paleoflood information;
- consistency of the results with probable maximum flood estimates, envelope curves of maximum flood discharges, and rainfall runoff modeling results;
- use of the Bulletin 17-B map skew, given that the skew map is out of date and was developed for instantaneous flood discharges, not maximum daily flows;
- the use of the expected probability correction;
- adequacy of the log-Pearson type III distribution for modeling flood distributions over a wide range of exceedance probabilities;
- adequacy of the Bulletin 17-B procedure for accounting for historical data;
- the potential advantages of censoring the lower part of the distribution so that the estimation depends only on the largest floods;
- the fact that the record from 1950 to the present has many more large floods than the 1905-1950 record; and
- potential changes in flood probability due to global climate or regional change.

The first two issues concern data used (or not used) in the USACE analysis, and are discussed in Chapter 2. The next six issues concern methods of flood frequency analysis, and are discussed in Chapter 3. The last two issues concern climate and its bearing on the standard assumption that flood discharges are independent and identically distributed in time; this is the focus of Chapter 4.

In evaluating the issues of data, analysis methods, and climate, the committee strictly adhered to scientific standards. Hence, each technical recommendation, presented in Chapter 5, is based on best judgment of what is consistent with the scientific literature. It is important, however, to recognize the following:

- Estimations of flood quantiles and probabilities are based on a number of underlying assumptions, the validity of which cannot be absolutely established (e.g., the assumption that flood discharges are independent and identically distributed in time).

- Even if the underlying assumptions are reasonably correct, there are large standard errors in flood frequency analysis; even flood records 100 years in length have insufficient information to allow accurate estimates of quantiles such as the flood flow exceeded with a probability of 1% in any year (100-year flood discharge).
- The differences between our best estimate of flood quantiles (such as the 100-year flood discharge) and those of the USACE are small compared to the likely uncertainties in the estimates.
- Critical policy decisions in the American River basin, such as certification of the levees, Sacramento's floodplain status, and the adoption of flood mitigation strategies, are extremely sensitive to the official estimates of flood probabilities and quantiles. Hence, even though our best estimates are not significantly different from those of the USACE in a statistical sense, the differences may have significant policy implications.

The last issue is particularly important, and is discussed in Chapter 5.

2

Data Sources

A variety of data types can be used in estimating flood quantiles or exceedance probabilities for the American River. These include systematic streamflow and precipitation data, historical and paleoflood data, and regional hydrometeorological information on extreme events. Flood frequency analysis traditionally has been based on systematic streamflow or precipitation records, where use of the latter requires the application of precipitation runoff modeling. Modem statistical innovations have enabled the use of historical and paleohydrologic data in flood frequency analysis. These data can provide information about extreme flooding over much longer time frames than systematic records, and thus could increase the accuracy of the frequency analysis (Cohn and Stedinger, 1987). Regional studies of maximum precipitation and flood discharges can provide information about extreme floods that can be used to check the accuracy of estimated flood distributions, particularly when these distributions are extrapolated (i.e., applied to flood magnitudes much larger than observed in the systematic record). This chapter begins with a general description of the various sources of data used in flood frequency analysis. It then focuses on specific data relevant to the American River watershed, and potential limitations of these data.

GENERAL DESCRIPTION OF FLOOD FREQUENCY DATA

Systematic Streamflow Data

The U.S. Geological Survey (USGS) has primary responsibility for operating a streamflow-gaging-station network in the United States. Systematic streamflow gaging by the USGS began in the late 1800s (Mason and Weiger, 1995). As of 1994, the USGS network consisted of 10,240 stations (Gilbert, 1995) and accounted for more than 85 % of the nation's stream-gaging stations. (About 3,000 of these stations employed crest-stage gages that provide only peak flow information). Historical records of daily streamflow and peak flows for almost 20,000 USGS stations are available for various periods of record. The data are published in annual USGS water data reports for each state and are available on the Internet (http://water.usgs.gov), through USGS data bases, and on compact disc (CD-ROM) from private vendors.

The accuracy of flood discharge data depends on whether large floods are directly measured by current meter surveys or are estimated by rating-curve extension or indirect measurement techniques (Rantz and others, 1982). Jarrett (1987) stresses the need to assess the reliability of extreme flood data, particularly data collected before 1950.

Flood frequency analysis of systematic flood data typically assumes that the data are independent and identically distributed in time (i.e., temporally uncorrelated and stationary). Local human activities, such as land use changes or reservoir construction, or climate change (regional or global) can make this assumption untenable. There are relatively few gaged streams on watersheds that have not been affected to some degree by human activities. At the same time, there are relatively few cases where human impacts on flood magnitude and frequency have been carefully documented. Lins and Slack (1999) evaluated flood data from watersheds that are considered to be relatively unimpacted by local human activities and did not find compelling evidence of climate-induced non-stationarity for floods. Note, however, that it is very difficult to detect climate-induced non-stationarity in flood data because of the high variability (Jarrett, 1994).

Precipitation Data

The National Weather Service is responsible for maintaining a network of meteorological stations in the United States. The current network includes about 300 primary stations staffed by paid technicians and over 8,000 cooperative stations operated primarily by volunteers (NRC, 1998b). As of 1975 there were about 3,500 non-recording precipitation gages with records of 50 years or more (Chang, 1981). Precipitation data are published in Climatological Data and Hourly Precipitation Data by the National Oceanic and Atmospheric Administration (NOAA). Digital records can be obtained from the National Climatic Data Center, from regional climatic centers, and various vendors. Note that many digital records do not include data collected prior to 1940.

Another source of extreme precipitation data for the United States is a catalog of extreme storms maintained by the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, and the National Weather Service. This catalog includes information on over 300 extreme storms including the 1862 storm in California and the Pacific Northwest. For each storm in the catalog, official climatic data as well as rainfall bucket survey data (if available) were compiled and storm characteristics analyzed. It should be noted that extreme storms and floods are not as well documented today as they were in the past, in spite of technological improvements that greatly facilitate such documentation.

Precipitation data are subject to large errors. The most serious problem is the undermeasurement at all operational precipitation gages by amounts that depend primarily on the type of gage (including wind shield), exposure, wind speed, and whether the precipitation is rain or snow. Precipitation measurements during snowfalls are particularly biased. For example, during a snowfall a wind-shielded gage typically undermeasures precipitation by about 40% in a wind of 25 km/hr (Larson and Peck, 1974). In the case of a systematic rainfall record, the problem may be exacerbated if the location and type of precipitation gage is changed during the period of record. This can lead to inconsistent data, which may appear to indicate climatic non-stationarity (Potter, 1979).

Historical Flood Data

Historical data are episodic observations of flood stage or conditions that were made before systematic data were collected (Jarrett, 1991). In the United States, historical data typically are available for 100 to 200 years (Thomas, 1987). In Egypt and China, historical data are available for several thousands of years (Baker, 1987; Pang, 1987). Historical data are obtained from a variety of sources, including newspapers, human observers, diaries, historical museums, and libraries. Historical descriptions of storms and floods are typically qualitative, and sometimes exaggerated and contradictory; hence, they require careful review (Engstrom, 1996; Pruess, 1996). Historical floods were generally recorded because they disrupted people's lives. The threshold of perception typically depends on the location of people, buildings, and economic activity, and may change in time and with observers (Stedinger and Cohn, 1986).

In statistical terms, historical (and paleoflood) data are usually treated as censored samples. An important type of historical data is knowledge of a level that has not been exceeded at a given location over a known period of time, which USGS has compiled and annotated at many gaging stations.

There are three potential problems with the use of historical data in flood frequency analysis. First, estimates of peak flood discharges associated with historical stage information are subject to error; such errors can be reduced, however, by careful hydraulic analysis, and their impact on flood frequency analysis can be minimized by explicitly accounting for them in the analysis. Second, the most serious error (and one that cannot be statistically accounted for) is an erroneous conclusion that a given level has not been exceeded over a known period of time. Such an error is less likely to happen in heavily populated areas. Finally, as in the case of systematic data, the use of historical data is conditioned on the assumption of stationarity. This can be problematic because of the hydrologic impacts which occurred during the early history of the United States and because of the scarcity of systematic data with which to assess these impacts.

Paleoflood Data

Paleoflood hydrology is the study of ancient flood events, which occurred prior to the time of human observation or direct measurement (Baker, 1987). Paleoflood data provide a perspective on long-term hydrologic and climatic variability that can be useful in flood project design and management. Paleoflood data complement short-term systematic and historical records. They provide information at ungaged locations, provide likely upper limits of the largest floods that have occurred in a river basin, and potentially decrease the uncertainty in estimates of the magnitude and frequency of large floods (Baker, 1987; Costa, 1987; Enzel et al., 1993; Jarrett, 1991; Kochel and Baker, 1982; Patton, 1987; Stedinger and Baker, 1987; Xu and Ye, 1987).

Paleoflood hydrology primarily is concerned with determining the magnitude and frequency of individual paleofloods (Baker, 1987; Baker et al., 1988; Costa, 1987; Gregory, 1983; Hupp, 1988; Jarrett, 1991; Kochel and Baker, 1982; Stedinger and Baker, 1987). Although most paleoflood studies involve prehistoric floods, the methodology is applicable to historic or modern floods (Baker, 1987). Two approaches are in current use. The geomorphic approach is based on the sizes of flood transported boulders (Costa, 1983; Gregory, 1983; Williams, 1984; Stedinger and Baker, 1987). The hydraulic approach, which is more commonly used today, is based on paleostage indicators that provide indirect evidence of the maximum stages in a flood (Baker, 1987; Hupp, 1987; Jarrett and Malde, 1987).

There are many kinds of paleostage indicators, including evidence of vegetation damage, accumulations of woody debris, and sedimentologic evidence. The latter includes erosional and depositional flood features along the margins of flow in a channel (Figure 2.1). Slack-water deposits of sand-sized particles (Figure 2.2) and bouldery flood bar deposits commonly are used as paleostage indicators. The strategy of a paleoflood investigation is to visit the places where evidence of out-of-bank flooding is most likely to be preserved. The types of sites where flood deposits commonly are found include: (1) locations of rapid energy dissipation where flood transported sediments would be deposited, such as tributary junctions, reaches of decreased channel gradient, abrupt channel expansions, or reaches of increased flow depth; (2) locations along the sides of valleys in wide, expanding reaches where fine-grained sediments or slack-water deposits would likely be deposited; (3) ponded areas upstream from channel contractions; and (4) locations downstream from moraines across valley floors where large floods would likely deposit sediments eroded from the moraines. Lack of evidence of extraordinary floods may be as important as tangible onsite evidence of flooding (Jarrett and Costa, 1988; Levish et al., 1994). Knowledge of the nonoccurrence of floods for long periods of time has great potential value in improving flood frequency estimates (Stedinger and Cohn, 1986). The actual value depends on the correctness of the assumed probability distribution and of the assumption that flood flows are independent and identically distributed. Paleoflood evidence is generally relatively easy to recognize and long lasting (e.g., Figure 2.3) because of the quantity, morphology, structure, and size distribution of sediments deposited by floods.

Once paleostages have been estimated, a hydraulic analysis must be conducted to estimate the corresponding discharges. The step backwater method (Chow, 1959) is a commonly used and reliable method for discharge estimation in which a one-dimensional gradually-varied flow analysis is used to calculate watersurface elevations as a function of discharge. For a given site, the discharge that produces the observed paleostage elevations is selected as the peak discharge. The analysis readily allows for evaluation of critical assumptions, such as choice of roughness coefficients, and for estimation of uncertainties. For complex channel reaches, two-dimensional hydraulic models are coming into use (Stockstill and Berger, 1994; Miller, 1994).

A third step in the analysis of a paleoflood is dating of the event. A commonly used and relatively accurate dating technique is radiocarbon dating (Baker, 1987; Kochel and Baker, 1982, 1988), by which absolute ages are determined from laboratory measurements of the ratio of radioactive carbon-14 to stable carbon-12 in a samples of organic carbon. Typical sources of organic carbon include wood, charcoal, leaves, humus in soils, and bone. A recent advance in radiocarbon dating based on the use of tandem accelerator mass spectrometry has resulted in more accurate age estimates and requires a smaller sample of organic carbon (Kochel and Baker, 1988). Using this approach, samples having an age of 10,000 years or less generally can be dated with an uncertainty of less than 100 years. When flood-scarred or -damaged trees are present, dendrochronological methods can be used to date floods. In some cases, these dates are accurate to the year and even the season.

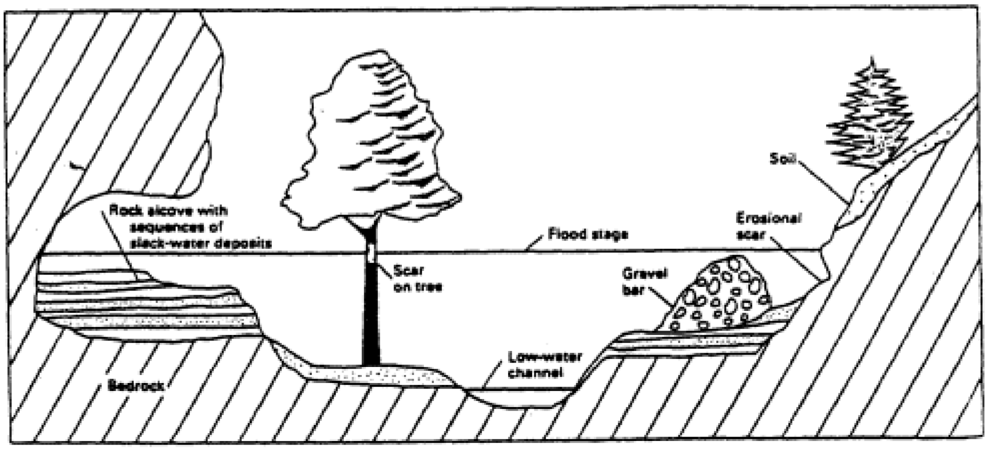


Figure 2.1
Diagrammatic section across a stream channel showing a flood stage and various flood features.
Source: Jarrett, 1991.

The use of paleoflood information in flood frequency analysis is subject to errors in the estimation of discharge peak and age, errors in field interpretations, and questions of hydrologic stationarity. Errors in the estimation of peak discharges and ages can be controlled by careful hydraulic and laboratory analysis. Furthermore, these errors can be quantified and incorporated into the flood frequency analysis. Qualified paleohydrologists can avoid errors in field interpretations by collecting information at several sites to provide internal checks. Note, however, that there are no universally accepted methods for quality assurance and control in the practice of paleohydrology.

The most problematic issue regarding the use of paleoflood information in flood frequency analysis is the statistical nature of climatic variability. Flood frequency analysis is traditionally based on the assumption that flood magnitudes are independent and identically distributed in time. As previously discussed, changes in watershed vegetative cover due to humans or natural disturbances (fires, blowdowns, etc.) can change the probability distribution of floods, and invalidate the assumption that floods are identically distributed in time. Climatic variability can also pose a problem. Over decades it may be a useful approximation to assume that climate and flood magnitudes are independent and identically distributed in time. Over thousands of years, such an approximation may not be warranted.

Several recent papers have provided evidence that flood magnitudes are not independent and identically distributed over the last 5,000 to 10,000 years. Based on a 7,000-year record of overbank floods for upper Mississippi River tributaries, Knox (1993, p. 430) concludes: "During a warmer, drier period between about 3,300 and 5,000 years ago, the largest, extremely rare floods were relatively small-the size of floods that now occur once every 50 years. After ~3,300 years ago, when the climate became cooler and wetter, an abrupt shift in flood behavior occurred, with frequent floods of a size that now recur only once every 500 years or more. Still larger floods occurred between about A.D. 1250 and 1450, during the transition from the medieval warm interval to the cooler Little Ice Age. All of these changes were apparently associated with changes in mean annual temperature of only about 1-2°C and changes in mean annual precipitation of ≤10-20%." Knox's evidence suggests that during the past 7,000 years, floods on upper Mississippi River tributaries have not behaved as independent and identically distributed random variables.

Figure 2.2
An ideal channel for studying slack-water deposits—the Escalante River in Utah. The person on the left is standing on a typical sequence of slack-water deposits, which were deposited where the flow velocity decreased in the canyon of the Escalante River.
Source: Robert H. Webb, U.S. Geological Survey.

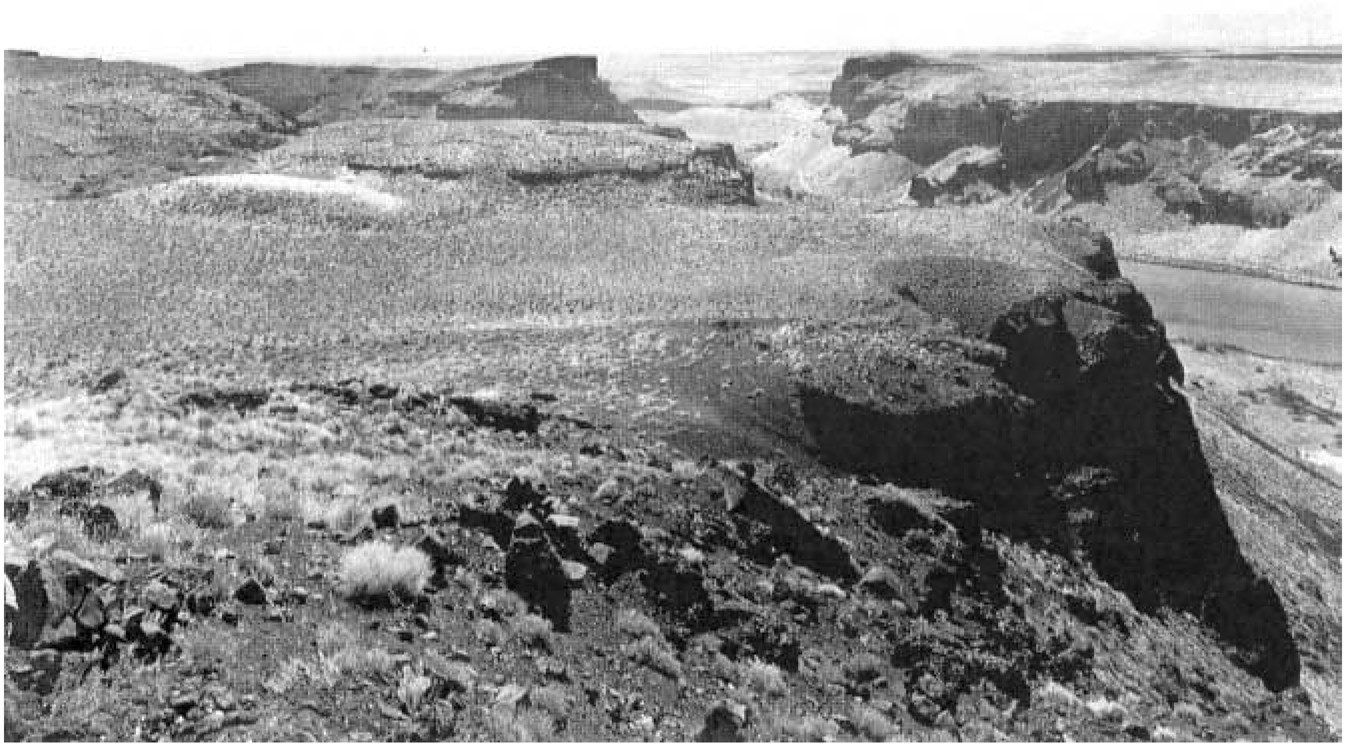


Figure 2.3

View upstream toward the canyon of the Snake River in Idaho at river mile 462. The surface of the basalt bench in the foreground, which is about 450 feet above the river (elevation 2,750 feet), was scoured by the Bonneville Flood about 15,000 years ago. The light colored mound in the lee of the bench in the upper left of the photograph is a grass-covered gravel bar deposited by the flood, which demonstrated the preservation potential of paleostage indicators.

Source: Reprinted, with permission, from the Geological Society of America, 1987. © 1987 The Geological Society of America.

Ely et al. (1993) used paleoflood data from 19 rivers in Arizona and southern Utah to conclude that "the largest floods in the region cluster into distinct time intervals that coincide with periods of cool, moist climate and frequent El Niño events. The floods were most numerous from 4,800 to 3,600 years before the present (B.P.), around 1,000 B.P., and 500 years B.P., but decreased markedly from 3,600 to 2,200 and 800 to 600 B.P." Figure 2 in Ely et al. (1993) indicates that about 70% of the extreme floods represented in the documented paleoflood record of the last 5,000 years occurred during the last 600 years. Unless the paleoflood record is grossly incomplete, this suggests that extreme floods in Arizona and southern Utah do not behave as independent and identically distributed random variables.

The committee is interested in the use of flood frequency analysis to predict and mitigate future flood risk. If floods are not well modeled as independent and identically distributed over the time period for which paleoflood information is available, use of this information in conventional flood frequency analysis may lead to biased estimates of future flood risk. For example, based on the data of Ely et al. (1993), conventional use of a 5,000-year paleoflood record from Arizona and southern Utah would result in underprediction of the future risk of extreme floods there. Estimation of the bias in this case or in any other case requires specification of a model of floods that accounts for climatic variability. As discussed in Chapter 4, we do not at this time have sufficient understanding of climate dynamics to confidently specify such a model.

Regional Analyses of Hydrometeorologic Extremes

Regional analyses of hydrologic extremes are based on the concept of substituting space for time. The idea is that a rare event that occurs in one part of a large homogeneous region could occur at other locations. Regional methods allow the analyst to make use of such rare events. Two kinds of regional analyses are at issue in the American River—the envelope curve of maximum observed flood discharges and the probable maximum flood (PMF).

A flood envelope curve is a mathematical expression that provides an upper bound of observed maximum instantaneous peak discharges for some region as a function of drainage area. Envelope curves have been long used in flood hydrology (Crippen and Bue, 1977; Costa, 1987), and were particularly useful before alternative methods of regional flood analysis were developed. A recent innovation is the incorporation of peak discharges estimated from paleoflood data (Enzel et al., 1993). A flood envelope curve is useful for "displaying and summarizing data on actual occurrences of extreme floods" (IACWD, 1986, p. 71). However, the envelope curve itself offers no means of estimating flood exceedance probabilities. Estimation of such probabilities requires the use a statistical framework, which in turn requires careful evaluation of regional homogeneity and spatial correlation.

For more than 50 years, the PMF has been used in the design of hydraulic features of high-hazard dams. The PMF is defined as "the maximum runoff condition resulting from the most severe combination of hydrologic and meteorologic conditions that are considered reasonably possible for the drainage basin under study" (Cudworth, 1987, p. 114). PMF estimates are derived from estimates of the probable maximum precipitation (PMP), which is the estimated upper limit of precipitation for a basin. In the United States, the estimation of PMP is based on data contained in the previously mentioned extreme storm catalog. The standard approach for estimating PMF includes (1) estimating the PMP for the basin; (2) deducting appropriate precipitation losses to estimate the excess rainfall available for runoff; (3) converting rainfall excess into a flood hydrograph; and (4) adding interflow and snowmelt hydrograph components to obtain the final PMF hydrograph (Cudworth, 1987). The PMF method is widely used for assessing maximum flood potential at a site. Although the concept of maximum limits for floods is widely accepted, methods used to estimate these limits are subject to large uncertainties. Over the years, estimates of PMP and PMF have typically increased. Furthermore, it is possible for a computed PMF to be exceeded at a given site. In a study of 61 watersheds, Bullard (1986) found that there had been nine rain flood events that had produced peaks greater than or equal to 80% of the PMF peaks estimated by methods of the U.S. Bureau of Reclamation (USBR), and two events that produced peaks greater than or equal to 90% of the USBR-estimated PMF.

AMERICAN RIVER DATA

The USACE based its American River flood frequency analysis solely on daily discharge data from the USGS gaging station at Fair Oaks (USGS station #11446500, drainage area 1,888 square miles) corrected for storage in upstream reservoirs. The validity of these data, particularly the data collected since the completion of Folsom Dam, has been questioned by various observers. In addition, critics have suggested that the frequency analysis should include the use of historical and paleoflood data and have argued that the results of the USACE flood frequency analysis are inconsistent with an existing flood envelope curve for California and with current estimates of PMF. These issues are explored in the remainder of this chapter.

Homogeneity of the Systematic Flood Record

The most important data set for use in flood frequency analysis for the American River is the set of annual maximum rain flood discharges for various durations. We focus on the three-day rain flood discharges, because three days is the most critical duration for designing and evaluating flood mitigation strategies for Sacramento. The systematic maximum three-day rain flood series covers the period 1905-1998 (Figure 2.4), and is based on the USGS station at Fair Oaks corrected for storage in upstream reservoirs. Figure 2.4 shows that the five largest three-day discharges in the series occur after 1950, as well as 10 of the top 13 discharges. Completion of the Folsom Dam in 1956 raises the question of whether the apparent increase in the frequency of large flood discharges is an artifact of the corrections for Folsom storage.

The USACE-estimated unregulated discharge on a daily basis using a simple mass balance is as follows. If $Q_{u,t}$ is estimated unregulated discharge for day t; $Q_{g,t}$

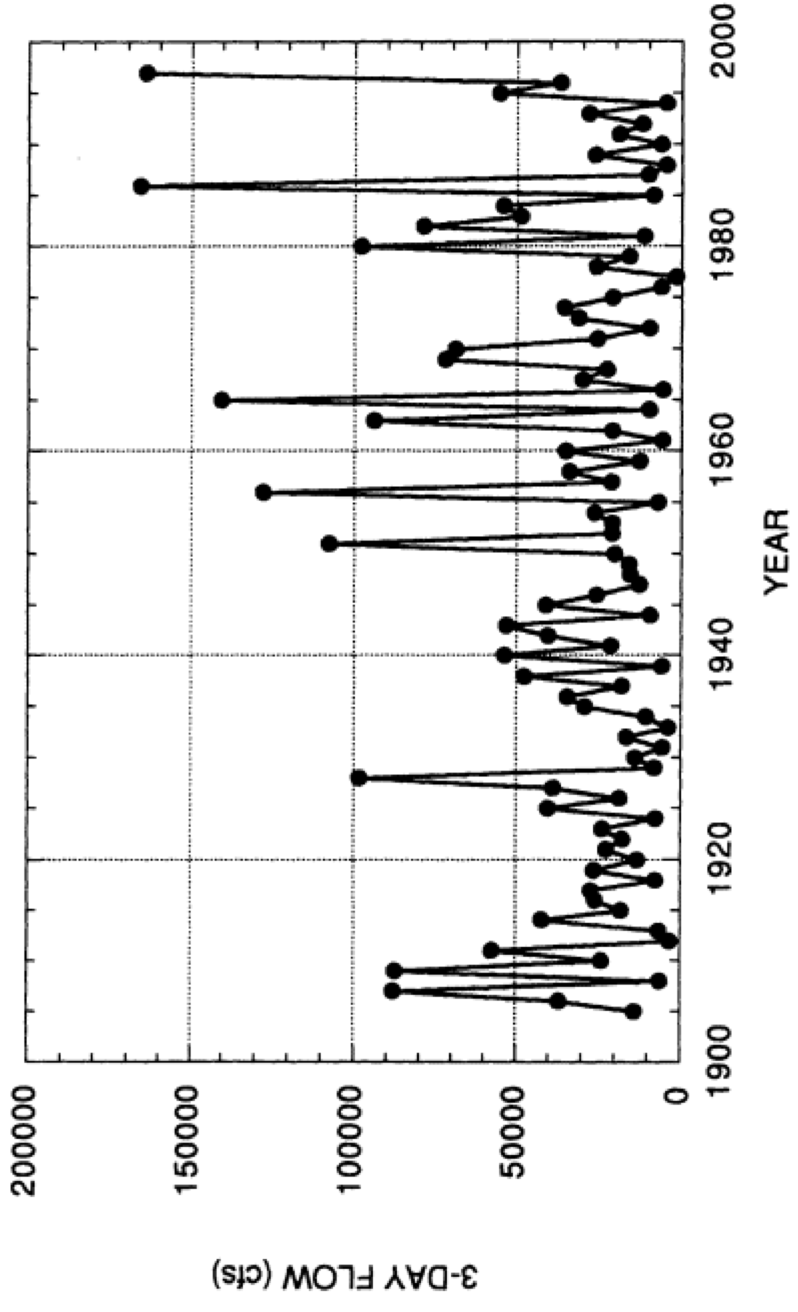


Figure 2.4
Annual maximum unregulated three-day rain flood flows for the American River at Fair Oaks for the period 1905-1998. Note that the five largest flows in the series occur after 1950, as do 10 of the top 13 flows.
Source: USGS gage record at Fair Oaks, corrected by the USACE for storage in upstream reservoirs.

is gaged discharge at Fair Oaks (below Folsom); $\Delta S_{f,t}$ is daily change in storage in Folsom Reservoir; and $\Delta S_{j,t}$ is daily change in storage in the five upstream reservoirs (j = 1...5), then

$$Q_{u,t} = Q_{g,t} + \Delta S_{f,t} + \sum_{j=1}^{5} \Delta S_{j,t-1} \qquad (1)$$

The lagging of storage changes in upstream reservoirs is intended to reflect flood wave travel times. Five significant upstream reservoirs have combined storage in excess of 700,000 acre-feet and collectively account for 90% of upper basin storage. Sources of error potentially associated with this procedure include errors in gage discharge ($Q_{g,t}$), errors in stage measurement ($\Delta S_{f,t}$), errors on the stage storage rating curve and errors in flood wave travel times.

The question of bias in flood magnitude estimates following dam closure was raised by Robert Meyer of the USGS at the July 1998 workshop hosted by the committee in Sacramento (Meyer, personal communication, 1998). Meyer presented results of double mass curve and regression analyses based on regional streamflow and precipitation data that suggested that the American River flood record may be non-homogeneous.

These observations, particularly given the concentration of large events in the latter (post-dam) portion of the record, prompted further investigation into the homogeneity of the American River flood record. The results of several independent analyses, summarized below, provide convincing evidence that the apparent shift in flood behavior commencing in the 1950s is most likely not, or at least not primarily, an artifact of the methods used to estimate unregulated flood discharges in the post-Folsom Dam period. These include David Goldman's (1998) double mass curve analysis, analysis of discharge records in surrounding basins, order-of-magnitude. estimates of the impact of storage measurement errors, and statistical analysis of long-term precipitation and temperature records from stations in or surrounding the American River basin.

Goldman (1998) constructed an alternative double mass curve comparing American River flood flows at Folsom with flood flows at North Fork Dam on the American, where discharge is uncontrolled. The curve (Figure 2.5) is linear, suggesting causes other than methodological error for Meyer's results. A similar analysis was performed by the committee using annual three-day flood volume data from six surrounding basins of comparable drainage area: the Feather (2 sites), Yuba, Mokelumne, Stanislaus, Toulumne, and Merced Rivers. Like the American, these basins were substantially regulated at some point in their periods of record, although dams were constructed at different times. Visual inspection confirms a high degree of similarity in the time series of three-day flood volumes across the seven basins, with larger events concentrated in the post-1950 portion of respective records. The bivariate test for statistically significant shift in mean (Maronna and Yohi, 1978; Potter, 1981) was applied using the American flood series as test series and the mean of surrounding stations as regional series. (This test is similar in concept to doublemass curve analysis, except that it provides an explicit measure of statistical significance.) The only statistically significant ($P<0.05$) shift in American mean flood magnitudes relative to regional values occurred in or around 1918, well before the period of regulation on the American.

Order-of-magnitude estimates of potential error related to stage measurement also point to other factors responsible for increased flood magnitudes in the more recent period. At capacity, Folsom Reservoir contains approximately 1,000,000 acre-feet of storage and covers approximately 12,000 acres (NRC, 1995). It is assumed that daily changes in storage ($\Delta S_{f,t}$) are obtained directly from stage measurements applied to a rating curve. For a hypothetical stage measurement error of 1.0 foot at maximum stage (storage), or approximately 0.4% relative to the 260-ft maximum depth of pool, the corresponding error in storage is 12,000 acre-feet, or 6,050 cfs-days. In comparing this number to the 1986 peak one- and three-day maxima of 171,000 and 166,000 cfs (daily mean), the resulting relative errors are 3.54% and 1.21%, respectively. For any stage below that design capacity, the corresponding percentages would be lower. These are presumably within the range of gaging error, particularly when gage measurements represent extrapolations of the rating curve well beyond any discharges measured by current meter, as would be the case for an extreme flood.

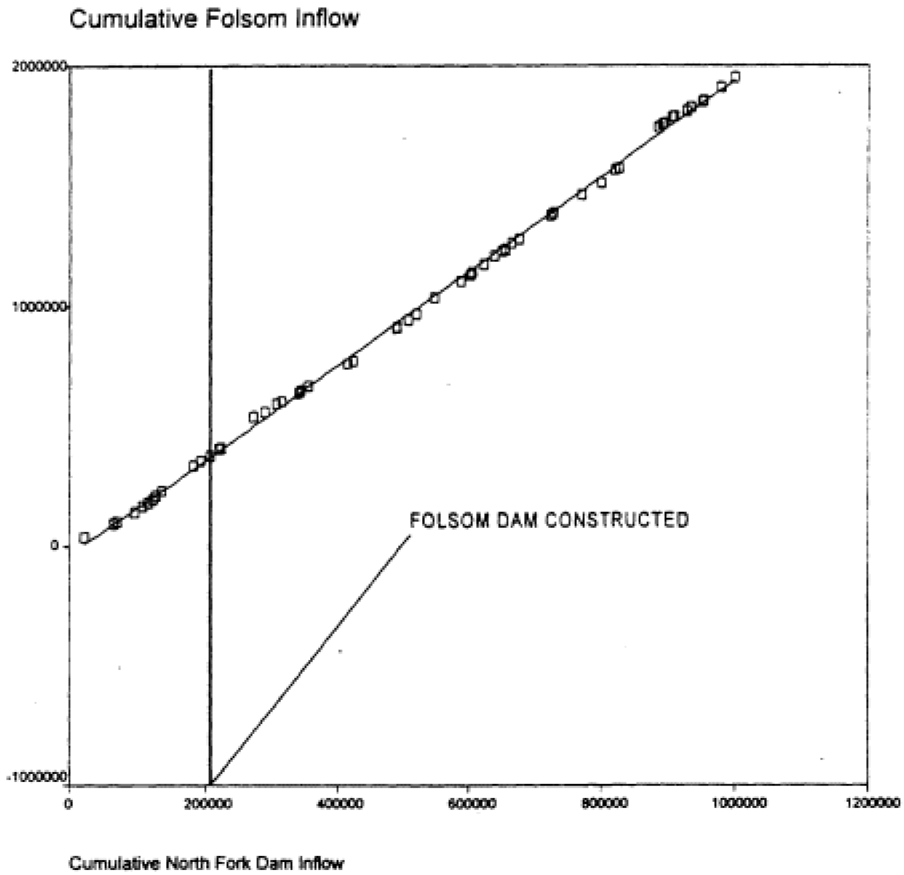


Figure 2.5
Cumulative peak annual inflows to North Fork Dam (North Fork of the American River) vs. cumulative peak annual inflow to Folsom Dam (1942-1996).

A more detailed analysis of flood record homogeneity was conducted with detailed precipitation and temperature records of duration comparable to the American River flood discharge series. The American River basin and surrounding areas contain a number of National Weather Service and cooperative meteorological stations active since the late 19th century or early 20th century. To construct a series of estimated basin average precipitations suitable for evaluating the homogeneity of American River flood records, daily data were assembled for the stations, shown in Table 2.1.

Daily precipitation and temperature data in electronic format were obtained from the Western Regional Climate Center (WRCC) for the period 1949-1997 for Represa, Auburn, Placerville, and Lake Spaulding; and for the period 1931-1997 for Nevada City and Lake Tahoe. Original data for the period 1900 (or earliest available year) to 1930 were obtained on microfiche from the National Climatic Data Center (NCDC) and digitized by Charles Rodgers (consultant to the committee). A system of cross checks allowed reasonable quality control, and the digitized daily precipitation data are judged to be as accurate as the printed sources from which they were taken. Since coverage for some early years was absent at key stations (e.g., Lake Spaulding) and many early records were of poor quality, a continuous set of daily precipitation records judged to be of acceptable quality could be assembled only for the water year 1915 through water year 1997. This is sufficient, however, to support an analysis based on 41 years of pre-regulation (1915-1955) and 42 years of post-regulation (1956-1997) precipitation and flood discharge data.

The bivariate test and several regression models were used to determine the homogeneity of the American River three-day discharge series relative to a series of estimated concurrent maximum three-day basin average precipitation. The latter series was constructed in two steps. First, we computed the weighted average of the daily precipitation amounts from the gages for each day of the seven-day period ending with the end of the discharge event. We then selected the maximum three-day precipitation total for each discharge event. The weights used to construct the basin average (Table 2.1) were derived from elevation-area data from the American River supplied by Robert Collins of the USACE Sacramento District. Figure 2.6 shows the time series of basin average precipitation. Note the apparent increase in large events since 1950, consistent with the observed increase in three-day maximum discharges.

In applying the bivariate test, the test series was the American River three-day flood volume and the regional series was the three-day basin average precipitation. The test was applied to the logarithms of the respective series, since both series are positively skewed in real space but approximately normal in log space. The test detected no significant shifts in mean, which can be interpreted as evidence that the behavior of American River floods, during the period 1956-1997 in particular, did not depart systematically from the pattern of precipitation in the catchment.

As an additional test of record homogeneity, a family of regression models was estimated to predict three-day American River flood volumes using basinweighted mean precipitation, temperature, and a variety of additional variables as potential predictors. The procedure used was to specify the best model, defined as the model that explained the greatest percentage of interannual variation in American

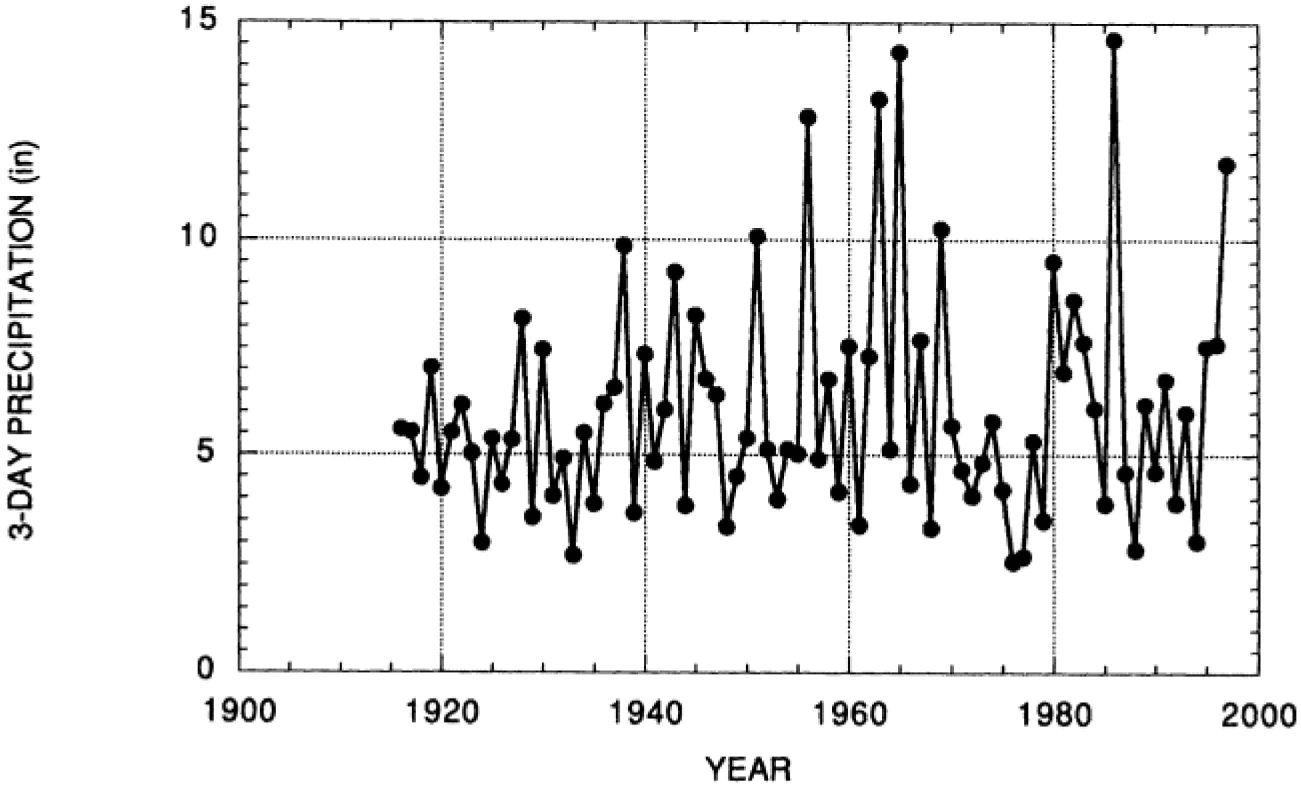


Figure 2.6
American River watershed three-day precipitation associated with maximum annual rain flood.

TABLE 2.1 Weather Stations Used to Estimate Basin Average Precipitationa

Gauge	Location	Elevation (ft MSL)	Weight[a]
Represa	Near Folsom Dam	295	.040
Auburn	On North Fork near Auburn damsite	1,295	.093
Placerville	On South Fork	1,890	.090
Nevada City	North catchment divide	2,600	.204
Lake Spaulding	North catchment divide	5,153	.261
Tahoe City	East of divide by Lake Tahoe	6,230	.312

[a] Used to estimate basin average precipitation.

River flood volumes in a physically plausible manner, and then add to that model an indicator ("dummy") variable having a value of 1 for the period 1956-1997—otherwise. If the value of the estimated linear coefficient on this indicator, equal to the intercept shift or shift in mean during this period, is statistically significant, it would be interpreted as evidence for a shift in hydrologic regime.

The basic model estimation results can be interpreted to indicate that variation in three-day event precipitation accounts for 75% of the interannual variation in three-day flood volumes. The addition of three-day storm temperature at higher elevations increases explanatory power by an additional 8.3% to 83.3%. Addition of variables for date of occurrence and antecedent precipitation does not significantly improve the model. When the period indicator is added to the model, explanatory power is increased by only 0.3%, and the t statistic for the period indicator in this equation, which has already accounted for the influence of precipitation and temperature, has a P value somewhat above 0.10. This suggests that any residual variation in flood volume magnitudes "explained" by period effects in a linear model already accounting for the influences of event precipitation and temperature, albeit crudely specified, is not statistically significant.

Historical Activities in the American River Basin

Before considering the historical and paleoflood data for the American River, it is instructive first to review the history of land use practices in the American River basin. Of particular importance are the activities associated with gold mining in the region, which began with the discovery of gold in 1848. Although the impacts of these activities on flood hydrology are not well known, it is important to consider them when evaluating the relevance of historical and paleoflood data.

Initial gold mining activities involved small placer claims along Sierra streams and probably had relatively minor effects. Hydraulic mining began in California in 1853, and by the mid-1860s giant hydraulic mines were in place. These mines had enormous impacts on the streams, particularly with respect to sediment loads. Hydraulic mining peaked in the late 1870s, and ended in 1884 due to federal legislation.

Gilbert (1917) estimated that hydraulic mining in the Feather, Yuba, Bear, and American River basins yielded nearly 1.1 billion cubic meters of debris, primarily mud, sand, and gravel. This enormous sediment load and the absence of any environmental controls led to severe aggradation of the streams draining the mines, with amounts ranging from several to as much as 30 meters (Gilbert, 1917). The first major flood to transport this sediment occurred in water year 1862. Transport continued in subsequent floods. The sediment moved primarily in pulses during winter floods, with amounts gradually decreasing after the curtailment of hydraulic mining. By 1988, American River channels near the mining district were largely free of mining sediments, except terrace sediment, and appeared to be at or near their pre-mined grade (James, 1988). NRC (1995) and James (1997) concluded that the lower American River reaches still have substantial mining sediment remaining and that cyclical patterns of aggradation and degradation occur, but that the net trend appears to be slow channel degradation and increasing channel flow capacity.

Vast areas of Sierra forests were cut in the mid- 1800s to support the mining industry (Beesley, 1996). Lumber was needed for fuel and construction of camps, towns, water flumes, mining structures, tunnels, and railroads. In the 1840s, the estimated annual lumber production in California was about 20 million board feet per year. In less than 30 years, annual lumber production increased to nearly 700 million board feet, primarily to support activities related to gold mining (Mount, 1995). Based on data from various sources, Beesley (1996) concluded that about one-third of the trees (primarily yellow and sugar pine) in the mining area in the Sierra Nevada had been harvested by about 1885. In the early 1900s, logging diminished, enabling the forest ecosystem to substantially recover, although pine was replaced primarily by white fir (Beesley, 1996). As a result of the rapid population growth of California after World War II, timber harvesting rapidly increased, reaching 6 billion board feet per year by 1960.

Grazing of domestic livestock, primarily sheep and cattle, has probably affected a larger proportion of the Sierra Nevada than any other human activity (Menke et al., 1995). Grazing was minimal prior to about 1860, then increased dramatically until the early 1900s. The effects of unmanaged grazing included increases in runoff and sediment yields and localized gully formation (Gilbert, 1917). With the advent of regulation by the U.S. Forest Service in 1905, better management practices were instituted, reducing the overall watershed impacts (Beesley, 1996).

Wildfire can produce extensive changes in streamflow and sediment yield (Florsheim et al., 1991; Meyer et al., 1995; Weise and Martin, 1995). Hydrophobic conditions often develop after a wildfire, as combustion of vegetation and organic matter produces aliphatic hydrocarbons that move as vapor through the soil and substantially reduce infiltration. Hydrophobic soils, decreased vegetation cover, and reduced surface storage following wildfire dramatically increase the potential for extreme flooding and soil erosion. Favorable runoff conditions may remain for several years to decades until burned areas sufficiently recover to pre-burn conditions (Evanstad and Rasely, 1995). Native Americans, who have inhabited California for at least 10,000 years, modified the Sierra Nevada landscape by burning and various agricultural practices (Anderson and Moratto, 1996). In the late 1950s, after more than a half century of active fire suppression, greater emphasis was placed on prescribed burning to reduce the buildup of fuelwood and hence decrease the potential of catastrophic fires (Weise and Martin, 1995). It is not known whether the hydrologic effects of prescribed burns are the same as those of wildfires.

Levees were built in the Sacramento area to aid in draining wetlands for agriculture and for protection from floods on the American and Sacramento Rivers. As noted in Chapter 1, the first levees were built following the flood of 1850. These levees failed in the 1852 flood, and were subsequently rebuilt to higher levels (Woodward and Smith, 1977). Following the disastrous flooding in 1861-1862, substantial efforts were directed towards major levee projects. Unfortunately, as a result of aggradation from mining sediments, the height of flood waters for a given discharge progressively increased. This led to levee failures during moderate floods, requiring additional levee improvements.

Most rivers in the Sierra Nevada have surface water impoundments for multi-use purposes to help support the rapid population growth in California, particularly after World War II. These impoundments can dramatically affect streamflows, reducing flood flows and increasing low flows. As a result of the substantial impact of impoundments on flood flows it is necessary to correct measured streamflows to establish unregulated conditions, as discussed previously in this chapter.

What are the implications of these various human activities with respect to the use of historical and paleoflood data for flood frequency estimation on the American River? The most obvious implication is that the enormous amount of mining sediment in the American River during the latter part of the 19th century makes it very difficult to accurately estimate historical flood discharges during that period, precisely the period when historical information is available. There is also the possibility that the net effect of human activity has been to increase the flood response of the American River. With the available information it is not possible to quantify this potential effect.

Historical Data

Reliable observations of historical floods on the American River began in 1848 with the discovery of gold at Sutter's Mill. Major floods damaged Sacramento in 1850, 1862, 1867, 1881, 1891, and 1907 (the systematic flood record begins in 1905). Of these, the flood of 1862 clearly had the largest peak discharge, although the maximum stage of the 1867 flood on the lower American River may have been higher as a result of channel aggradation (McGlashan and Briggs, 1939).

The winter of 1861-1862 was extremely wet with few interruptions of the heavy rains from early November 1861 to mid-January 1862. The culminating event was a warm storm in January that had a three-day precipitation of 12.2 inches at Nevada City, the only station in the upper American River basin having records (Weaver, 1962). This was exceeded at this site by only the February 1986 storm (15 inches) and the January 1997 storm (12.7 inches). Flooding was extreme on all rivers from the Klamath south to San Diego (Hoyt and Langbein, 1955; McGlashan and Briggs, 1939). Lynch (1931) concluded that the flood of 1862 was probably the largest in California since the settlement of the Spanish missions in 1769; he had little information for northern California. McGlashan and Briggs (1939) indicated that the floods of 1861-1862 appear to have been the largest in California since at least the early 19th century. The flood is described as covering the entire Sacramento valley with a vast inland sea (Guinn, 1907) except Marysville Buttes (Ellis, 1939). According to Engstrom (1996) the inland sea or lake ranged from 250 to 300 miles long and from 20 to 60 miles wide. Sacramento was submerged and almost ruined by the floods (Guinn, 1907). Bossen (1941) estimated the peak flow on the American River at Fair Oaks to be 265,000 cfs.

The utility of the historical record from about 1848 to 1907 (and perhaps even part of the early systematic gaged record) is questionable because of unknown cumulative effects of land-use changes associated with gold mining. The largest peak flood (1862) in the systematic and historic period occurred during the period of maximum watershed disturbance. Limited precipitation data in Sacramento and Nevada City available during the winter of 1861-1862 suggests that the rainfall and snowmelt contributing to the peak discharge was comparable to the record storms in 1986 and 1997. The estimated peak flood discharge in 1862 was only slightly larger than the floods in 1986 and 1997, suggesting that even with the extensive basin disturbance in the last half of the nineteenth century, basin response may not have been much different from today. One possible explanation is that snowpack covering disturbed surfaces may have masked the potential increase in runoff from mining and vegetation removal. It is also possible that the estimated peak discharge of the 1862 event is low. In any case, it is prudent to cautiously incorporate the historical data in the flood frequency analysis.

Paleoflood Data

As this report was being prepared, the U.S. Bureau of Reclamation (USBR) was concluding a comprehensive paleoflood investigation of the American River and nearby basins. The primary objective of the USBR study was to characterize the probabilities of flood magnitudes greater than those contained in the historical record for use in risk assessment of Folsom Dam. Summarized below are some of the major findings of the paleoflood study provided by Dean Ostenaa (U.S. Bureau of Reclamation, written communication, 1998).

The American River, both upstream and downstream from Folsom Dam, is flanked by a distinct series of stream terraces. These terraces represent abandoned floodplains whose surface morphology and underlying soils accurately record the time since the last major flood. The main objective of the USBR study was to identify and assign ages to terrace surfaces adjacent to the river that serve as limits or paleohydrologic bounds for the stage, and therefore discharge, of past large floods over particular time intervals.

Paleohydrologic records were developed at 12 sites along the American, Consumnes, Mokelumne, and Stanislaus Rivers. Despite the extensive mining activity locally along these rivers, the geologic record of floods remains intact and hydraulic conditions are definable in localized reaches conducive to paleoflood reconstructions. Chronology for paleohydrologic bounds was established by 60 radiocarbon ages, 21 archaeological sites, published soil surveys, and 39 soil/stratigraphic sections. Paleohydrologic discharge estimates were established by a variety of hydraulic modeling techniques. For some sites, discharge estimates were obtained by comparison to measured and estimated discharges at nearby gaging stations. For other sites, detailed topographic surveys provided the basis for two-dimensional flow modeling of study reaches up to 12 miles in length. Paleoflood sites were located in bedrock-controlled reaches; channel geometry for the reach near Fair Oaks, which has changed substantially in the 20th century, was reconstructed from topographic surveys made in 1907.

USBR study results indicate that the flood experience in the American River over the last 50 years is not anomalous. Floods of a magnitude similar to the January 1997 flood have occurred during the past few hundred to several thousand years. Geomorphic and stratigraphic evidence also indicates that there have been floods somewhat larger than the January 1997 flood, but there is no evidence of floods with peak discharges substantially larger than that of January 1997. Peak stage indicators consisting of fine-grained flood sediments, which included mining debris, were used to estimate the peak stage of the largest flood, probably the flood of 1862. The estimated stage was slightly higher than the 1997 peak stage. The peak estimated discharge at Fair Oaks was 260,000 cfs, which is close to the estimate of Bossen (1941). Paleoflood data for the lower American River indicate that a peak discharge of about 300,000 cfs to 400,000 cfs has not been exceeded in the past 1,500 to 3,500 years. These results are consistent with paleoflood data at sites upstream of Folsom Dam and at sites on other rivers in the region.

The quality of the USBR data and analysis is excellent. The committee finds no reasons to disagree with the paleoflood information that the USBR has assembled. As discussed previously, the committee has serious doubts about the assumption that flood magnitudes have been completely independent and identically distributed in time during the period represented by the paleoflood information. Although paleoflood chronologies have not been well documented in the Sierra Nevada (the USBR study is the first systematic attempt to document paleofloods in the region), other paleoclimatic studies have indicated systematic variations in climate there that are consistent with regional and global patterns. For example, paleoecological data (Woolfender, 1995) indicate that the Sierras experienced persistent above-average temperatures during the Medieval Warm Period (approximately A.D. 950-1350) and persistent below-average temperatures during the Little Ice Age (about A.D. 13501850). During the latter period, the Sierras experienced multiple advances of alpine glaciers and a decrease in the number of fire events (Birman, 1964; Burke and Birkland, 1983; Curry, 1969; Gillespie, 1982; Scuderi, 1984, 1987; Swetnam, 1993). Given that extreme floods on the American River occur in winter storms that mainly produce rain rather than snow, it is possible that the frequency of extreme floods would have been lower during the Little Ice Age.

The key issue regarding the usefulness of any data on past floods to a particular planning or design problem is the information the data provide on the potential for flooding during the planning horizon. If floods can be assumed to be independent and identically distributed in time, then all past information is equally relevant to estimating the likelihood of future floods. If this assumption cannot be made, the relative usefulness of particular data on past floods depends on the actual distribution of floods in time, the age of the data, the length of the planning horizon, and the exceedance probabilities of interest. If we had a correct mathematical model of the variation of floods in time i.e., an alternative to the independent and identically distributed model we could estimate the parameters of that model to appropriately weight data from past floods. Unfortunately, we only have a very general understanding of how floods vary in time, and must rely heavily on judgment. Where paleoflood information is inconsistent with modem flood data (i.e., a systematic flood record), the judgment might be not to use the paleoflood data in the flood frequency analysis. As we will see in Chapter 3, the American River provides such a case.

Even if American floods are assumed to be independent and identically distributed, the nature of the USBR paleoflood data somewhat limits its utility for flood planning and management. In particular, these data consist of levels (and hence flows) that have not been exceeded in the last 1,500 to 3,500 years. There is little direct information about the magnitude and frequency of the smaller floods that are of most interest to flood management in Sacramento—floods that occur every 100 to 200 hundred years. While it is true that the use of non-exceedance data in a flood frequency analysis can improve the estimation of the exceedance probabilities of smaller flows, the value of the data critically depends on whether the assumed frequency distribution is correct for flows up to the non-exceedance flow. As we shall see in Chapter 3, although our "best" log-Pearson type III model of the American River 3-day flows provides a good fit to the systematic and historic data, it does not appear to provide an adequate model for significantly larger flows.

Clearly there are potential problems associated with the use of the USBR paleoflood information to estimate exceedance probabilities and flood quantiles for the American River. Consequently, it was decided to not use this information to estimate the committee's recommended flood frequency relationship for the American River.

Envelope Curves

Meyer (1994) developed an envelope curve for peak flood discharges in California based on the highest recorded peak discharges from 1,296 gaging stations (Figure 2.7). For drainage areas greater than 1 square mile, the envelope curve is defined by

$$Q = 10{,}500 A^{1.13}\left(A^{0.5} + 5\right)^{-1.37}$$

where A is the drainage area in square miles and Q is the envelope discharge in cfs. For the American River at Fair Oaks the value of Q is 267,000 cfs.

For several reasons, Meyer's envelope curve is of limited usefulness in estimating the flood frequency distribution for the American River. One potential problem is that the curve does not include data from floods that occurred during periods of regulated flow. Note that most of the larger Sierra Nevada streams have been regulated during the period since 1950, when floods have been most severe on the American River and neighboring rivers.

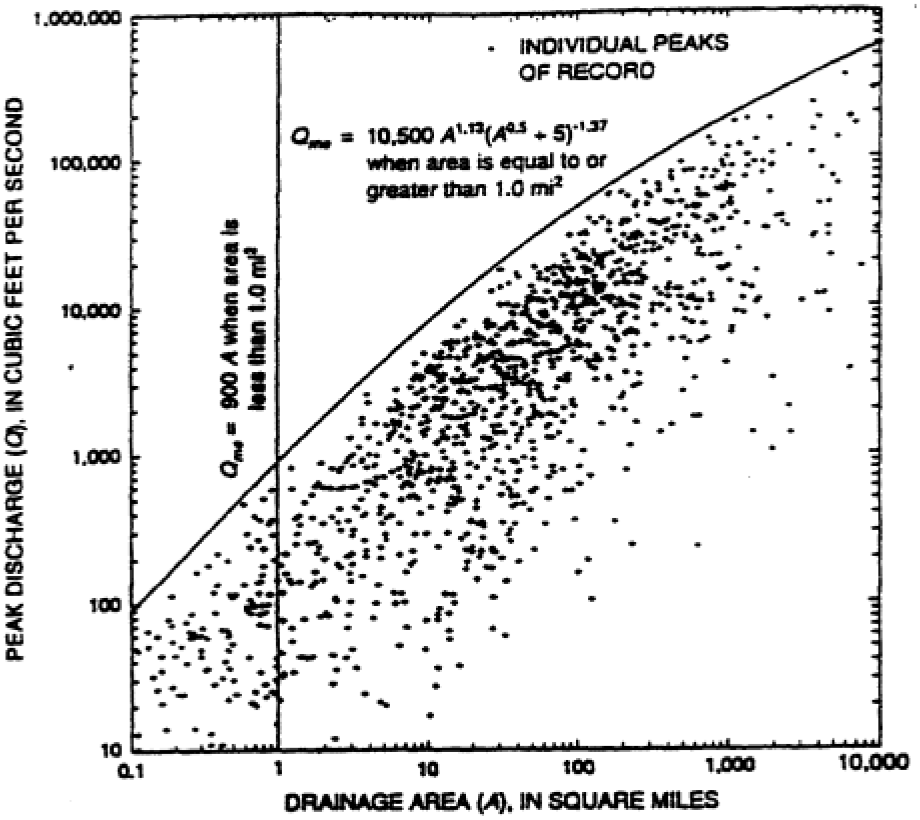


Figure 2.7
Selected peak discharges and regional envelope curve.
Source: Meyer, 1994.

Other problems result from spatial correlation and heterogeneity. Floods on large rivers in California are highly correlated in space, making it difficult to estimate probabilities of exceeding envelope discharges. For example, the annual flood discharges of the seven Sierra Nevada rivers used in Chapter 3 to compute a regional skew (Table 3.2) have an average pairwise cross correlation of 0.87. Furthermore California streams and rivers are highly heterogeneous with respect to flood magnitudes. Basins with the same drainage area are likely to vary in the magnitude of the floods they produce. For example, four floods on the American River (Table 2.2) have peak discharges within 10% of the envelope discharge of 267,000 cfs; of these, the peak discharge of the 1997 flood was estimated to be about 10% larger. Given the precision of flood peak estimates, these four observations essentially lie on the Meyers envelope curve, indicating that the curve does not provide an upper bound for American River floods. This combination of strong heterogeneity and spatial correlation makes it difficult to estimate probabilities of exceeding envelope discharges.

TABLE 2.2 Maximum Peak Discharges on the American River (Unregulated Conditions at Fair Oaks)

Year	Discharge	Source
1862	265,000	Bossen, 1941
1963	240,000	1987 Folsom Control Manual
1964	260,000	1987 Folsom Water Control Manual
1997	295,000[a]	Roos, 1999[a]

[a] Estimated at Folsom Dam. Source: Maury Roos, memorandum to Kenneth Potter dated February 16, 1999.

Probable Maximum Flood

In October 1996, the U.S. Bureau of Reclamation, in consultation with the USACE Sacramento District, used HMR 58 to estimate a mean probable maximum storm amount for the American River basin of 29.62 inches (Pick, 1996; NWS, in press). Using loss rates based on saturated soil for unfrozen ground and snow cover for frozen ground, the USBR calculated one- and three-day probable maximum flood discharges of 575,000 and 401,000 cfs, respectively, for regulated conditions upstream. Due to the combined volume of upstream storage and likely extent of occupied storage at flood time, the equivalent unregulated volumes were expected to exceed regulated values by only a few percentage points. In 1997, following the January 1 flood, USACE Sacramento District re-estimated the probable maximum flood for the basin by applying loss rates equivalent to those observed for this large event (0.7 inches loss of 11.8 inches total) to the probable maximum storm derived in 1996. The resulting three-day runoff was 29.07 inches and the maximum three-day average flow was 485,000 cfs.

PMF estimates for the American River provide some information about the upper tail of the flood distribution. In theory the PMF is the maximum flood that can be expected at a site, the PMF concept is largely empirical, and hence a PMF estimate should be thought of as a very large flood discharge that is highly unlikely to be exceeded. While the committee is unable to specify the distribution of the likely values of the exceedance probability of a PMF for the American River, empirical data suggest that the exceedance probability should probably be smaller than 1×10^{-4} and almost surely smaller than 1×10^{-3}. In the case of the American River, the committee decided to use the two PMF estimates as likely upper bounds on the flood quantile associated with a probability of 1×10^{-3}.

SUMMARY

A variety of data are available for use in flood frequency analysis on the American River. Based on the committee's consideration of these data, it has concluded the following:

- The three-day mean of the 1862 flood (estimated to be 265,000 cfs) is likely the largest peak discharge on the American River since 1848 (and perhaps since the beginning of the 19th century). This historical information should be used in American River frequency analysis, although there are questions about its accuracy and about its relevance given the potential hydrologic impacts of hydraulic gold mining.
- Although the quality of the paleoflood information developed by the U.S. Bureau of Reclamation is excellent, it has two problems. First, explicit use of this information in flood frequency requires the assumption that floods are independent and identically distributed in time or the use of a particular non-independent and identically distributed model. Existing paleoclimatic data call into question the assumption, but are not yet of sufficient quality to allow development of such models. Second, the USBR paleoflood information does not include any information about paleofloods of the magnitudes of greatest interest-discharges with exceedance probabilities from 0.5 up to and beyond 0.002. For these reasons, the use of the USBR paleoflood information was approached with caution.
- Meyer's envelope curve of maximum flood discharges is not especially useful to American River frequency analysis.
- The two most recent PMF estimates for the American River at Folsom Dam represent reasonable upper bounds on the three-day flood quantile associated with a probability of at most 1×10^{-3}.

3

Flood Frequency Estimates for the American River

INTRODUCTION

Effective planning and design of flood risk management projects require accurate estimates of flood risk. Such estimates allow a quantitative balancing of flood control efforts and the resultant benefits, and also enhance the credibility of floodplain development restrictions. They allow determination of the design flows from specified exceedance probabilities, as well as the expected benefits associated with alternative flood risk management proposals. These considerations are critical for the American River, where billions of dollars of property are at risk from flooding.

Fitting a continuous mathematical distribution to data sets yields a compact and smoothed representation of the flood frequency distribution revealed by the available data, and a systematic procedure for extrapolation to flood discharges larger than those historically observed. While the American River flood record at Fair Oaks is almost 100 years in length, there is a goal of providing flood projection for at least the flood that has a chance of 1 in 200 of being exceeded in any year. This requires extrapolation beyond the data, as well as smoothing of the empirical frequency curve to obtain a more consistent and reliable estimate of the 100-year flood.

A variety of distribution functions and estimation methods are available for estimating a flood frequency distribution. The guidelines for frequency analysis presented in Bulletin 17-B (IACWD, 1982) were established to provide consistency in the federal flood risk management process. In estimating a flood frequency distribution for the American River, the committee believed it was desirable to follow the spirit of these guidelines, although not necessarily the exact letter. The committee based its estimation on the log-Pearson type III distribution, as specified in Bulletin 17-B. With only a traditional systematic gaged record, we employed the conventional log-space method of moments recommended by Bulletin 17-B. When additional historical flood information is included or some peaks are censored, the Expected Moments Algorithm is used as the generalization of the conventional log space method of moments method. The Expected Moments Algorithm, developed well after the publication of Bulletin 17-B, makes more effective use of historical and paleoflood information than does the weighted moments method recommended by Bulletin 17-B for use with historical information.

This chapter is organized as follows. An overview of the basic approach of Bulletin 17-B is followed by a discussion of recent innovations in flood frequency analysis that post-date Bulletin 17-B but are nevertheless consistent with its approach. Estimates of flood frequency distributions for the American River using various combinations of systematic, historical, and paleodata are presented along with a recommended distribution. Finally, evidence suggesting that the recommended distribution should not be extrapolated beyond a return period of 200 years is presented.

BULLETIN 17-B

Recommended procedures for flood frequency analyses by federal agencies are described in Bulletin 17-B (IACWD, 1982). Thomas (1985) describes the history of the development of these procedures. The recommended technique is based on fitting a Pearson type III distribution to the base-10 logarithms of the peak discharges. The flood flow Q associated with cumulative probability p is then

$$\log\left[Q_p\right] = \overline{X} + K_p S$$

where $\overline{X}$ and S are the sample mean and standard deviation of the base-10 logarithms X_i, and K_p is a frequency factor that depends on the skew coefficient and selected exceedance probability. The mean, standard deviation, and skew coefficient of station data are computed using

$$\hat{\mu}_x = \overline{X} = \sum_{i=1}^{n} x_i \Big/ n$$

$$\hat{\sigma}^2 = S^2 = \sum_{i=1}^{n} \left(x_i - \overline{X}\right)^2 \Big/ (n-1)$$

$$\hat{\gamma}_x = G = n \sum_{i=1}^{n} \left(x_i - \overline{X}\right)^3 \Big/ (n-1)(n-2)S^2$$

Estimation of the Skew Parameter

Because of the variability of at-site sample skew coefficients, Bulletin 17-B recommends using a weighted average of the station skew coefficient and a generalized skew coefficient, a regional estimate of the log space skewness. In the absence of detailed studies, the generalized skew coefficient G_g for sites in the United States can be read from Plate I in the Bulletin. Assuming that the generalized skew coefficient is unbiased and independent of station skew coefficient, the mean square error (MSE) of the weighted estimate is minimized by weighting the station and generalized skew coefficients inversely proportional to their individual mean square errors:

$$G_w = \frac{G_s / MSE_{G_s} + G_g / MSE_{G_g}}{1/MSE_{G_s} + 1/MSE_{G_g}}$$

Here G_w is the weighted skew coefficient, G_s is the station skew coefficient, and G_g is the generalized regional estimate of the skew coefficient; *MSE[•]* is the mean square error of the indicated variable. McCuen (1979) and Stedinger and Tasker (1986a,b) discuss the development of skew coefficient maps and regression estimators of G_g and $MSE[G_g]$.

Outliers

Unusual high or low annual floods are normally called outliers. Bulletin 17-B defines outliers as "data points that depart significantly from the trend of the remaining data." High outliers are retained unless historical information is identified showing that such floods are the largest in a period longer than the systematic record. Low outliers pose a problem. Due to the log transformation, one or more unusual low flow values can distort the entire fitted frequency curve. To avoid this problem Bulletin 17-B recommends a test of whether a low outlier is statistically significant (IACWD, 1981; Stedinger et al., 1993). Flood peaks identified as low outliers are omitted from the computation of $\bar{X}$, S, and G, and a conditional probability adjustment is applied to account for the omission. In practice the low outlier test rarely leads to the identification of any more than a few outlying observations.

Historical and Paleoflood Information

Bulletin 17-B recommends a historical flood moment adjustment to account for knowledge that a given number of events exceeded some discharge threshold *(Qh)* in a period of known duration prior to the systematic flood record. This adjustment, in effect, "fills in the ungaged portion of the historic period with an appropriate number of replicates of the below-Qh portion of the systematic record" (Kirby, 1981, p. c-47). Although the Bulletin 17-B historical adjustment was intended primarily for use with historical data, it can also be applied to paleoflood data.

Alternative Treatments of Outliers and Historical and Paleoflood Information

Both outliers and historical and paleoflood data can be handled in the framework of censored data. The influence of low outliers can be eliminated by censoring below a low threshold. Historical and paleoflood data can be treated as observations above a high threshold. Research subsequent to the publication of Bulletin 17-B has identified efficient statistical methods for treating censored data.

Censoring

Censoring below a threshold can be an effective way to account for the fact that commonly assumed parametric distributions (such as the log-Pearson type III distribution) may be inadequate to fit the "true" distribution at a given site. At the very low end, the fact that use of annual flood data (i.e., the largest peak flow in a year) can result in inclusion in the data set peak flows that are clearly not associated with floods. Floods associated with distinctly different hydrometeorological processes, such as hurricanes, convective storms, and rain-on-snow, can lead to complex distributional shapes. In some cases, it is clear that certain mechanisms do not produce large floods, and peak discharges associated with these mechanisms can be separated in the analysis. (In the case of the American River, peak discharges at late spring or early summer snowmelt events are excluded from the analysis.) It is also possible to use mixture models in the analysis or highly parameterized distributions (such as the Wake by) that have complex shapes. These techniques suffer from estimation problems caused by the large number of parameters. It may be preferable to resort instead to methods for censoring the data set below some threshold. Although censoring reduces the quantity of sample data, Monte Carlo results indicate that censoring can actually improve estimation efficiency (Wang, 1997). The practice of low censoring effectively allows the analyst to place the estimation focus where it belongs, on the upper tail of the distribution (NRC, 1988).

There are several approaches that can be used in estimation with data censored below a given threshold. Non-parametric approaches avoid the assumption of a specific distribution function. Parametric approaches are based on an assumed distribution either for the entire population or for exceedances of a specified threshold.

Non-parametric estimation methods, which typically use kernel-based estimators of the density or quantile function, can be applied to estimation of the upper tail of a distribution (Moon and Lall, 1994). Particularly appropriate is the use of kernel functions with bounded support, as only the data values falling within a finite range of an estimated quantile have a bearing on the resulting estimate. Breiman and Stone (1985) give a non-parametric method for tail modeling, which essentially involves fitting a quadratic model to the upper part of the data. Non-parametric methods in general, and especially kernel-based methods, are often criticized when they are used for extrapolation beyond the range of the data; but extrapolation beyond the data poses problems for all methods of estimation. The committee did not explore the application of non-parametric methods to the American River data because such an approach would diverge significantly from the Bulletin 17-B guidelines.

There are several estimation methods that can be applied to fit a chosen distribution, such as the log-Pearson type III, to values exceeding a given threshold. The method of maximum likelihood is efficient for many distributions (Leese, 1973; Stedinger and Cohn, 1986), but it often has convergence problems for the log-Pearson type III. Alternative methods include distributional truncation (see Durrans, 1996); partial probability weighted moments (Wang, 1990,1996; Kroll and Stedinger, 1996); probability plot regression (Kroll and Stedinger, 1996); LH moments (Wang, 1997); and the Expected Moments Algorithm (Cohn et al., 1997). The last method was developed explicitly for use with the log-Pearson type III distribution.

An approach sometimes applied to estimation with data censored at relatively high levels is to choose a distribution appropriate for the upper tail of the data. In some cases, there is theoretical support for the choice of distribution. For example, if a random variable has a generalized extreme value distribution, then the distribution of exceedances of a sufficiently high threshold is of the generalized Pareto type (Pickands, 1975; Smith, 1985). Smith (1987, 1989), Hosking and Wallis (1987), and Rosjberg et al. (1992) have applied this result to flood frequency analysis.

A fundamental question in censoring, for which there is little guidance, is the choice of the censoring threshold. Several investigators have considered this issue (Pickands, 1975; Hill, 1975; Hall, 1982; Hall and Welsh, 1985), with the general conclusion that the threshold level should depend on unknown population properties of the tail. Thus, these theoretical results are of limited usefulness for small samples. The use of LH moments (Wang, 1997) renders unnecessary the choice of a censoring threshold, but introduces in its place the need to choose the order of the LH moments used. Kernel-based non-parametric estimators also eliminate the need to explicitly choose a censoring threshold, but one is implicitly established based on the bandwidth estimate. Further, one can argue that the bandwidth estimate should depend on the quantile being estimated (Tomic et al., 1996), and this gives rise to a non-unique censoring threshold when multiple quantiles are of interest. The net effect of all this is that it is difficult to give any definitive guidance on the selection of a censoring threshold. An investigator must use professional judgment to a significant degree, though it is possible to obtain some guidance and insight through investigations of physical causes of flooding at a site, studies to assess the sensitivities of quantile estimates to the choice of censoring threshold, and comparisons with nearby hydrologically similar sites.

Historical and Paleoflood Data

As discussed in Chapter 2, historical and paleoflood information represents a censored sample because only the largest floods are recorded. The use and value of such information in flood frequency analyses has been explored in several studies (Leese, 1973; Condie and Lee, 1982; Hosking and Wallis, 1986; Hirsch and Stedinger, 1987; Salas et al., 1994; Cohn et al., 1997). Research has confirmed the value of historical and paleoflood information when properly employed (Jin and Stedinger 1989). In particular, Stedinger and Cohn (1986) and Cohn and Stedinger (1987) have considered a wide range of cases using the effective record length and average gain to describe the value of historical information. In general, the weighted moments estimator included in Bulletin 17-B is not particularly effective at utilizing historical information (Stedinger and Cohn, 1986; Lane, 1987).

Maximum Likelihood Estimation (MLE) procedures can be used to integrate systematic, historical, and paleoflood information (Stedinger et al., 1993). Ostenaa et al. (1996) use a Bayesian approach to extend standard MLE procedures. This extension better represents the uncertainty in the various sources of information. The previously mentioned Expected Moments Algorithm of Cohn et al. (1997) can also be used with historical and paleoflood information. The Expected Moments Algorithm is as efficient as standard maximum likelihood approaches and works well with the log-Pearson type III distribution.

EXPECTED PROBABILITY

Flood frequency analysis often focuses on estimation of the flood quantile x_{1-q}, the quantile that will be exceeded with probability q = 1/T. However, different statistical estimators of x_{1-q}have different properties (Stedinger, 1997; Beard, 1997). Most estimators provide an almost unbiased estimator *of* x_{1-q}:

$$E\left[\hat{x}_{1-q}\right] \approx x_{1-q}$$

However, interest may be in a value that in the future will be exceeded with probability q, so that

$$P\left\{X > X_{1-q}\right\} \approx q$$

when both X and X_{1-q} are viewed as random variables. If a very long record is available, these two criteria would lead to almost the same design value. With short records, they lead to different estimates because of the effect of the uncertainty in the estimated parameters.

Beard (1978) developed the expected probability correction to ensure that the second criterion is met. However, this correction generally increases the bias in estimated damages calculated for dwellings and economic activities located at fixed locations in a basin (Stedinger, 1997). This paradox arises because the estimated T-year flood is a (random) level computed by the hydrologist based on the fitted frequency distribution, whereas the expected damages are calculated for human and economic activities at fixed flood levels. Recently NRC (1995) concluded that, for the economic evaluation of projects, an expected probability adjustment should not be made because of the upward bias it introduces. Beard (1997, 1998) disagreed with that conclusion. Although a correction for expected probability may be appropriate in some decision-making frameworks, the committee decided not to apply such a correction to its recommended American River frequency distribution.

SUMMARY OF COMMITTEE APPROACH

In estimating the probability distribution of three-day rain flood discharges for the American River at Folsom, the committee decided to adopt an overall approach that was consistent with the philosophy of Bulletin 17-B guidelines. This includes the assumption of the log-Pearson type III distribution and estimation based on preserving log-space moments. Estimation was based on traditional method of moments and the Expected Moments Algorithm. The latter method was chosen over maximum likelihood and other methods because it (1) can be applied readily to the log-Pearson type III distribution; (2) has been shown to be relatively efficient; and (3) is consistent in principle with Bulletin 17-B. It was also decided to use EMA to explore various low censoring limits.

ANALYSIS OF AMERICAN RIVER DATA

The committee used the following data to explore estimation of the probability distribution of three-day rain floods on the American River at Folsom Dam (although not all of the data were used to estimate its recommended distribution):

- annual maximum average three-day rain flood discharges for the period 1905-1997, as reconstructed by the USACE;
- the estimated peak of the 1862 flood (265,000 cfs), assumed to be the largest instantaneous peak flood discharge since 1848;
- paleoflood information from the U.S. Bureau of Reclamation (i.e., non-exceedance of 300,000-400,000 cfs during the last 1,500-3,500 years).
- the skew map from Bulletin 17-B;
- estimated log skews for maximum annual three-day rain flood discharges from the Feather River at Oreville, Yuba River at Maryville, Mokelumne River, Stanislaus River, Tuolumne River, and Merced River; and
- two PMF estimates for the American River at Folsom Dam (three-day average flows of 401,000 cfs and 485,000 cfs).

Estimation of Average Three-Day Flows from Instantaneous Peak Flows

Use of the historical and paleoflood data required that a relationship be developed between instantaneous peak discharge and maximum three-day average discharge. This relationship was derived from a log-log linear regression with the observed three-day maximum as the dependent and the instantaneous peaks as the independent variables.

The instantaneous peak flows corresponding to Fair Oaks (below Folsom) were obtained from the USACE, Sacramento District. For the period water years (WY) 1905-1955 these are, with certain exceptions, identical to USGS annual peaks at Fair Oaks. The exceptions occur in years for which the USGS peak of record is either unknown (WY 1918), a snowmelt, as distinct from a rainfall event (1910, 1912, 1913, 1929 and 1933); or when the maximum three-day discharge is associated with an event other than that which produced the instantaneous maximum (1908, 1914, 1915, 1916, 1937, 1941, 1946). In the period since 1956, estimates of unregulated instantaneous maxima are generally not available, although the USACE and others have estimated peak flows for 1956-86, and for 1997. It must be assumed that the magnitudes of reconstructed peak flows are known with less precision than are gaged flows.

A log-log ordinary least squares (OLS) regression was first estimated using the 38 measured, rainfall-generated instantaneous peaks (Q_p) and corresponding mean three-day discharges (Q_3) from the 1905-1955 (unregulated) period. This equation, expressed in real (cfs) terms, is:

$$Q_3 = 1.031 * Q_p^{0.941} \quad R^2 = 0.937; \text{ standard error} = 0.086 \text{ in } \log(10) \text{ units}$$

Although the log-space fit appears satisfactory, the use of this equation to predict volumes for events significantly larger than those used in estimating the equation would involve considerable extrapolation, with attending increases in confidence bounds, since the largest peak observed in this period was 180,000 cfs (WY 1951). Several larger events occurred in the latter period (1956-1997), and a second equation was estimated that included these (reconstructed) data. This equation, based on 68 observations (low flows in 1964 and 1977 were excluded) is:

$$Q_3 = 0.922 * Q_p^{0.954} \quad R^2 = 0.952; \text{ standard error} = 0.086 \text{ in } \log(10) \text{ units}$$

The second model differs very little from the model based on measured data only, suggesting that USACE procedures are not seriously biased (Figure 3.1). Since it appeared reasonable to assume an adequate degree of homogeneity between earlier and later records, a third equation was fitted to the upper 50% of the data in order to minimize the influence of low observations, and to further reduce the error bounds on predicted volumes. This final equation, based on 35 observations (half measured, half reconstructed) was estimated as: (Figure 3.2)

$$Q_3 = 0.394 * Q_p^{1.027} \quad R^2 = 0.885; \text{ standard error} = 0.088 \text{ in } \log(10) \text{ units}$$

This equation was used to predict both the magnitude and the 95% confidence bounds of the three-day flow associated with the 1862 floods and the paleoflood threshold, as summarized in Table 3.1.

Generalized Skew Coefficient

A critical parameter in the development of a frequency curve in the Bulletin 17-B framework is the generalized skew coefficient. While on average the logarithms of annual peaks at U.S. gages have a skew near zero, floods in particular regions are thought to have skewness coefficients that can be greater or less than that value. Unfortunately, sample estimates of the coefficient of skewness are very unstable, even with long records. For example, even with a 90-year record, such as that available for the American River, the standard error of estimate of the sample skewness coefficient is 0.25.

To help get around this large error and to stabilize estimates of flood exceedance probabilities and quantiles, Bulletin 17-B provides a skew map that can be used to compute a generalized skew. That map is based on 2,972 stations across the United States that had at least 25 years of record as of WY 1973. Efforts were employed to reject low outliers, but no effort was made to use historical information.

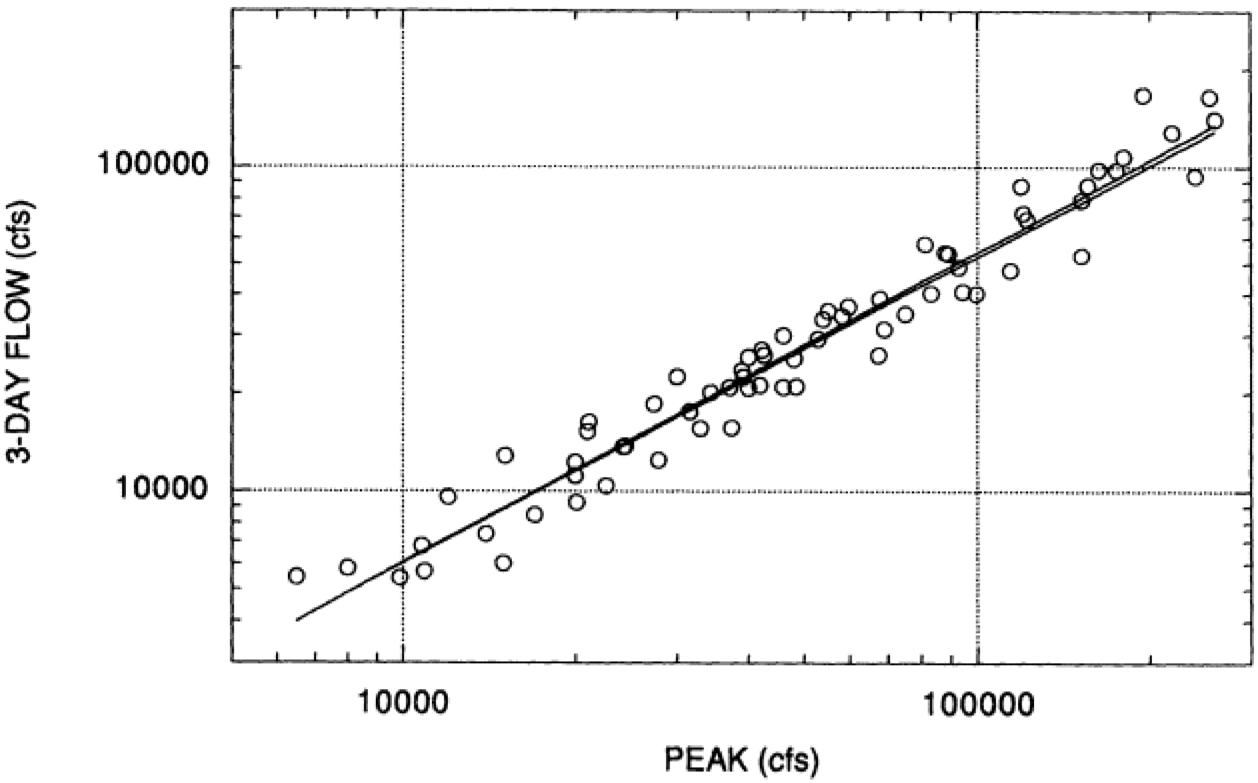


Figure 3.1
Log-log relationships of three-day flow on peak flow, American River. Both regressions are based on data from the unregulated period of record (1905-1955); the regression line with the larger slope is also based on flow estimates for the period 1956-1997.

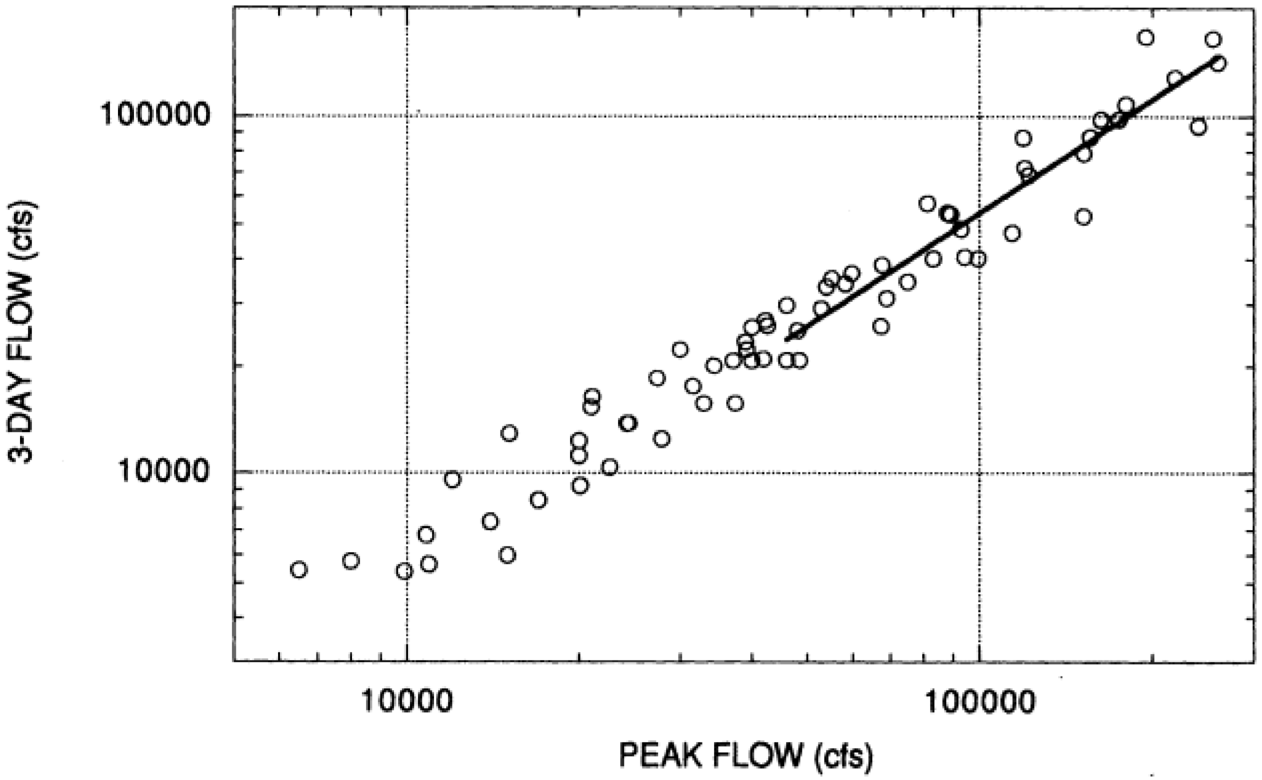


Figure 3.2
Log-log relationships of three-day flow on peak flow, American River, based on the largest 50% of the peak flow data (regulated and unregulated).

The American River basin is in an area where map skew values change rapidly with location; hence the map skews are likely to be less reliable. For the location of the American River gage at Fair Oaks, the map value is about 0.0.

Given the age of the Bulletin 17-B skew map and a concern with three-day volumes rather than annual peaks, the committee chose to estimate an alternative regional ("map") skew. This regional skew estimate is based on log skews computed from maximum annual three-day rain flood data from seven large west slope Sierra rivers (USACE, 1998). For each of these discharge series there are about 25 more years of data than were used to construct the Bulletin 17-B skew map. The estimated log skews are given in Table 3.2. (Note that the skew for the Merced was adjusted to account for a low outlier. Bulletin 17-B procedures were used to detect and correct for the low outlier.) Averaging these values yields a regional skewness coefficient -0.1 for three-day flows.

Estimating the standard error of our alternative regional skew estimate is complicated by the highly cross-correlated the flood data from the seven rivers. (The average pairwise correlation between the flood series is 0.89.) A Monte Carlo experiment was conducted to determine the sampling error of the average skewness coefficient for seven stations with n = 100 years of record when the correlation among concurrent flows was 0.89. While a single station had a standard error of 0.25 (variance 0.063), the standard error of the sample average of seven stations decreased by only 5%, to 0.21. (This result is consistent with a formula provided in Stedinger [1983].) We are in the unfortunate position of being unable to resolve with any precision the value of the sample skewness coefficient for the American River. More stations could be included in the analysis, but there are no other large basins in the northern and central Sierra Nevada that are like the American River.

The two estimates of regional skew, 0.0 and -0.1, bracket the at-site skew of -0.06. The latter regional skew was derived specifically for three-day maxima and for large basins in the Sierra Nevada, like the American River, it would appear to be the more relevant of the two. Moreover, the former, based on the Bulletin 17-B skew map, is also limited in its precision by the high correlation among floods in the same year, and is based on shorter records for annual maxima.

TABLE 3.1 Estimated Three-Day Discharge Magnitudes and 95% Confidence Limits

	1862 Event	Paleo Lower	Paleo Upper
Est. peak (cfs)	265,000	300,000	400,000
Est. three-Day Q (cfs mean)	147,000	167,000	224,000
Ratio Q_3/Q_p	0.55	0.56	0.56
Lower 95% conf. bound	95,000	108,000	143,000
Ratio to Q_p	0.36	0.36	0.36
Upper 95% conf. bound	226,000	258,000	352,000
Ratio to Q_p	0.85	0.86	0.88

TABLE 3.2 Sample Log(10) Skews for West Slope Central Sierra Basins

Basin	Area	Period	1-Day Q	3-Day Q	7-Day Q
Feather	3,624	1902-1997	-0.258	-0.230	-0.252
Yuba	1,339	1904-1997	-0.389	-0.332	-0.412
American	1,888	1905-1997	-0.187	-0.062	-0.159
Mokelumne	627	1905-1997	0.067	0.067	0.008
Stanislaus	904	1916-1997	-0.056	0.000	0.016
Toulumne	1,533	1897-1997	-0.190	-0.132	-0.180
Merced[a]	1,037	1902-1997	-0.086	0.014	0.015
Mean			-0.157	-0.096	-0.138
Std. Dev.			0.148	0.144	0.163

Calculations by HEC-FFA v3.0 (1992)[a] low outlier (1977) removed according to Bulletin 17-B procedures. SOURCE: USACE, Sacramento District.

If either 0.0 or -0.1 is combined in a weighted average with the sample skew of -0.06 using the Bulletin 17-B weights, and the result is rounded to the nearest tenth, the result is -0.1. Unfortunately, the Bulletin 17-B weights are not optimal in this case because an unbiased estimate of the precision of the regional skewness estimators has not been employed (Tasker and Stedinger, 1986). That consideration would result in more weight on the regional estimate of -0.1. In addition, the error in the regional estimates is almost surely highly correlated with the error in the at-site estimator, and this would further change the optimal weights. The committee recommends that the regional skew value of -0.1 be adopted as the weighted skew coefficient for the logarithms of the three-day rain flood discharges for the American River.

The choice of the skew coefficient can be considered a critical decision and Bulletin 17-B encourages hydrologists to perform site-specific studies to improve estimates of the skewness coefficient. The Bulletin 17-B skew map was developed almost 25 years ago and has a very steep gradient in the region of the Fair Oaks gage making its precision questionable in this area. USACE (1998) incorrectly read the Bulletin 17-B skew map as +0.1 by using the centroid of the basin rather than the location of the gage, which yields 0.0 for a weighted skewness coefficient. When a map skew of 0.0 is combined with the station skew of -0.067 and rounded a value of -0.10 is obtained. Table 3.2 provides estimates of skewness coefficients for the American River and six other rivers for three durations: 1-day, 3-day, and 7-day using the available records up through 1997. The skews of the American River for those three durations equal -0.187, -0.06, and -0.159, which average to -0.136. If one looks regionally over the seven sites in the table, then the computed skewness coefficients for 1-day, 3-day, and 7-day are -0.157, -0.096, and -0.138, which average to -0.130. After rounding to two-decimal digits, skew values for all three durations support choice of -0.10 as the skewness coefficient for three-day volumes on the American River.

Alternative Frequency Estimates for the American River Data

The committee chose five cases (with subcases) to explore alternate estimates of the probability distribution of three-day average rain flood discharges on the American River at Fair Oaks. The first case duplicates the USACE analysis (USACE, 1998). The remaining four cases vary with respect to the skew estimate and the use of historical and paleoflood data. All cases are consistent with the spirit of Bulletin 17-B.

Case 1: Systematic Record with Zero Skew (Sys. w/Zero Skew)

This is a duplication of the USACE approach (without the expected probability correction), using the conventional method of moments, as specified in Bulletin 17-B.

Case 2: Systematic Record with Weighted Skew (Sys. w/Skew -0.1)

This case is based on the committee's estimate of weighted skew equal to -0.1, using the conventional method of moments, as specified in Bulletin 17-B.

Case 3: Systematic Record and Historical Data with Weighted Skew (Sys. & Hist. w/ Skew -0.1)

Historical information is added in this case, through the use of the expected moments algorithm (EMA). Three subcases are run.

Case 3a: Three-day discharge for 1862 flood between the 95% confidence limits of 95,000 cfs and 226,000 cfs; all other floods in period 1848-1904 between 0 and 95,000 cfs.

Case 3b: Three-day discharge for 1862 flood between 95,000 cfs and 226,000 cfs; all other floods in period 1848-1904 between 0 and 226,000 cfs.

Case 3c: Three-day discharge for 1862 flood equal to 147,000 cfs; all other floods in period 1848-1904 between 0 and 147,000 cfs.

Note that Cases 3a and 3b are intended to bracket the results of using the historical data with a fixed skew, while 3c gives a best estimate.

Case 4: Systematic Record and Historical Data with Skew Estimated by EMA (Sys. & Hist. w/EMA Skew)

The EMA is applied to the systematic record and the historical information without specifying the skew; hence the skew is estimated by the EMA. This case has three subcases.

Case 4a: Three-day discharge for 1862 flood between 95,000 cfs and 226,000 cfs; all other events in period 1848-1904 between 0 and 95,000 cfs.

Case 4b: Three-day discharge for 1862 flood between 95,000 cfs and 226,000 cfs; all other floods in period 1848-1904 between 0 and 226,000 cfs.

Case 4c: Three-day discharge for 1862 flood equal to 147,000 cfs; all other floods in period 1848-1904 between 0 and 147,000 cfs.

Note that Cases 4a and 4b are intended to bracket the results of using the historical data with a skew estimated by EMA, while Case 4c gives a best estimate.

Case 5: Systematic Record and Historical and Paleoflood Information with Skew Estimated by EMA (Sys. & Hist. & Paleo. w/EMA Skew)

The EMA is applied to the systematic record and the historical and paleoflood information without specifying the skew. This case has three subcases.

Case 5a: Three-day discharge for 1862 flood between 95,000 cfs and 226,000 cfs; all other floods in period 1848-1904 between 0 and 95,000 cfs. All floods in the 3,350 year period from approximately 1,500 B.C. through 1847 A.D. are less than 108,000 cfs (the lower 95% confidence limit of the lower paleoflood non-exceedance threshold).

Case 5b: Three-day discharge for 1862 flood between 95,000 cfs and 226,000 cfs; all other floods in period 1848-1904 between 0 and 226,000 cfs. All floods in last 1,350 year period (prior to 1848) less than 352,000 cfs (the upper 95% confidence limit of the upper paleoflood non-exceedance threshold).

Case 5c: Three-day discharge for 1862 flood equal to 147,000 cfs; all other floods in period 1848-1904 between 0 and 147,000 cfs. All floods in last 2,350 year period (prior to 1848) less than 197,000 cfs (the median estimate of the three-day flow associated with the average of the upper and lower paleoflood non-exceedance limits).

Note that Cases 5a and 5b are intended to bracket the results of using the historical and paleoflood data with a skew estimated by EMA, while Case 5c gives a best estimate.

Results

Table 3.3 displays the results of the flood frequency analysis; Cases 1, 3c, and 5c are plotted in Figure 3.3. Estimates of Q_{100}, the discharge with annual exceedance probability of 1 in 100, range from about 87,000 cfs for the case with the lowest paleoflood exceedance threshold (Case 5a), to 205,000 cfs for the case duplicating the 1998 USACE estimate (Case 1). Excluding case 1, which the committee believes is based on too high a log-skew, and the cases using paleoflood data, the range of estimates of Q_{100} is much smaller, from 169,000 cfs to 191,000 cfs. Note that our best estimated distribution using the paleoflood information (Case 5c) falls well below the data (Figure 3.3). The recommended distribution of three-day flows for the American River at Fair Oaks is derived from Case 3c, which is based on the use of a weighted log skew of -0.1 and the median estimator of the three-day flow associated with the 1862 flood. The estimate of Q_{100} for this case is 185,000 cfs. There is little difference between case 3c and 4c, where for case 4c the skew was estimated with the systematic and historical data.

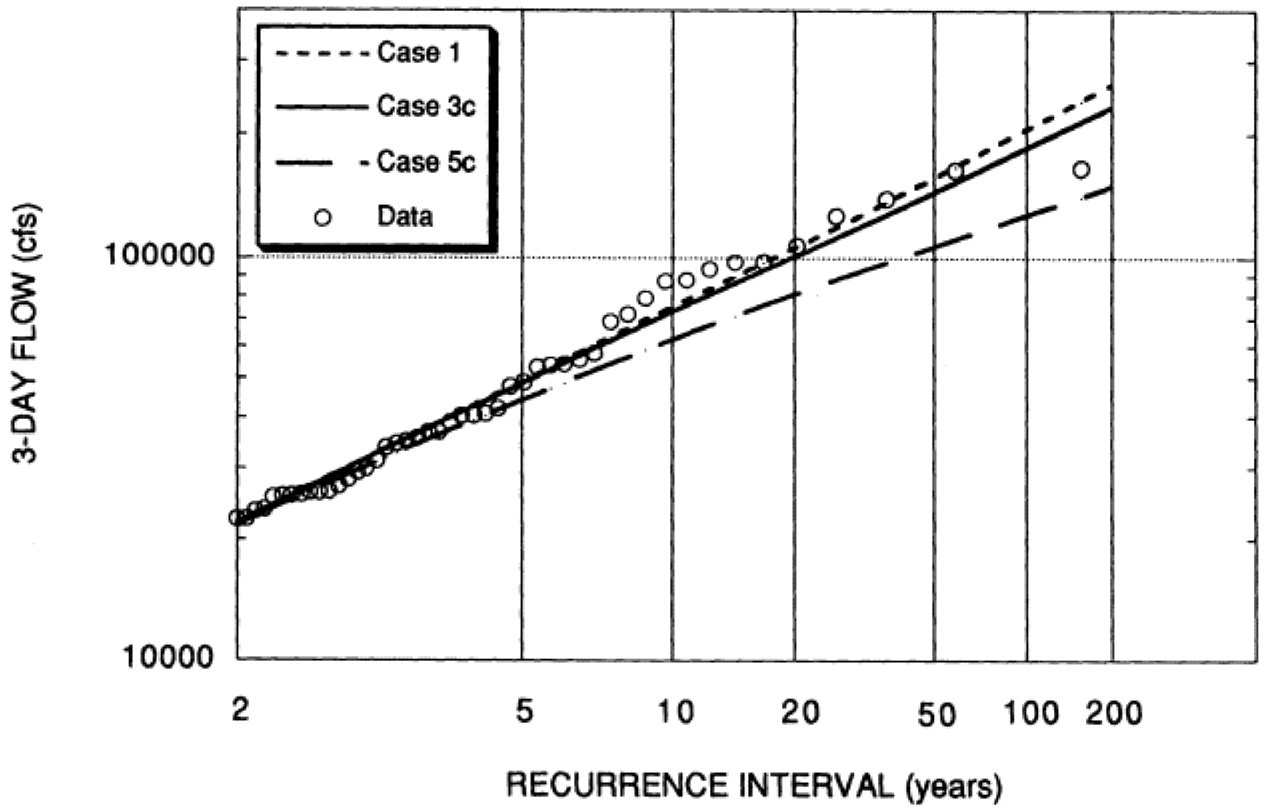


Figure 3.3
Estimated flood frequency distributions for annual maximum unregulated three-day rain flood flows, American River at Fair Oaks, Cases 1, 3c, and 5c. Case 1 is the 1998 USACE distribution, Case 3c is the distribution recommended by the committee, and Case 5c incorporates the USBR paleoflood data. Only the upper half of the distributions is shown. Plotting position is from Cunnane (1978).

TABLE 3.3 Final Results of Flood Frequency Analysis for Case Studies

	Sys. w/ Zero Skew	Sys. w/ Skew -0.1	Sys. & Hist. w/ Skew -0.1			Sys. & Hist. w/ EMA Skew			Sys. & Hist. & Paleo w/ EMA Skew		
Case	1	2	3a	3b	3c	4a	4b	4c	5a	5b	5c
Case description											
Ns[a]	93	93	93	93	93	93	93	93	93	93	93
Nh[b]	0	0	56	56	56	56	56	56	56	56	56
UB on H[c]	0	0	95,000	226,000	147,000	95,000	226,000	147,000	95,000	226,000	147,000
Q1862 LB[d]	0	0	95.000	95,000	147,000	95,000	95,000	147,000	95,000	95,000	147,000
Q1862 UB[e]	0	0	226,000	226,000	147,000	226,000	226,000	147,000	226,000	226,000	147,000
Np[f]	0	0	0	0	0	0	0	0	3,350	1,350	2,350
UB on P[g]	0	0	0	0	0	0	0	0	108,000	352,000	197,000
Estimated parameter values											
Ln-mean	9.9830		9.9438	9.9923	9.9769	9.9447	9.9923	9.9774	9.7883	9.9775	9.9243
Ln-StDev	0.9656	0.9656	0.9349	0.9667	0.9552	0.9359	0.9666	0.9558	0.8105	0.9451	0.8967
Skew	0.0000	-0.1000	-0.1000	-0.1000	-0.1000	-0.1254	-0.0974	-0.1141	-0.4895	-0.221	-0.379
Log10-mean	4.3355	4.3355	4.3186	4.3396	4.3329	4.3189	4.3396	4.3331	4.2510	4.3332	4.3101
Log10-StDev	0.4193	0.4193	0.4060	0.4198	0.4149	0.4065	0.4198	0.4151	0.3520	0.4104	0.3894

		Sys. w/ Zero Skew	Sys w/ Skew -0.1	Sys. & Hist. w/ Skew -0.1			Sys. & Hist. w/ EMA Skew			Sys. & Hist. & Paleo. w/ EMA Skew		
Case		1	2	3a	3b	3c	4a	4b	4c	5a	5b	5c
Flood Quantile												
0.9	10:1	74,500	74,000	68,500	74,500	72,500	68,000	74,500	72,500	48,000	70,600	61,800
0.95	20:1	106,000	103,000	94,500	104,000	101,000	94,000	104,500	100,500	60,000	92,800	80,500
0.98	50:1	157,500	149,500	135,000	151,000	145,500	133,500	151,000	144,500	7,550	133,900	106,800
0.99	100:1	204,500	190,500	171,000	193,000	185,000	168,500	193,000	183,500	87,500	166,300	127,800
0.995	200:1	260,500	238,000	212.000	241,000	230,500	208,000	241,500	228,000	99,000	202,000	149,500
0.998	500:1	348,500	310,000	274,000	314,000	299,500	267,500	315,000	295,500	114,500	254,200	179,400
0.999	1000:1	428,000	373,000	328,000	378,000	360,000	318,500	379,000	353,500	126,000	297,700	202,900
0.9999	10000:1	785,500	640,000	553,000	649,000	613,500	528,500	652,000	598,000	163,000	467,800	284,800
PMF Information												
P[Q>401000]		1.35E-03	7.5E-04	4.3E-04	7.9E-04	6.5E-04	3.7E-04	8.0E-04	6.0E-04	2.6E-15	2.3E-04	4.7E-06
Return Period		8.0E+02	1.3E+03	2.3E+03	1.3E+03	1.5E+03	2.7E+03	1.2E+03	1.7E+03	3.8E+14	4.3E+03	2.1E+05
P[Q>4850001		6.4E-04	3.4E-04	1.9E-04	3.7E-04	2.9E-04	1.5E-04	3.7E-04	2.6E-04	7.1E-38	8.1E-05	5.6E-07
Return Period		1.6E+03	2.9E+03	5.4E+03	2.7E+03	3.4E+03	6.6E+03	2.7E+03	3.8E+03	1.4E+37	1.2E+04	1.8E+06

[a] Ns is the length of the systematic record.

[b] Nh is the length of the historical record.

[c] UB on H means upper bound for the historical period.

[d] Q 1862 LB means the lower bound on the estimate of the 1862 flood discharge.

[e] Q 1862 UB means the upper bound on the estimate of the 1862 flood discharge

[f] Np means length of paleoflood record.

[g] UB on P means upper bound on the flood discharges in the paleoflood record.

A guideline for the analysis was that the exceedance probability for the PMF values should be less than 0.001. This expectation is met for Cases 2, 3a,b,c and 4a,b,c for both PMF values, though not by much. In particular, among those 7 alternatives, the exceedance probability of the lower PMF of 401,000 cfs was always between 1-in-1,300 and 1-in-2,700. For Case 1 with a skewness coefficient of 0, the exceedance probability of the lower PMF was only 1-in-800, which seems too low; for the higher PMF value of 485,000 cfs, the probability decreased to 1-in-1600, and for Cases 2, 3c and 4c was about 1-in-3,000.

As is the case here, flood frequency analysis is generally faced with significant data limitations and as a result estimated flood quantiles are of limited accuracy. To estimate the 100-year or 200-year flood with the 93 years of systematic data available for the American River is to stretch the limits of the data set. Use of the historical information back to the middle of the 19th century helps, but the precision of the 100- and 200-year events is still far less than desirable.

Two sources of errors should be considered. The first is errors that result from use of a probability distribution that fails to describe the character of the true distribution of floods. Here the log-Pearson type III distribution has been employed as recommended in Bulletin 17-B. As suggested later in this report, it seems that the log-Pearson type III distribution has trouble describing the distribution from which the flood record is drawn without overestimating the magnitude of quantiles with return periods greater than 200 years. The committee does not try to quantify this model error. A second source of error is the sampling error that results from using limited-size data sets to estimate the parameters of the log-Pearson type III distribution. The magnitudes of the floods observed in any year vary widely, and if a different set of floods had occurred during the period of record, different parameters would have been computed. This parameter estimation error or sampling error can be quantified in several ways.

A simple measure of the precision of a quantile estimator $\hat{Q}_p$ of a quantile Q_p is the estimator's variance $Var[\hat{Q}_p]$, or its standard error, *SE,* where

$$SE^2 = Var[\hat{Q}_p].$$

The variance and the standard error are descriptions of the average distance between the estimator and the quantile Q_p from one possible sample to another.

Confidence intervals are another description of precision. For the committee's analysis of the American River, 90% confidence intervals were constructed for different quantile estimators. In log space, the endpoints of each confidence log interval equal the quantile estimator plus or minus 1.645 times the estimated standard error of the estimator. The real-space endpoints equal the exponential log space endpoints. In repeated sampling, intervals constructed in this way should contain the true quantiles approximately 90 percent of the time. This asymptotic normal formula for quantile estimators is widely used (Kite, 1988; Stedinger et al., 1993, section 18.4.1). Monte Carlo simulations were conducted to estimate the standard errors of the calculated formulas for Cases 2-4, and the results were checked against those calculated with maximum likelihood estimators.

The Monte Carlo results, as well as formulas provided in Stedinger (1983) and Chowdhury and Stedinger (1991), provide the standard errors of estimators as a function of the parameter values, which parameters are estimated and the length of the data set. The confidence intervals reported below for Cases 1 and 2 assume that the skewness coefficient is known, and only the location and scale parameters of the log-Pearson type III distribution were estimated. Such a computation is recommended by Bulletin 17-B. Unfortunately, these confidence intervals are too narrow, because they ignore the error in the estimated coefficient of skewness (Chowdhury and Stedinger, 1991). Case 3 also assumes that the coefficient of skewness is known. In estimating confidence intervals for Case 3c, our recommended case, the committee chose to use the confidence intervals obtained for Case 4c, which employed the at-site skewness estimator.

The confidence intervals for Cases 1, 2 and 4c are in Table 3.4. The confidence intervals for Case 4c provide a good description of the uncertainty for Cases 3 and 4 because both are based on an estimated skewness coefficient and use of historical information. This is particularly important for the more extreme quantiles. Confidence intervals for Cases 1 and 2 should be wider than those computed for Case 4, because the frequency analyses in Cases 1 and 2 did not use historical information.

For the most part, the committee's recommendations do not deviate significantly from the USACE results. There is really relatively little difference between the estimated quantiles for Case 1 as proposed by the USACE and Case 3c recommended by the committee. The difference is that Case 3c uses a refined and slightly different site-specific regional skewness coefficient with the available historical flood information for the American River. When the differences between the quantiles are viewed with the perspective provided by the 90 percent confidence intervals, they are quite close at the 200-year and even the 500-year return period event. Beyond, the frequency curves begin to diverge.

The important message provided by confidence intervals for Case 4c is that the uncertainty in the estimated quantiles is very large (see Figure 3.3). The confidence intervals for Cases 1 and 2, computed assuming the skewness coefficients are known (and ignoring historical information), are not much better. Based on the likely variability in quantile estimators from sample to sample—even with historical information back until the middle of the 19th century, a 90 percent confidence interval for the true 100-year flood for Case 4c is from 131,000 cfs to 257,000 cfs. This is also a good description of the uncertainty in the 100-year flood estimate for the recommended Case 3c. Given the available record for the American River and the attempts to develop an improved regional estimate of the skewness coefficient, this is as well as the 100-year flood can be estimated. For the most part, this sampling uncertainty is substantially larger than the differences in quantile estimates obtained by the different assumptions adopted in Cases 1-4. Thus, the major source of error in the determination of flood quantiles for the American River and flood risk for Sacramento appears to be the hydrologic record limited to 150 years of experience, coupled with the variability of the magnitudes of floods from year to year.

TABLE 3.4 Confidence Intervals for Cases 1,2, and 4c[a]

Return Period	Low End Point	Quantile Estimator	Upper End Point
90% Confidence Intervals for Case 1[b]			
10	60,000	75,000	93,000
20	82,000	106,000	136,000
50	118,000	157,000	210,000
100	149,000	205,000	281,000
200	185,000	260,000	367,000
500	240,000	349,000	507,000
1,000	288,000	428,000	636,000
90% Confidence Intervals for Case 2[b]			
10	59,000	74,000	92,000
20	81,000	103,000	132,000
50	113,000	149,000	197,000
100	140,000	191,000	258,000
200	171,000	238,000	330,000
500	217,000	310,000	443,000
1,000	256,000	373,000	543,000
90% Confidence Intervals for Case 4c[c]			
10	60,000	72,000	88,000
20	81,000	100,000	126,000
50	109,000	145,000	192,000
100	131,000	184,000	257,000
200	154,000	228,000	338,000
500	184,000	295,000	475,000
1,000	206,000	354,000	607,000

[a] Intervals for case 4c assumed to apply to Case 3c

[b] Computed assuming specified skewness coefficient is correct.

[c] Describes the uncertainty in Case 3c recommended by the committee.

Low Censoring

Application of the Bulletin 17-B low outlier test to the American River average three-day rain flood discharge series does not indicate any low outliers, although the 1977 data point is noticeably lower than the rest of the data. Nonetheless, the committee decided to use the EMA to evaluate the effect of censoring the data. The conditions of Case 3c (our preferred case) were used; the censoring threshold was varied 5,000 cfs to 35,000 cfs, in increments of 5,000 cfs. (The median three-day flow is 22,340 cfs; 35,000 cfs has an estimated exceedance probability of about 0.3.) Figure 3.4 gives the results. As can be seen, censoring up to 35,000 cfs does not have a significant effect on the estimated distribution.

Beyond Bulletin 17-B

The log-Pearson type III distribution was selected as a national standard because it provided a reasonably good fit to empirical flood distributions from a wide range of U.S. watersheds. There is no reason, however, to believe for any watershed that the log-Pearson type III or any relatively simple distribution will fit the distribution of annual floods over the entire possible range of flows. For this reason, various researchers have suggested the use of mixture models, highly parameterized distributions, non-parametric estimation methods, and estimation methods based on censoring below a high threshold. These methods have not been commonly adopted in practice, in part because their use sometimes results in relatively high estimation variances.

While our preferred estimate of the frequency distribution of three-day flows on the American River is consistent with the systematic and historical data, there is no assurance that it can be extrapolated for very high recurrence intervals. Consider, for example, the two recent PMF estimates. Based on our preferred distribution, the estimated exceedance probabilities for these PMF estimates are about 3×10^{-4} and 6×10^{-4}. While these are lower than our proposed absolute minimum standard of 1×10^{-3}, they are not much lower. The paleoflood information also calls into question the wisdom of extrapolating our preferred distribution for very large recurrence intervals. Note, however, it was decided not to use the USBR paleoflood information to extrapolate the frequency distribution of three-day rain flood flows because of concerns about the validity of the assumption that floods are independent and identically distributed during the period represented by this information.

To explore the extrapolation issue, the committee conducted some simple analyses using the precipitation data that it assembled for the American River basin. The object of these analyses was to gain insight into the possible shape of the upper tail of the American River flood frequency distribution, not to provide an alternative distribution estimate.

Based on the weights given in Table 2.1, the committee developed a partial duration series of three-day basin average precipitation for the period 1906-1998 using daily data from the Represa, Auburn, Placerville, Nevada City, Lake Spaulding, and Tahoe City gages (refer to Chapter 2 for a discussion of these data). A threshold of 6 inches was used, yielding an average of about one event every two years. To these data we fitted a shifted exponential distribution by the method of moments applied to the threshold exceedance data. Figure 3.5 shows the empirical and fitted distribution of the precipitation data. The probabilities for the precipitation data have been adjusted to account for the data from a partial duration series (Langbein, 1948). Judging from the plot, the fit is adequate. Also shown in Figure 3.5 is the empirical three-day discharge distribution and the committee's preferred estimated flood frequency distribution.

The most notable feature of Figure 3.5 is the crossing of the estimated

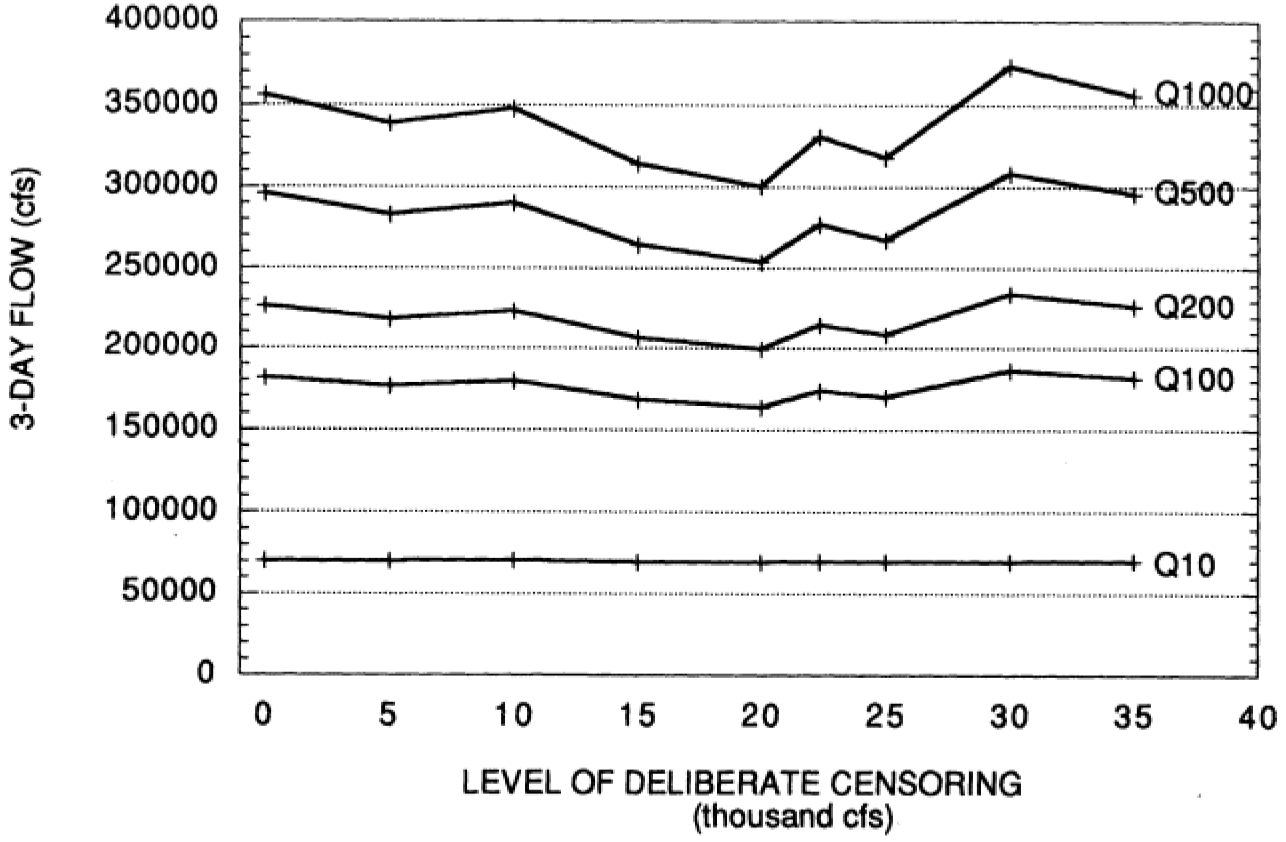


Figure 3.4
Impact of deliberate censoring on EMA flood quantile estimates (Case 3c).

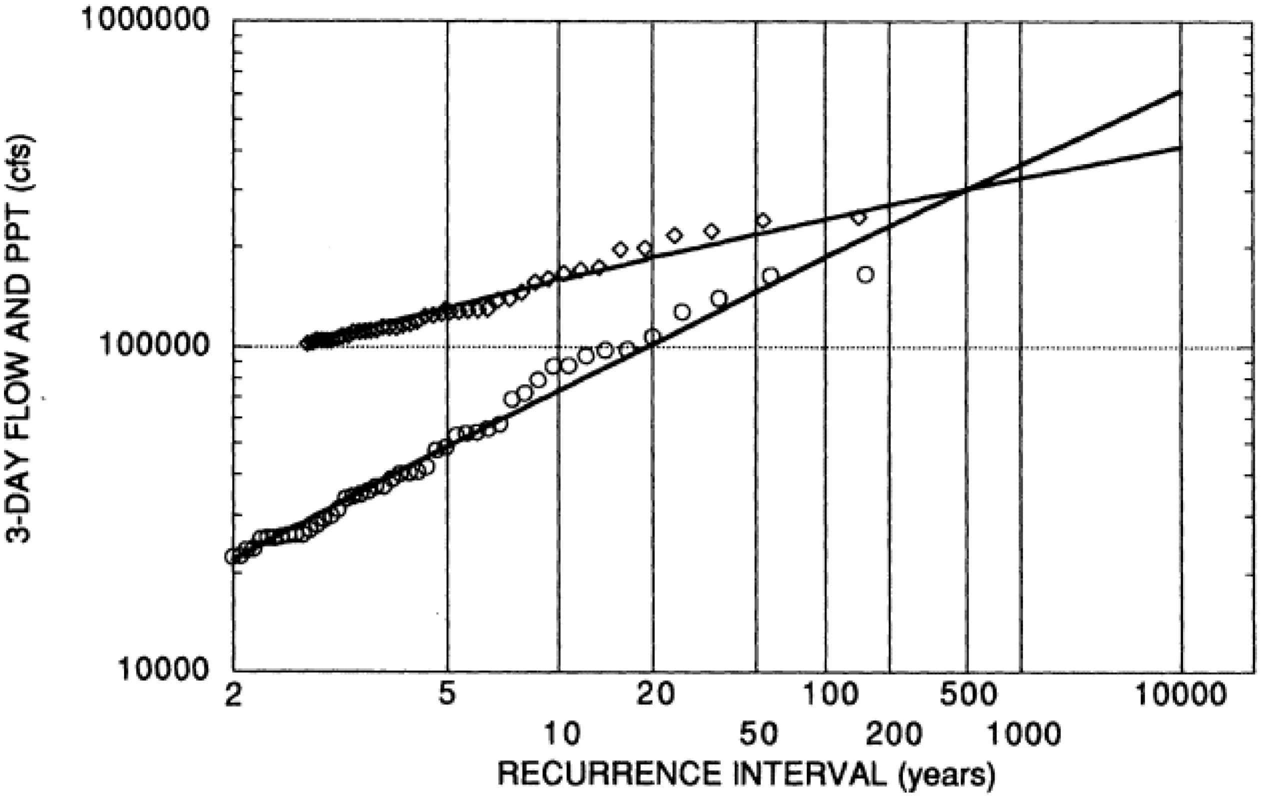


Figure 3.5
Estimated frequency distribution for average three-day rain flood flows and basin average precipitation. Only the upper half of the distributions is shown. Plotting position is from Cunnane (1978).

precipitation and discharge distributions. This crossing of distribution curves provides compelling evidence that the log-Pearson type III distribution that in the committee's opinion "best" fits the systematic and historical data does not fit the distribution of significantly larger flows. What is most important is the large difference in the slopes (standard deviations) of the two distributions. This difference appears to be too great to be due to errors in our basin average precipitation series. It is also difficult to believe that the "correct" distribution of basin average precipitation would abruptly bend upward for larger than observed precipitation amounts. It seems more likely that the distribution of three-day flood discharge bends downward for larger than observed discharges.

Based on the precipitation data and a simple rainfall-runoff model it is possible to suggest how the discharge distribution might deviate from the log-Pearson type III distribution for large discharges. In developing a simple rainfall runoff model it would be desirable to have for each event in the three-day partial duration precipitation series a corresponding three-day average flow. Such flows are readily available for the period prior to the closure of Folsom Dam in 1955. For flows after 1955, corrections for upstream storage in Folsom and subsequent reservoirs were generally made only for the annual flood. Use of those flows might result in a biased rainfall runoff model since they are not random. This left the committee with data from 22 out of the total of 42 partial duration precipitation events. Using these 22 pairs of precipitation and flow volumes, the committee estimated a linear regression for predicting discharge. The regression equation and associated statistics are given by:

$$Q = 1.18\,P - 6.45$$

where Q is the three-day flow volume (inches) and P is the three-day basin average precipitation (inches). (For precipitation amounts exceeding 36 inches, runoff depth predicted by this relationship exceeds the precipitation depth. Based on the estimated exponential model, the probability of a three-day precipitation amount exceeding 36 inches is less than 5×10^{-7}.)

The coefficient of determination for the regression is 0.65 and the standard error of regression or standard derivation of residuals is 1.3 inches. Figure 3.6 shows the data and the estimated regression. There is very large scatter in the plot of three-day runoff versus three-day precipitation. This is due to the critical role of antecedent conditions (soil moisture and snowpack) in determining runoff-volumes.

Based on the distribution fitted to the partial duration precipitation series, the estimated regression, and an assumed distribution of regression residuals, it is possible to estimate the probability distribution of the upper tail of the three-day flood discharges. The committee assumed that three-day precipitation amounts larger than 6 inches were exponentially distributed (as illustrated in Figure 3.5). Using the regression equation with normally distributed errors as a simple statistical rainfall runoff model, the committee computed by numerical integration the probability distribution of three-day runoff. The resulting distribution was corrected for the simulated discharges that constituted a partial duration flood series (Langbein, 1948).

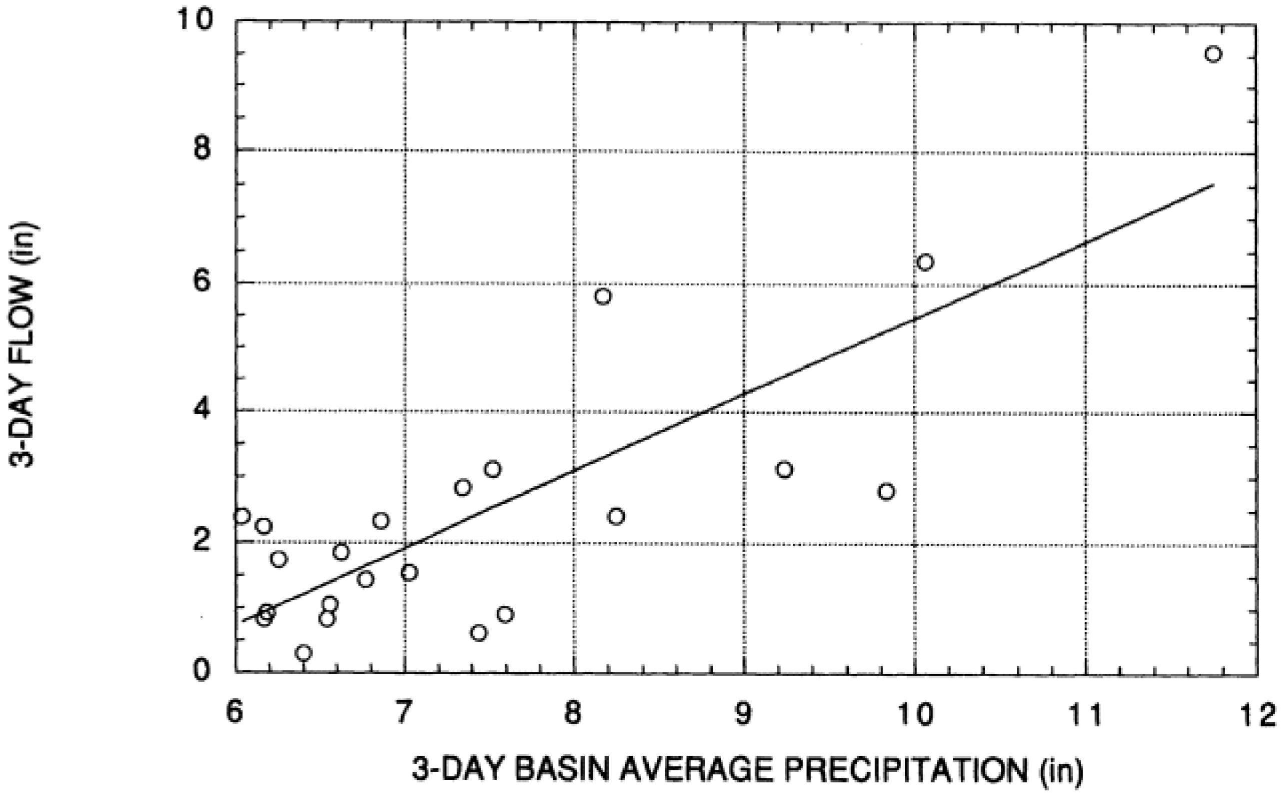


Figure 3.6
Regression model of three-day rain flood flows and basin average precipitation.

Figure 3.7 shows the distribution based on the rainfall-runoff modeling, along with the empirical and fitted distributions of precipitation and discharge. The estimated quantiles fit the discharge data very well. They cross the estimated log-Pearson type III distribution at about the 100-year discharge and asymptotically approach the precipitation distribution. One inch of discharge as indicated in this figure is equivalent to an average three-day streamflow of 16,922 cfs.

Also shown in Figure 3.7 is the distribution resulting from Case 5c based on the paleoflood information. Case 5c is based on the median estimate of the three-day flow associated with the average of the upper and lower non-exceedance limits. Hence the "best" estimated distribution based on the paleoflood information is well below the distribution based on rainfall-runoff modeling.

The committee does not claimed that its rainfall-runoff estimate of the three-day flood distribution is correct, although it believes that beyond the 1-in-500-year discharge, it better represents the "true" distribution than does the committee's "best" log-Pearson type III distribution. The analysis can and should be improved as follows:

- Unregulated three-day flows should be estimated for all major storms for which there is systematic precipitation data.
- A more thorough effort should be made to develop a series of basin average precipitation for the major storms in the systematic record.
- Frequency analysis of the basin average precipitation series should be based on a regional precipitation analysis and should consider distributions other than the shifted exponential (i.e., the generalized Pareto).
- Using the extended precipitation and discharge series, alternative rainfall-runoff models should be explored.
- An error analysis should be conducted to determine the uncertainties in the estimated probability distributions.

The results of such an analysis would provide useful information about the upper tail of the probability distribution of three-day flows on the American River.

SUMMARY

Following the spirit of Bulletin 17-B, the committee estimated the probability distribution of average three-day flood discharges for the American River at Fair Oaks using various combinations of systematic, historical, and paleoflood data. Results based on the systematic and paleoflood data are consistent, implying a log skew (to the nearest tenth) of -0.1. Averaging station skews at comparable Sierra Nevada rivers gives a similar result. Use of the paleoflood data implies that the log skew is much more negative, and as a result when the paleoflood data is used with the systematic and historical data, the resulting fitted log-Pearson type III distribution does not provide an adequate description of the flood flow frequency relationships for floods with exceedance probabilities from 0.5 up to and beyond 0.002. Frequency analysis based on a series of basin average precipitation data supports the latter possibility.

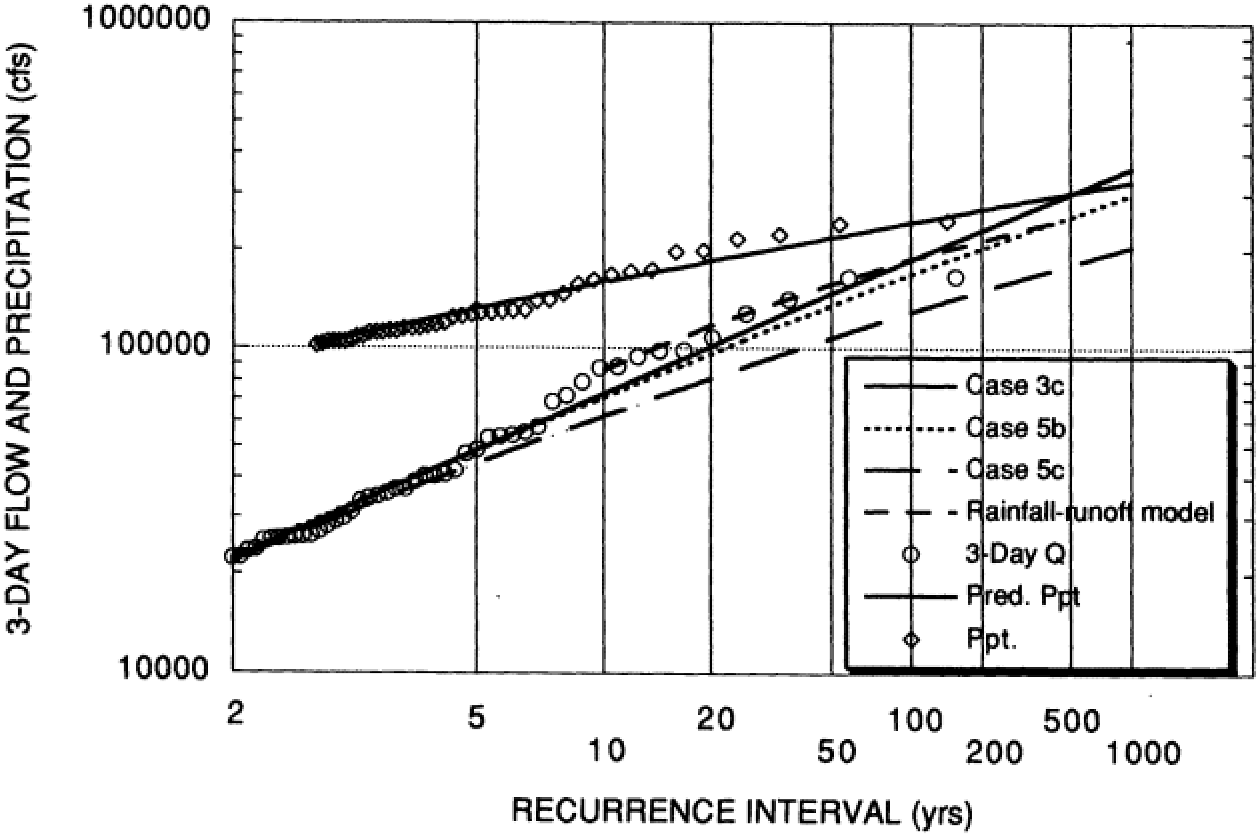


Figure 3.7
Estimated frequency distribution for average three-day rain flood flows based on the rainfall-runoff model. Also shown are the estimated distributions for Cases 3c and 5c. Only the upper half of the distributions is shown. Plotting position is from Cunnane (1978).

The committee's recommended flood frequency distribution for three-day rain flood flows on the American River is based on the application of the Expected Moments Algorithm to systematic data and historical data with an assumed log skew of -0.1. Approximate confidence intervals were obtained by Monte Carlo simulation. The committee believes that this approach meets the spirit of Bulletin 17-B guidelines. Based on the evidence that the "true" distribution flattens for very large floods, the committee is hesitant to recommend the use of its selected distribution for annual exceedance probabilities less than 1 in 200. If it is necessary to extrapolate the distribution for smaller exceedance probabilities, the recommended distribution provides a basis that is consistent with Bulletin 17-B guidelines, however, other estimation approaches should be investigated, including the rainfall-runoff approach explored by the committee.

4

Climate and Floods: Role of Non-Stationarity

Flood frequency analysis, as traditionally practiced, is marked by an assumption that annual maximum floods conform to a stationary, independent, identically distributed random process. Furthermore, the assumption that floods are independent and identically distributed in time is at odds with the recognition that climate naturally varies at all scales, and that climate additionally may be responding to human activities, such as changes over the past century in atmospheric composition or in global land use patterns, which have changed the climate forcing and perhaps the hydroclimatic response on regional scales in recent decades. Porparto and Ridolfi (1998) demonstrate that estimated flood exceedance probability can increase quite rapidly with time even in the presence of rather mild rising trends in the annual maximum flood. As mentioned in Chapter 2, Knox (1993) makes the same point. Thus, it is important to acknowledge that non-stationarities are likely to be present in the records and to discuss potential sources of such trends or non-stationarities.

There is considerable evidence of regime-like or quasi-periodic climate behavior and of systematic trends in key climate variables over the last century and longer (see NRC, 1998a for one overview). The unambiguous attribution of cause for such non-stationarities in a finite record is difficult, given the rather rich, nonlinear dynamics of the climate system. Even with stationary underlying dynamics (i.e., no change in the governing equations or parameters), finite sample statistics of a nonlinear dynamical system can be non-stationary as the system evolves from one regime to another. The nature of the nonlinear oscillations of the system as well as regime probabilities and its mean state may change as the external forcings (e.g., solar radiation or greenhouse gases) are changed.

The stationarity assumption in flood frequency analysis has persisted because of (a) short historical records that limit a formal analysis of non-stationarities, (b) the lack of a formal framework for analyzing non-stationary flood processes and the associated annual risk, and (c) institutional adherence to engineering practice guidelines. As record lengths have increased, trends in floods and other processes have been observed. The ongoing global climate change debate and identification of interannual and decadal ocean-atmosphere oscillations (e.g., El Niño Southern Oscillation), and their teleconnections to continental hydroclimate, have led to increased awareness of this issue.

Cyclical or monotonic non-stationarities pose a serious challenge to flood frequency and risk analysis and flood control design and practice. If cyclical or regime-like variations arise due to the natural dynamics of the climate system, a relatively short historical record may not be representative of the succeeding design period. Further, by the time one recognizes that the project operation period has been different from the period of record used for design, the climate system may be ready to switch regimes again. Thus, it is unclear whether the full record, the first half or the last half of the record, or some other suitably selected portion is most useful for future decisions without a better understanding and prediction of the climate regimes. This is one issue faced in an analysis of the American River and Sacramento flood protection question. In addition, if a monotonic trend in floods is indicated in a reasonably long record and the possibility of global climate change effects is considered, projections of future flood potential are still unclear. For one, the effects of global climate changes may be more in the variability of the process than the mean, and may translate into an increased probability of recurrence of certain regimes of climate more than others. No means for the believable projections of such changes have as yet emerged. Deterministic coupled ocean-atmosphere general circulation models do not yet adequately reproduce observed low frequency climatic patterns or watershed scale precipitation and hence their utility for answering this question is limited.

The thrust of these comments is that the uncertainty associated with the flood frequency estimates presented in Chapter 3 is likely to be considerably greater than that indicated by the statistical estimates. Some of the non-stationarities of the American River flood records and related hydroclimatic records are documented in this chapter.

GENERAL METEOROLOGICAL FEATURES OF MAJOR FLOODS

The utility of connecting atmospheric circulation patterns to flood events is now well established. Hirschboeck (1987ab, 1988) demonstrated that catastrophic floods as well as trends in floods may be best understood in terms of large-scale and regional circulation pattern anomalies. She also proposed mixture estimation methods for flood frequency estimation conditional on the frequency of atmospheric circulation patterns. Time constraints precluded such an analysis for the American River basin. The discussion here is similarly motivated in that an explanation for changes in the flood frequency of the American River is sought in terms of associated changes in the large-scale atmospheric circulation patterns.

In the ensuing discussion, the term "annual" will refer to a winter-centered 12-month period, such as the water year (Oct-Sept) or the period July-June. Similarly, "winter" will in general refer to the entire cool portion of the year, not just December-February as in much meteorological literature.

Central California has a modified Mediterranean climate. Precipitation usually builds to a maximum in winter and subsides to nearly nothing in the summer, so that there are essentially two seasons rather than the traditional four. Consequently, major Sierra Nevada flooding occurs predominantly in the middle of the wet season and rarely in the summer months. Heavy snowmelt years can bring streams to slightly over their banks in late spring, but this type of flooding is not catastrophic. The 10 largest annual maximum floods in the 1905-1997 period on the American River in the Fair Oaks record occurred between late November and early

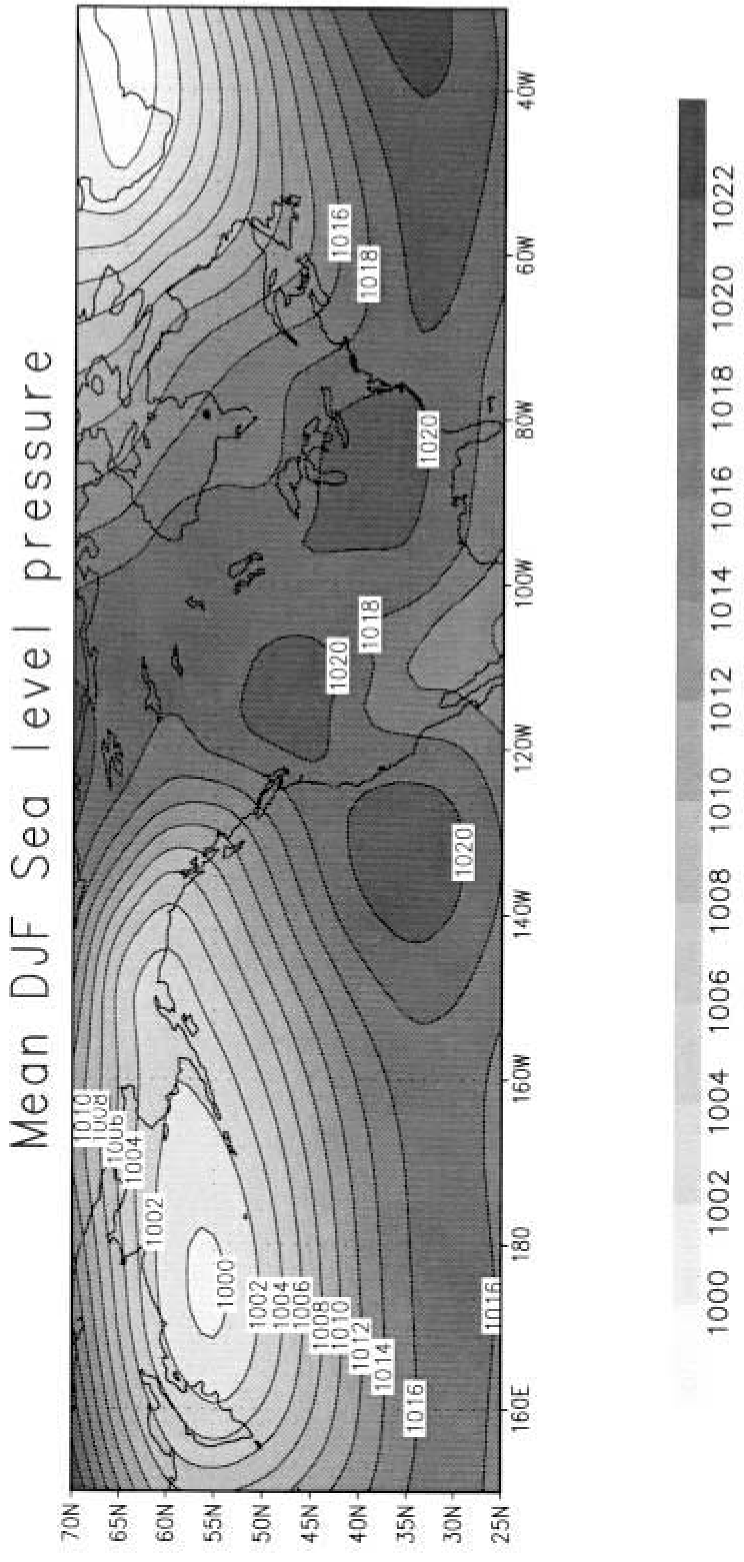
March. The 10 smallest annual maximum floods occurred between March and July or in December, reflecting lower winter precipitation and colder winter temperatures in those years.

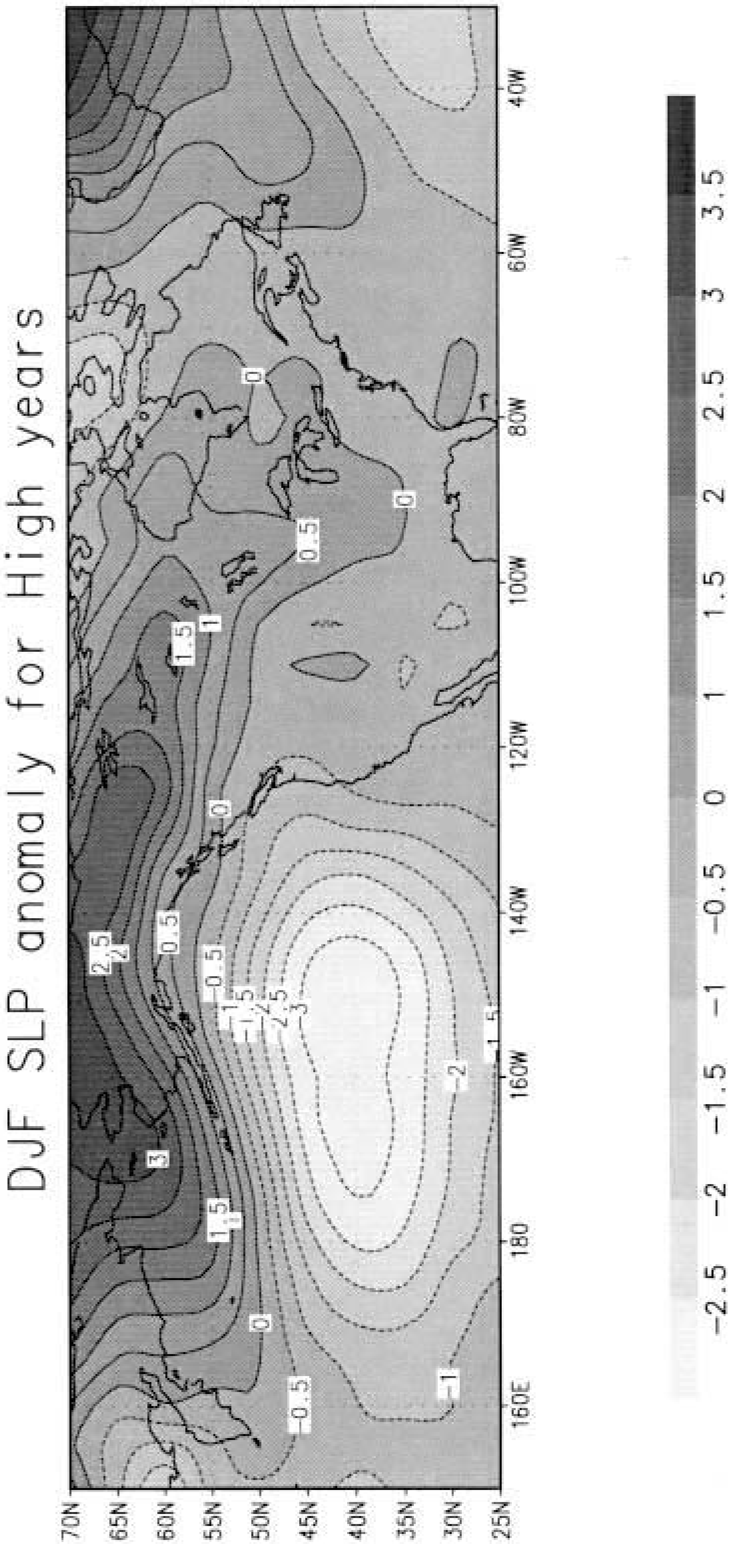
The Sierra Nevada floods of winter are produced by strong onshore atmospheric flow patterns containing numerous embedded disturbances. The flow generally has a southwest to northeast orientation, typically tapping deeply into tropical and subtropical moisture. This orientation is nearly perpendicular to the elevation contours east of Sacramento, where the terrain steadily ramps up from sea level to about 7,500 feet at pass level, and near 10,000 feet at the peaks. Vertical velocities caused by the forced ascent of the rapidly moving air are quite large. The associated cooling and moisture condensation proceeds at a high rate. High freezing levels and warm temperatures cause rain at higher elevations, often to near the tops of the mountains. Snowmelt is often a contributing factor, but rain is the main ingredient. Antecedent conditions (degree and depth of low elevation snowpack, soil moisture from prior to the first snowfall) can be significant. Large floods begin when such an atmospheric flow regime persists with little deviation for two to three days. Precipitation rates can be so high that in some situations, even a difference of an hour or two in duration can make a critical difference in the size and shape of a flood pulse. Descriptions of one such event (1996-1997 New Years Flood) are given in Redmond and Pulwarty (1997), and of the response in California Flood Emergency Action Team (1997).

An examination of the large scale atmospheric conditions associated with the December-January-February (DJF) circulation for different types of years is instructive. The mean DJF sea level pressure map (Figure 4.1a) shows a deep low pressure center located in the central North Pacific, and two broad high pressure centers located over the southeastern Pacific and over the Great Basin and northern Rockies. The corresponding mean atmospheric flow will be counter clockwise around the low pressure center and clockwise about the high pressure center. The presence of the two high pressure centers in the mean DJF pattern reflects a climatological tendency for deflection of storms to the typically wetter, more northerly portions of the western United States.

Winter precipitation is brought to the Sierra Nevada by transient systems, typically 20-25 each year, that are coupled to the jet stream. On occasion, these midlatitude systems entrain moisture from the subtropics, and even the tropics, and deliver even more precipitation than the average system. The strength and position of the mean upper air flow, and of the disturbances which both feed from and feed back into the jet stream (and which are influenced in part by access to heat and moisture at lower latitudes) are linked to the pattern of sea surface temperatures in the tropical and extratopical Pacific Ocean.

A composite of the average anomaly (departure from the full record) DJF sea level pressure for the 10 years with the largest annual maximum American River floods is shown in Figure 4.1b. The largest negative anomaly is found considerably to the southeast of the area with climatologically lowest pressure (the "Aleutian Low" in Figure 4. 1a). This implies a slight filling and shifting of the Aleutian Low to the southeast. Of note is that pressures near California are only slightly less, and that most of the change in pressure is well away from the mainland, so that an


Mean DJF Sea level pressure
70N
65N
60N
55N
50N
45N
40N
35N
30N
25N
160E
180
160W
140W
120W
100W
80W
60W
40W
1000
1002
1004
1006
1008
1010
1012
1014
1016
1018
1020
1022


DJF SLP anomaly for High years
70N
65N
60N
55N
50N
45N
40N
35N
30N
25N
160E
180
160W
140W
120W
100W
80W
60W
40W
2.5
2
0.5
-0.5
-1
-1.5
-2
-2.5
-3
3
1.5
1
0
-0.5
-1
-1.5
-2
1.5
1
0
0.5
0
0
-2.5
-2
-1.5
-1
-0.5
0
1
1.5
2
2.5
3
3.5

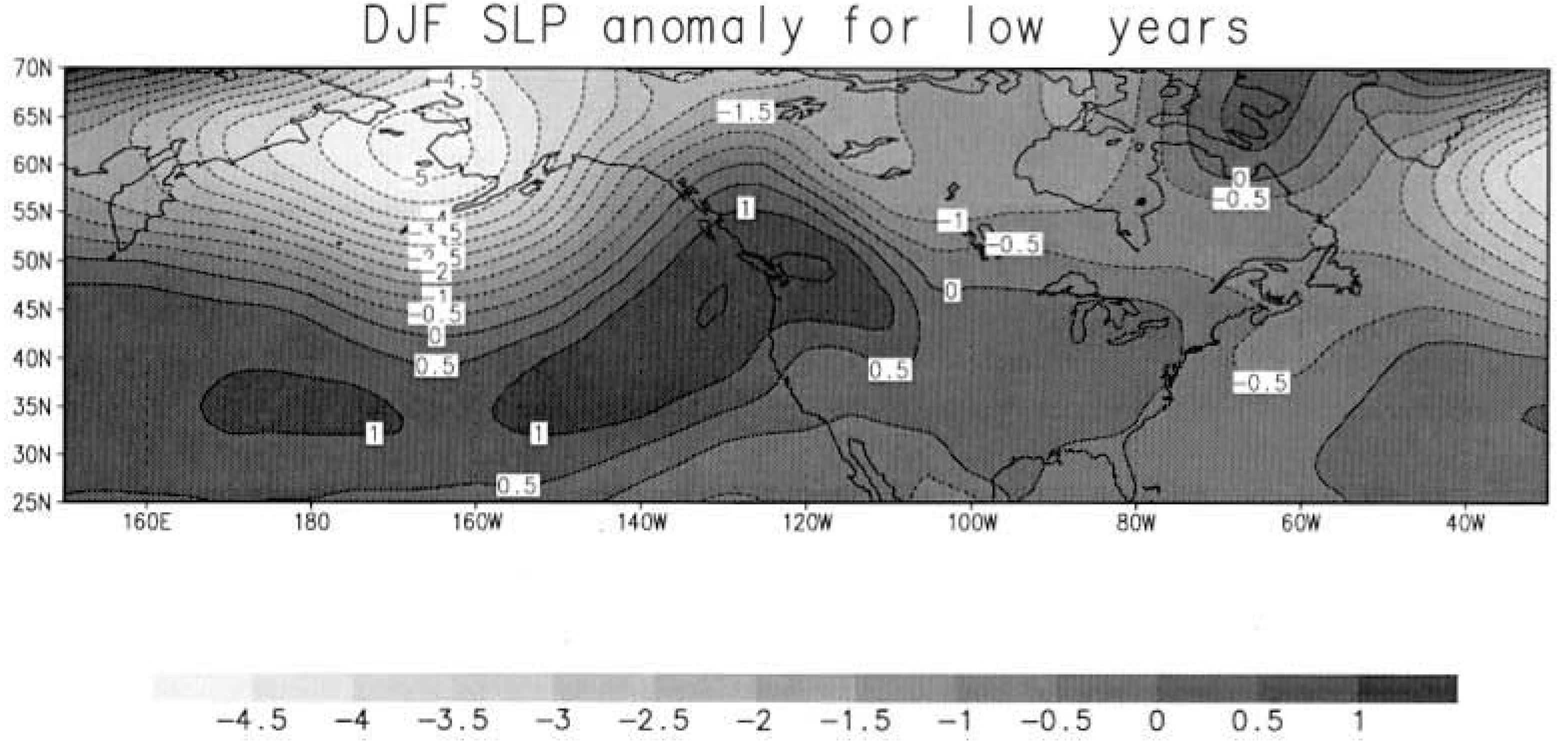


Figure 4.1
DJF sea level pressure (mb) patterns for (a) the 1900-1997 period, (b) the years with the 10 largest annual maximum floods (ending year of winter 1907, 1928, 1951, 1956, 1963, 1965, 1980, 1982, 1986, and 1997), and (c) the years with the 10 smallest annual maximum floods (ending year of winter 1912, 1913, 1931, 1933, 1961, 1966, 1977, 1988, 1990, and 1994). The mean sea level pressure is plotted in (a) and anomalies from this climatology are plotted in (b) and (c).

increased east-west surface pressure gradient exists. The upper air pattern (not shown) is an accentuated version of the surface pattern. An enhanced south to north flow component is noted, well offshore, turning east at higher latitudes, with "landfall" over the Pacific Northwest. During flood episodes within these winters, periods that may only last 5-10 days, this pattern shifts closer to the coast and becomes temporarily greatly accentuated, and delivers abundant moisture to the "favored" site. This is consistent with the observation that winters with California floods do not appear to be otherwise particularly wet (see below).

A similar compositing was performed for the 10 years with the smallest annual maximum rain-fed floods, and results are shown in Figure 4.1c. In this case, the anomaly is positive over a broad area nearly coincident with the band of climatological high pressure, extending at its eastern end over the northern west coast and the northern Rockies. This even more strongly entrenched high pressure constitutes a pattern known as "blocking," in which the prevailing upper flow shunts storms far to the north, more toward the Alaska Panhandle. Such patterns are very persistent and hard to dislodge. In these circumstances, very few frontal systems are able to penetrate through to central California.

Consequently, in terms of flood potential and changes in flood frequency in the American River region, one needs to understand changes in the low frequency variability of the associated atmospheric flow patterns. These patterns are in turn related to oceanic temperature and ultimately oceanic circulation patterns, which are also related to atmospheric circulation patterns in an endlessly circular fashion, and hence to low frequency variability in ocean-atmosphere interactions such as the El Niño/Southern Oscillation and the Pacific Decadal Oscillation. These low frequency forcings and global climate change issues are discussed further in a later section.

Large floods need not reflect the character of the entire winter. Notably, the floods in December 1955 and February 1986 occurred in what would have otherwise been dry years, and the 1996-1997 July-June total would have been just slightly above average. After a second smaller storm later in January, the next four months were the driest in records spanning 150 years. The discussion of the average DJF sea level pressure patterns is consequently useful only because it addresses changes in the probabilities of flood causing events.

OBSERVED CLIMATE AND STREAMFLOW VARIABILITY

Non-Stationarity of American River Floods

Since 1950, there have been seven annual maximum floods on the American River that have equaled or exceeded the largest previous flood in the systematic record. The estimated frequency of exceedance of extreme floods has correspondingly increased. The 100-year event for the three day annual maximum flood for the American River at Fair Oaks estimated using the log normal distribution from 2- or 51-year moving windows shows a near monotonic increase over the period of record (Figure 4.2). A moving window analysis of the mean and standard

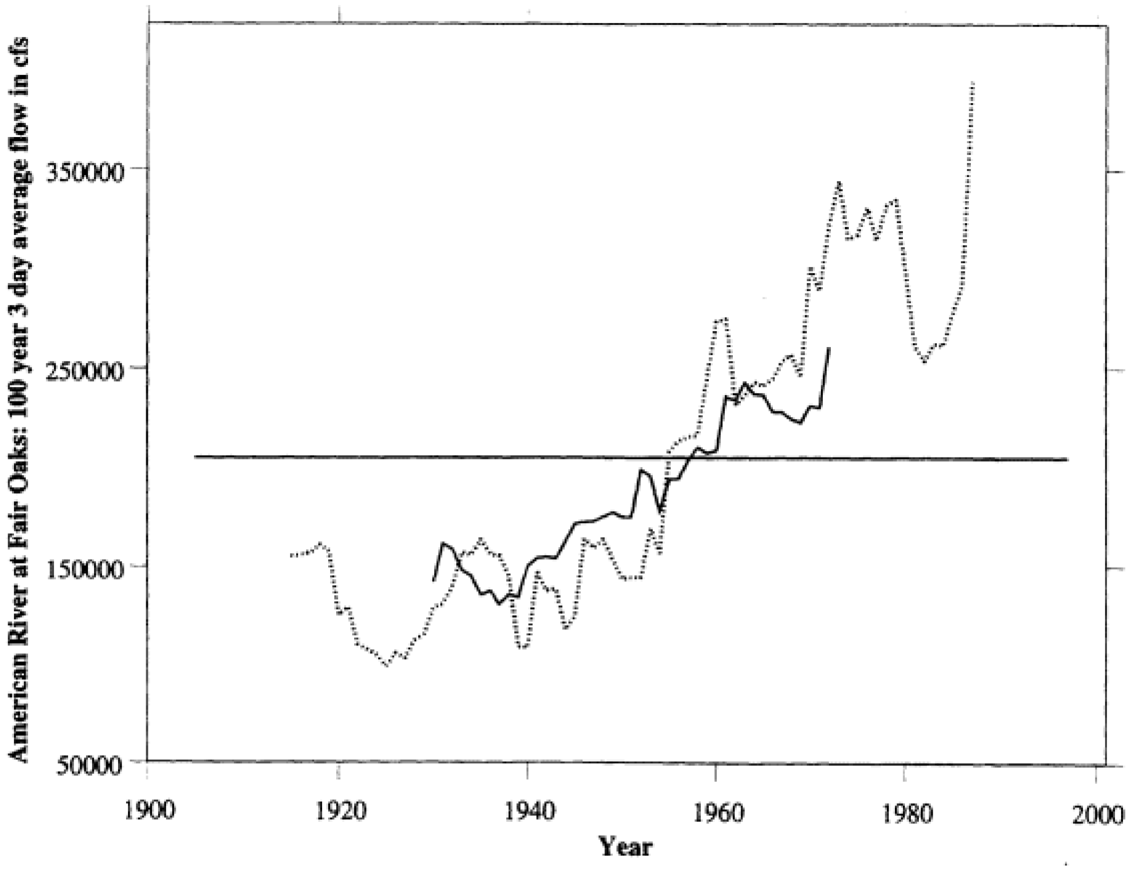


Figure 4.2
Trends in the 100-year, three-day annual maximum flow (cfs) at the American River at Fair Oaks gage computed using a log normal distribution with 51-year (heavy solid) and 21-year (dashed) moving windows. The 100-year event (204,674 cfs) estimated using the log normal distribution with the 1905-1997 record is shown by the solid horizontal line.

deviation of the three-day annual maximum flood reveals that the trend in the 100-year flood is primarily due to the trend in the standard deviation (toward increasing variance) of the annual floods. For the associated precipitation record, whereas year-to-year variability recently has increased greatly, trends in total precipitation (for seasons or for the wettest episodes) are barely discernible. Similar conclusions are reached for the one-day and five-day annual streamflow maxima.

A perspective for the American River basin flood trends is next developed through a review of climatic trends in nearby basins and in the United States. Even under a scenario of global climate change, given our understanding of climate dynamics, there is no expectation that the trends in floods or precipitation would be geographically similar.

Trends in Systematic Records of Other Nearby Basins

Precipitation records for locations in and near the American River basin show the latter half of the 20th century slightly wetter than the first half. The number of significantly wet years, however, shows a considerable difference between the earlier and later parts of the record. For example, at Placerville (elevation 1,700 ft, 124-year average is 39.92 inches) in the 22 years from 1874 through 1895, 5 years exceeded 55 inches (1 in 4.4 years); then just one year in the 55 years from 1896 through 1950 (1 in 55); and 6 years in the 47 years from 1951 through 1997 (1 in 7.8 years). At higher elevation Bowman Lake (5,390 ft, 98-year average 66.44 inches), just north of the North Fork basin, in the 51 available years from 1898 through 1950, 5 years exceeded 87 inches (1 in 10.2); followed by 11 cases in the remaining 47 years from 1951 through 1997 (1 in 4.3). Similarly, the later years also show more cases of *dry* winters, so that in general the number of extreme *wet or dry* years is increasing. This pattern for the 20th century is similar to those just over the mountain crest, from a station with an excellent record, Tahoe City, in the adjoining Truckee/Tahoe basin (elevation 6230 feet) just east of the American River. For the winter months of October through March, this site has only 1 year that exceeds 40 inches from 1910-1950 (1 in 41), compared with 11 years from 1951-1998 (1 in 4.4). The decadal trends in this series are illustrated in Figure 4.3 using a 10 year running mean of the winter precipitation.

The temporal history of multi-day precipitation extremes is perhaps of more direct interest in the flood context. The time series of maximum 10-day precipitation for each water year is shown in Figure 4.4 for Lake Spaulding (elevation 6,160 feet). Though only a slight upward trend exists overall, the number of instances of very wet episodes increases during the latter half of the 20th century. For example, there are two years where 10-day maximum exceeded 22 inches in the 48 available winters from 1898 through 1950 (1 in 24), and 9 in the 47 years from 1950-1951 through 1996-1997 (1 in 5.2). A similar increase from the first to the second half of the century is seen in three-day amounts exceeding 14 inches. The three-day annual maximum basin precipitation for the American River basin estimated using the precipitation stations at Repressa, Auburn, Placerville, Nevada, Spaulding, and Tahoe shows similar trends. Its correlation with the three-day annual maximum flow at the

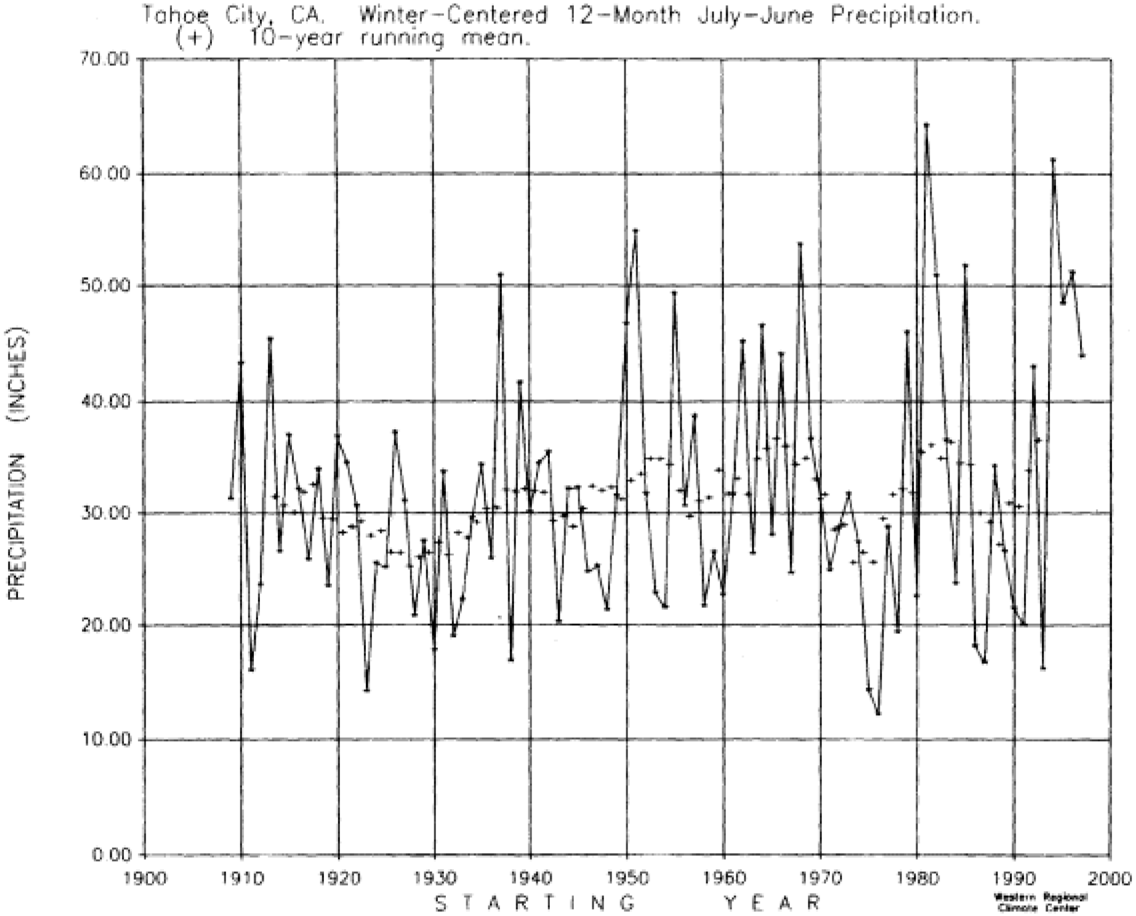


Figure 4.3
Tahoe City, California (elevation 6230 feet) winter-centered 12-month July-June precipitation. Plus marks represent 10-year running means centered on plotted year.

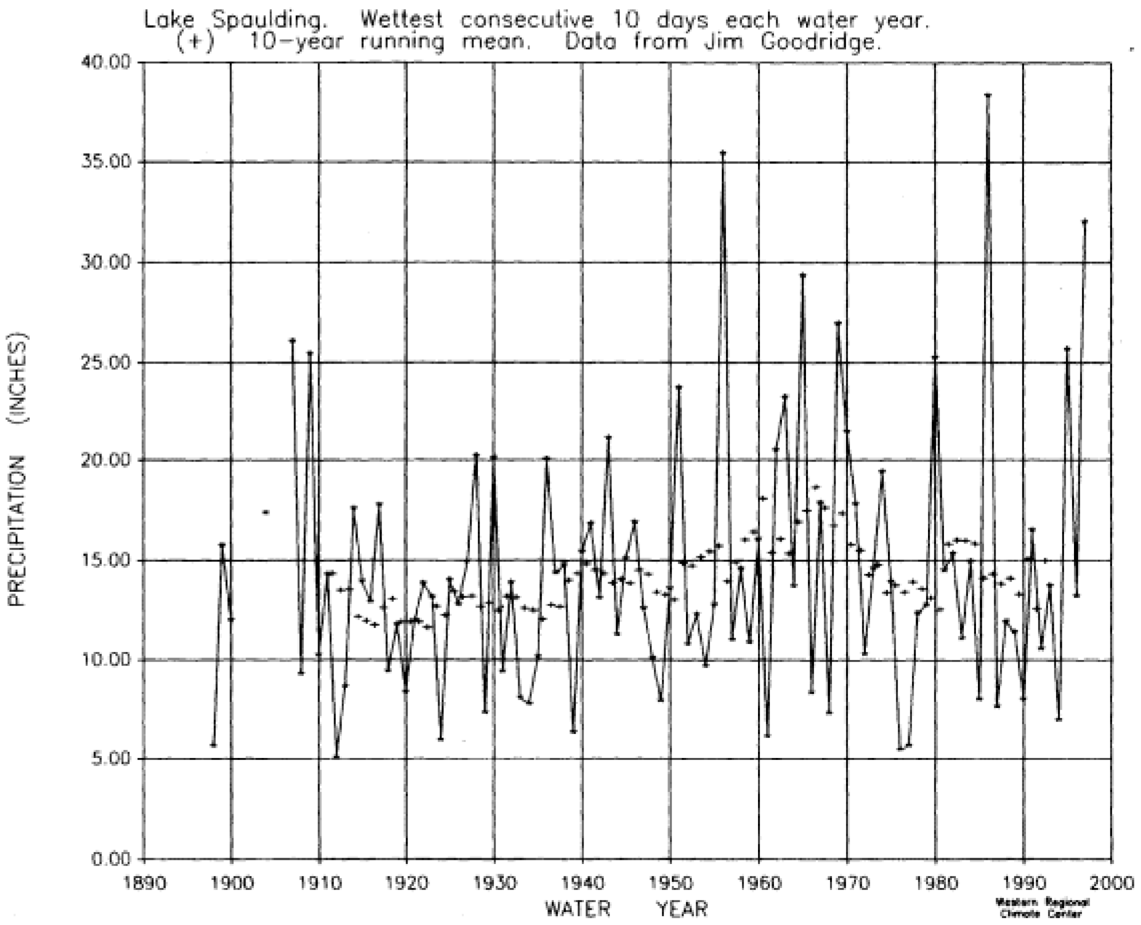


Figure 4.4
Lake Spaulding, California, (elevation 5,160 feet) maximum 10-day precipitation for each water year. Plus marks represent 10-year running mean centered on plotted year. Data provided by J.D. Goodridge.

American River at Fair Oaks gage is 0.88. This suggests that the non-stationarity in the American River flood series is of climatic origin and is unlikely to be caused by errors in the allocation of Folsom flood storage to the peak flows.

The California Department of Water Resources uses an eight station index to help track precipitation over a larger area, the Sacramento River basin. These eight stations are in basins starting just north of the North Fork of the American, extending to just west of Shasta Dam. The index consists of a simple arithmetic average of their daily precipitation. Because the generating mechanisms for winter precipitation function on large scales, correlation deteriorates slowly with distance. Water year correlation between the eight station and Placerville precipitation for data in a recent period (1931-1992) is 0.91, 0.92 with Bowman Lake, 0.96 with Lake Spaulding, and 0.86 with Tahoe City. The eight station index begins in 1921, but shows the same increase in high precipitation years beginning in mid-century, as well as an increase in the number of low precipitation years. For example, July-June 8-Station precipitation totals of 70 inches or more occur twice in the 29 winters from 1922-1923 through 1950-1951 (1 per 14.5 years), and then 10 times in the next 47 years through 1997-1998 (1 per 4.7 years). Since the 1930s, there is no overall trend in the eight station mean. Of particular note, the last 20 years have brought the driest and the wettest individual years in the record, and also the driest and wettest four-year running averages.

The conditions that produce floods on the west slopes of the Sierra Nevada also cause heavy runoff on the east slopes, which drain into the elevated playas of the western Great Basin (Pupacko, 1993). In a sense ,west-side precipitation "spills over" to the narrower band of steep slopes on the east side. Thus, major Sierra floods usually occur on both sides of the crest at the same time, and evidence from the east-facing basins is relevant to west-facing basins. Major floods on the Truckee River in Reno, for instance, coincide with those on the American River, the adjoining basin to the west of Lake Tahoe (Rigby et al., 1998). Flood series from the Truckee (Garcia, 1997; Hess and Williams, 1997; Rigby et al., 1998), Carson (Thomas and Williams, 1997), and Walker (Thomas and Hess, 1997) Rivers also show general accord.

The increased variability and the increase in the number of extremes in the latter half of the century is consistent with corresponding trends in the American River floods.

Trends in California

Over the State of California as a whole, both measures (the number of significantly wet years and the magnitude of the largest multi-day wet events during each year) appear to have increased considerably during the second half the century. Goodridge (1998) identified a fixed set of 95 long-term records distributed around the state. His analysis shows that there are no cases where the 95-station annual average exceeds 33 inches in the 40 winters from 1898 through 1937 (0 per 40), and 2 cases in the 53 years from 1898-1950 (1 per 26 years), followed by 8 cases in the 48 years from 1951 through 1998 (1 per 6 years). Because the station set is fixed, this is not a result of wetter sites being used for later years. Although stations in many parts of the state exhibit this behavior, some areas show opposing effects. The biggest and most regionally consistent effects are seen in the central parts of the state at all altitudes.

Goodridge (1997a, 1998) also performed similar analyses of maximum n-day precipitation for each water year, averaged over all stations for each year, for fixed sets of stations with digitized daily data. An 83-station set shows five cases (years) with an average 10-day maximum of at least 8.5 inches in the 53 years from 1898 through 1950 (1 per 10.6 years), and nine such cases in the next 47 years from 1951 through 1997 (1 per 5.2 years).

U.S. Trends

On the national scale (lower 48 state average), there is little evidence for an increase of precipitation over the last century (see, for example, NCDC Climate Variations Bulletin, http://www.ncdc.noaagov/pub/data/cvb/cvb1297.pdf). This search has been conducted with multistation aggregates averaged over climate divisions (California has seven). Using these divisions, Karl et al. (1996) show a downward trend in the state over the last century. The station mixture that forms the aggregate changes with time. Conversely, an analysis with a set of 95 fixed stations in California (Goodridge, 1998) stations showed a slight rise in annual precipitation from 1898 through 1997. A slightly longer record (Goodridge, 1997b) of 76 fixed stations showed no trend from 1883 through 1995.

Karl et al. (1996) and Karl and Knight (1998) used daily records from an area with relatively good records, the continental U.S., to uncover evidence of more extreme events and, in particular, greater numbers of heavy precipitation days in more recent decades. Karl et al. (1995) found that the fraction of the total precipitation contributed by daily amounts of 2 inches or more in the United States had increased during the 20th Century. Using an updated procedure on a 1 x 1 degree grid, Karl and Knight (1998) showed that the contribution of 2-inch daily precipitation amounts increased from 9% of the annual U.S. total in 1910 to 11% of the annual total in 1995. Using a set of 182 daily climate records, Karl and Knight (1998) looked at trends in the contribution by decile to the annual total, across the United States and in regional blocks of the country. They find that the upper ten percentile of daily precipitation (for only those days with precipitation, rainless days excluded) contributed about 36% of the annual total in 1910, a fraction which rose to 40% in 1996. This approach tries to overcome the noisiness of precipitation records with large sample sizes. These analyses require long time series of homogeneous daily data, a situation difficult to find in many countries. For the United States as a whole, the study by Karl and Knight further shows little evidence of a stepped increase in the fractional contribution by heavier events at any point during the 20th Century.

A finer breakdown shows the growth in the upper 5th percentile to be even greater. A regional block of California and Nevada stations shows that the frequency of precipitation in this upper 5% increased more than any other region of the country. The behavior noted by Karl is consistent with the expectation of more rain per rainy day, as climate models indicate for a warmer globe (see below).

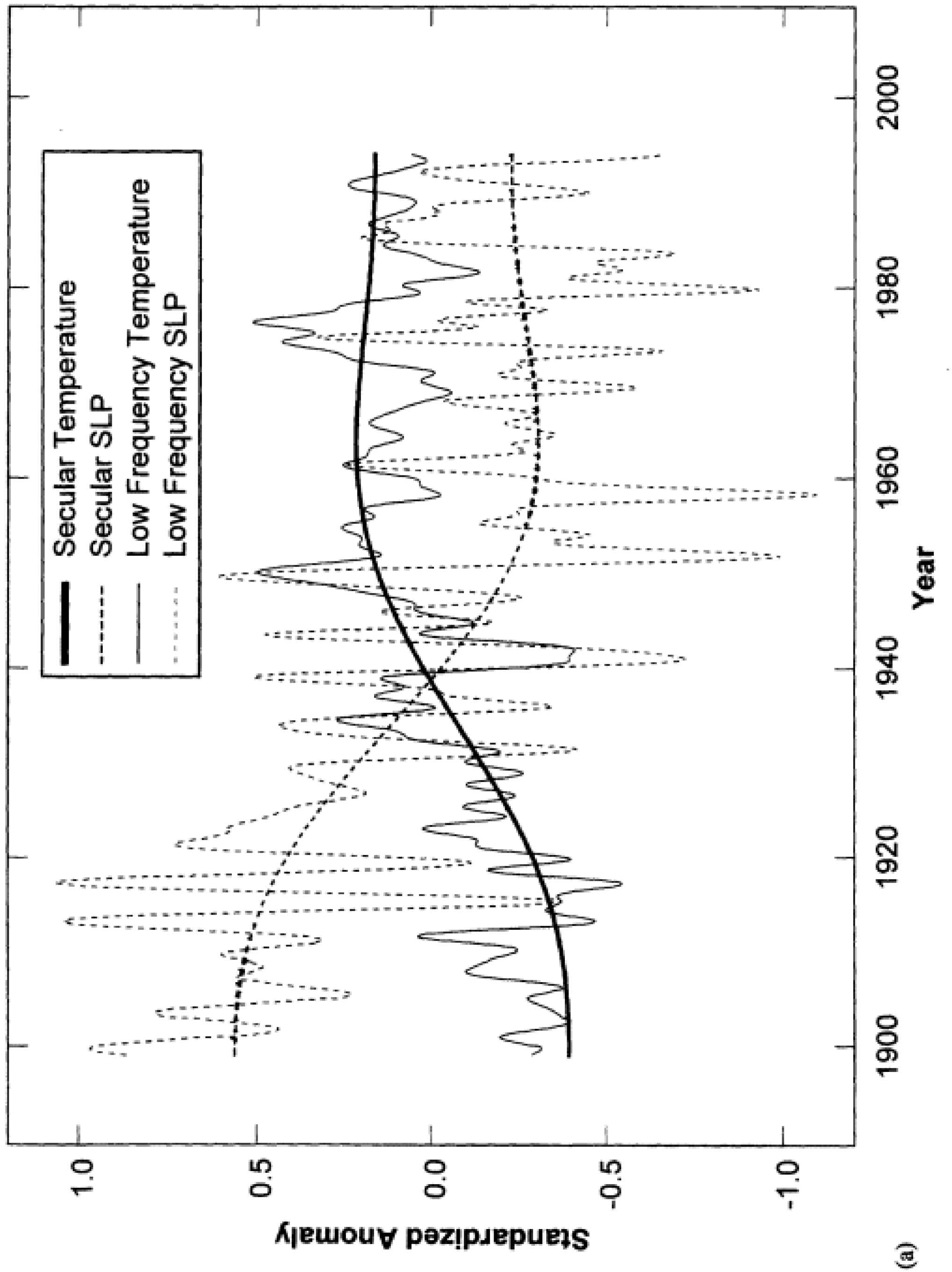
Relation of American River to Trends in Hemispheric Circulation

A space-time-frequency domain analysis of hemispheric pressure and temperature data was performed by Mann and Park (1996). Gridded (degree by degree) monthly records of Northern Hemisphere sea level pressure (SLP) (Trenberth and Paulino, 1980) and surface temperature (Jones and Briffa, 1992; Jones, 1994) for the period 1899-1996 were used to identify and reconstruct space and time patterns of quasi-oscillatory, large-scale climate patterns at quasi-biennial (approximately 2.2 years), ENSO (approximately 3-6 years), decadal (approximately 10 years), interdecadal (approx. 16 years period) and secular (greater than 20 years) frequency bands using a 40 year moving window multi-taper method/singular value decomposition (MTM-SVD). These patterns are identified as space-time oscillations in SLP and surface temperature in these frequency bands. The frequency bands indicated were identified through a Monte Carlo statistical significance test for the fractional variance explained across all the series analyzed. The simultaneous analysis of these data sets helps one identify dynamically consistent, space-and-time coherent patterns of low frequency climate evolution. The hemispheric space-time oscillations identified can be projected as a time series to any of the 5x5 degree grid points for each frequency band.

The projections of the five quasi-oscillatory SLP and surface temperature space-time patterns for the frequency bands indicated above were evaluated at the grid points in the vicinity of the American River stream gage at Fair Oaks. The spatial averages of the projections for the four closest grid points are shown in Figure 4.5a. The low frequency SLP and surface temperature projections are obtained from the MTM-SVD analysis by summing over the reconstructions for the secular, interdecadal, decadal, ENSO, and quasi-biennial bands at the closest grid point. Note the secular trend for a shift to a lower SLP and warmer temperature at the American River region since about 1940. The spectral coherence between the American River annual maximum flood and the projected low frequency SLP and temperature is significant for the frequency bands where there is spectral power in the climate signal (Figure 4.5b). The spectral coherence analysis estimates the correlation between two time series as a function of frequency. The low frequency projections of the SLP and surface temperature series were first converted to annual time series by picking off the value of the projection for the month of the annual maximum flood in a given year. The spectral coherence between these annual climatic time series and the annual maximum flood series were then computed. Here, the correlation is statistically significant for the frequency bands where the climatic series have statistical power. Thus, the non-stationarity in the frequency and timing of the American River floods is likely due to interannual, decadal, and centennial scale variability in the hemispheric climate. The latter may be related to either natural dynamics or human enhanced global climate changes, or both.

Changes in Seasonality

In addition to the changes in precipitation and floods, changes in the seasonality of these fields have also been noted. Wang and Mayer (1995) present


Secular Temperature
Secular SLP
Low Frequency Temperature
Low Frequency SLP
Standardized Anomaly
1.0
0.5
0.0
-0.5
-1.0
Year
1900
1920
1940
1960
1980
2000

(a)

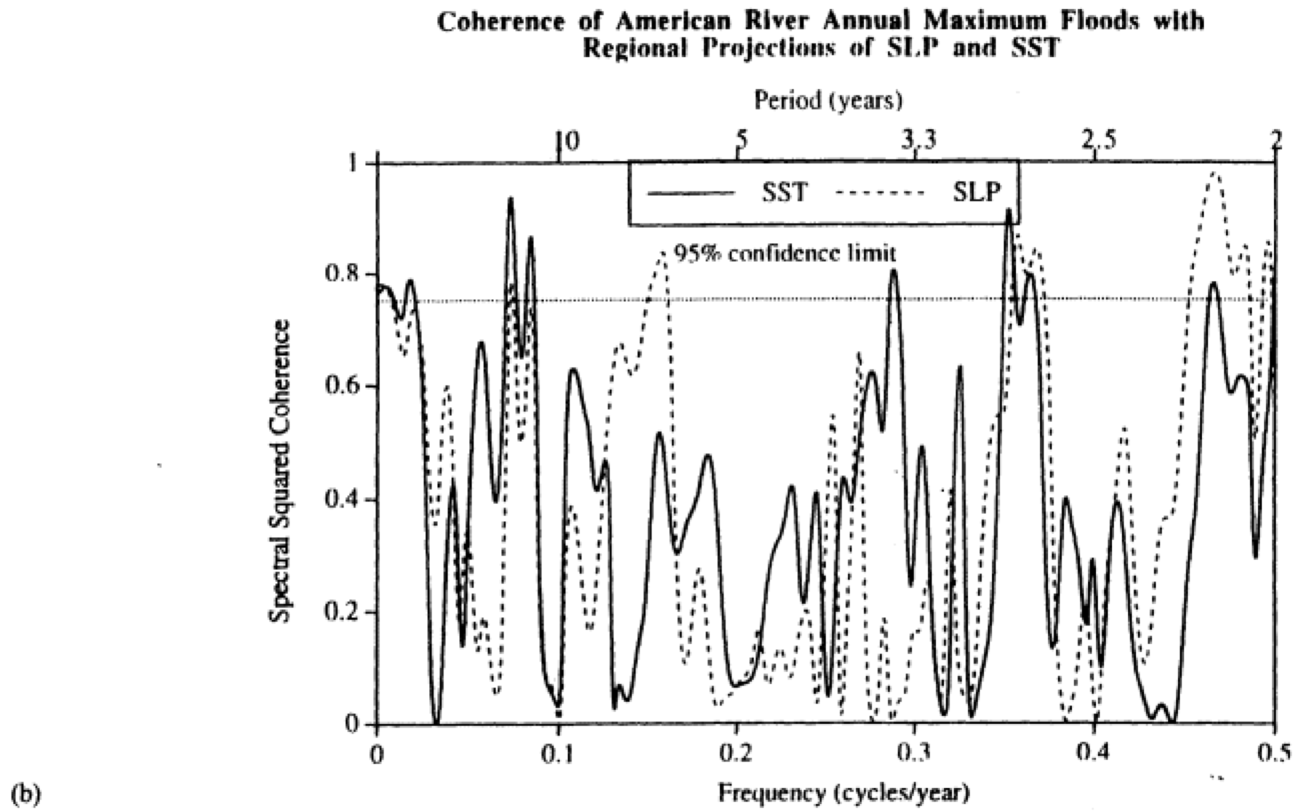


Figure 4.5
(a) The secular and low frequency components of SLP and temperature at the grid point nearest the American River from MTM-SVD. Note the secular trend towards warmer temperatures and lower pressure in the region, post-1940, coincident with the increased flood incidence and shift in flood timing. (b) Spectral coherence of the annual maximum flood series with the low frequency projections of SLP and temperature for the flood month. The correlations are significant in the quasi-biennial, ENSO, decadal, and secular bands. Hence, the large-scale, low-frequency climate patterns that affect the regional pressure and temperature fields are likely responsible for the non-stationarity in the annual maximum flood process.

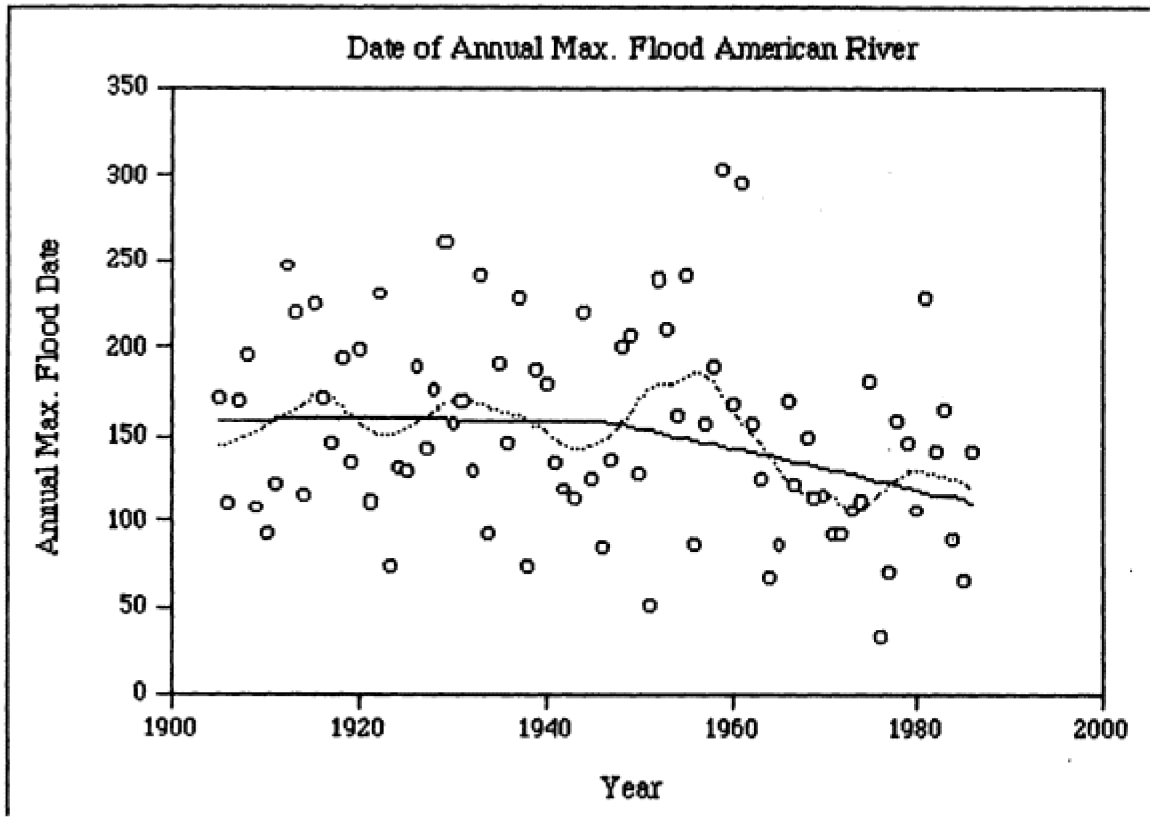


Figure 4.6
Date of annual maximum flood for the American River near Fair Oaks. The date is with reference to the water year, which starts on October 1. Centennial and decadal trends are shown by the solid (56-year smooth) and the dotted line (14-year smooth).

data on changes in the seasonality of flooding for the United States. They constructed regional time series of the percentage of annual floods occurring in each of the four seasons for the period 1912 through 1984. For the western United States, they noted a sharp increase in the percentage of floods occurring in the winter since about 1950. Similar trends in the date of the annual maximum flow of the American River can be seen in Figure 4.6. A secular trend is pronounced since 1950, with significant superimposed decadal variability throughout the record. These change are synchronous with the apparent non-stationarity in the American River flood record. In the context of Wang and Mayer's analysis, it appears that the apparent non-stationarity in the American River flood record is part of a climatic phenomenon occurring over a large region.

Many investigators have noted similar trends in the timing of West Coast streamflow. In an analysis of streamflow data (corrected for human impacts) from the major streams draining the west side of the Sierra Nevada mountains, Roos (1987) and Aguado et al. (1992) observed a decreasing trend in the percentage of annual runoff occurring in the period of April-July. Studies of trends in streamflow by other investigators, including Wahl (1991), Pupacko (1993), Danard and Murty (1994), and Dettinger and Cayan (1995), provide evidence that the change in seasonal runoff observed in the Sierra Nevada streams is in fact a regional phenomenon.

The physical cause for these trends in streamflow has also been the subject of inquiry. Aguado et al. (1992) focused on the potential role of variations in rainfall and temperature in the timing of Sierra Nevada runoff. They conclude that the more frequent occurrence of high autumn precipitation, particularly in November, has contributed to the increase in November-December-January fractional flows and the decrease in May-June-July fractional flows. They speculate that the trends represent normal climatic fluctuations rather than a signal of anthropogenic warming. Pupacko (1993) considered temporal streamflow patterns for the North Fork of the American River for the period 1939 through 1989. He noted an increase in November through March runoff beginning in 1965. He speculated that since 1965 more precipitation is falling as rain and less water is being stored as winter snowpack. This shift in the seasonality of precipitation is consistent with the findings of Rajagopalan and Lall (1995). They observed that the wet season, defined in terms of either the frequency or magnitude of precipitation, may have moved forward by as much as 30 days at some locations in the Great Basin.

Dettinger and Cayan (1995) found that trends in runoff and snowmelt since the late 1940s in northern and central California are most pronounced in moderate-altitude basins, which are sensitive to changes in mean winter temperatures. Such basins have broad areas in which winter temperatures are near enough to freezing that small increases result initially in the formation of less snow and eventually in early snowmelt. A declining fraction of the annual runoff has come in April-June. They noted that weather stations in central California, including the central Sierra Nevada, have shown trends toward warmer winters since the 1940s. A series of regression analyses indicate that the observed decadal-scale winter temperature trends can explain the runoff-timing trends.

Dettinger and Cayan (1995) argue that earlier snowmelt in California may be caused by a trend toward warmer winters in California and a concurrent, long-term fluctuation in winter atmospheric circulations over the North Pacific Ocean and North America. The fluctuation began to affect California in the 1940s, when the region of strongest low-frequency variation of winter circulations shifted to a part of the central North Pacific Ocean that is strongly linked to California temperatures through the Pacific-North American teleconnection pattern (Leathers et al., 1991). Since the late 1940s, winter wind fields have been displaced progressively southward over the central North Pacific and northward over the west coast of North America. These shifts in atmospheric circulation are associated with concurrent shifts in both West Coast air temperatures and North Pacific sea surface temperatures, and with earlier snowmelt and increased spring moisture fluxes in the American River basin.

The investigations into the changing seasonality of flow, temperature, and precipitation were recently augmented by an analysis of trends in snow water equivalent (SWE) in the Sierra Nevada by different elevation zones and months. Johnson (1998) analyzed comprehensive snow course data collected over the last 60 years and concludes that several basins in the region have experienced lower snow water equivalents and earlier snowmelt below an elevation of 2,400 m. There is higher variability in the SWE trends at higher elevations; however, the general trend is for increased SWE and earlier melt.

Trends in Longer Proxy Records

Given indications of low-frequency climatic variability at interannual, decadal, and century scales, insights from long climate indicators are of interest. Long records of hydroclimatic variables in the western United States based on tree ring reconstructions have shown significant interdecadal variations in recent centuries. Although growth is a complicated function of several climatic elements, tree ring reconstructions can provide estimates of annual precipitation, and perhaps even flood occurrence. Earle (1993) reconstructed annual streamflow using tree ring chronologies for several major rivers in California, including the American River. He found that significant prolonged periods of high and low flows have occurred during the last 440 years and that first half of the century (1917-1950) was the driest in the reconstructed record for California rivers. Scuderi (1993) described a 2,000-year reconstruction of seasonal (June-January) temperatures in the Sierra Nevada. He found evidence of a strong 125-year cycle in temperatures (with a peak in the cycle in the late-1900s) that may be related to solar activity.

Meko et al. (1998) have recently used a variety of tree ring series from much of the Central Valley, the central and southern Sierra Nevada, southern Oregon, and far western Nevada to reconstruct year by year estimates of the Four Rivers Index (Sacramento, Feather, Yuba, American streamflow). Statistical models that consistently account for 60-65% of the modern variance can be extended over the last 500 to 700 years, and less accurate models (because there are fewer long tree ring series) can be used back to 700 A.D. The method by which the growth curve is removed (young trees have wider rings) can potentially influence the reconstruction of low-frequency (several decades) variability. However, individual year-to-year variations, of greatest interest here, are hardly affected at all.

Of most interest in the present context are individual wet years (wet enough to have contained a major flood episode). Wet years do not necessarily contain a flood, but dry years probably do not. As previously noted, major Sierra Nevada floods seem to occur in years with modest annual runoff, and seldom or never in the years with the highest annual runoff. The latter years are characterized by very heavy snowpack and extended periods with large volumes of snowmelt-driven runoff. This will be discussed further below under ENSO.

The tree ring reconstructed annual Four Rivers Index for 700-1961 A.D. is presented in Figure 4.7a. Using a 51-year moving window and assuming a log normal distribution, the 0.99 quantile was estimated for the index and is shown in Figure 4.7b. Even though the tree ring flow reconstruction process removes some of the low-frequency variability in the original record, there is evidence of protracted low-frequency flow regimes (both high and low) in these reconstructions as seen through the 51-year moving window.

SOURCES OF SIERRA NEVADA CLIMATE VARIABILITY

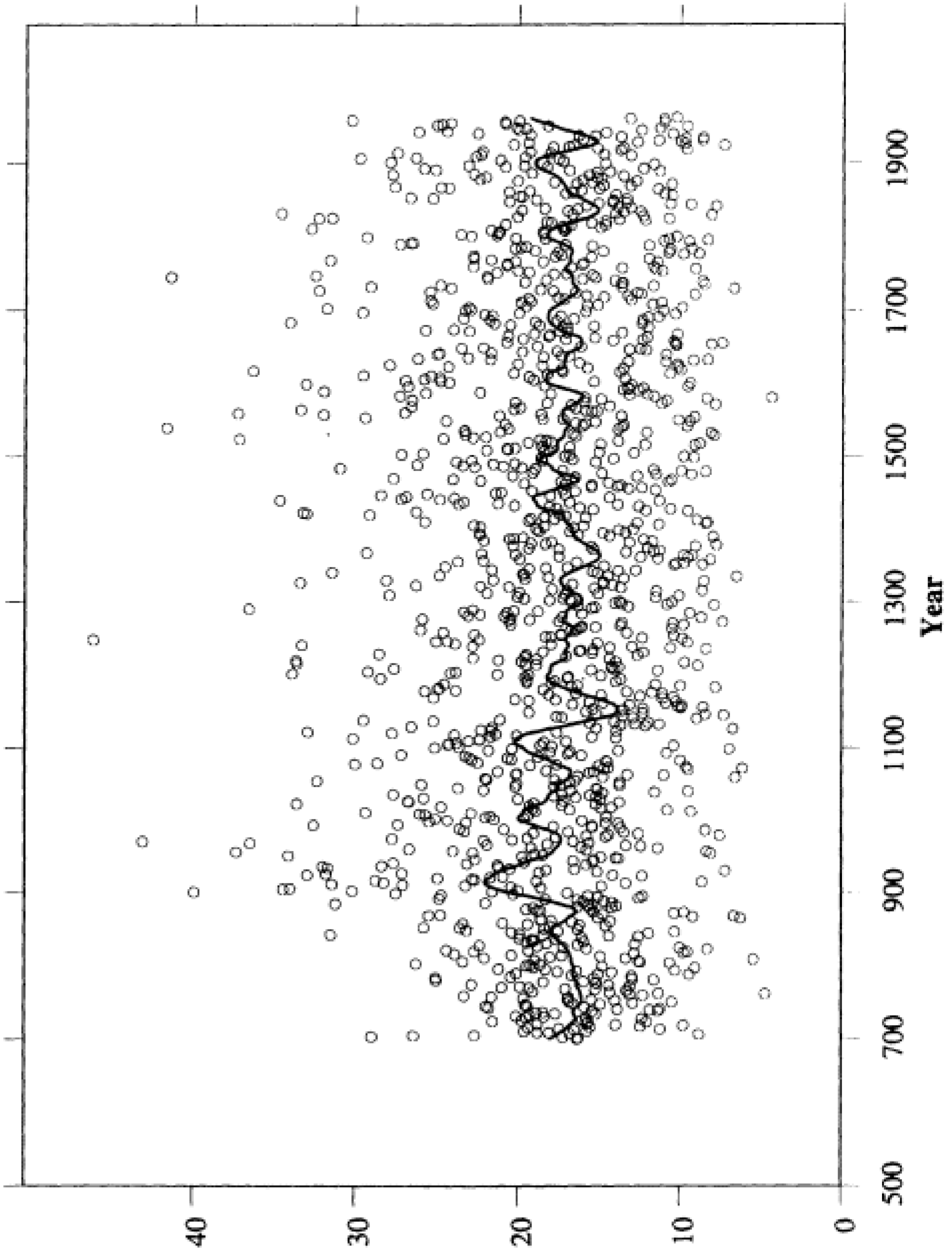
There are many possible physical sources of low-frequency variability of central Sierra Nevada climate behavior. These include quasi-periodic modes of ocean-atmosphere circulation, such as ENSO, as well as considerations related to global climate change due to increases in greenhouse gases and land use. Their importance lies in the way frequencies of atmospheric circulation patterns (e.g., see Figure 4.1 presented earlier) responsible for large winter floods are modified over decadal time scales. Some of them remain plausible but primarily speculative; others we can say more about. These will be addressed next.

El Niño / Southern Oscillation (ENSO)

In the interval between the 1982 and 1983 El Niño and the build-up of the equally large 1997-98 El Niño a great deal was learned about California climate and its relation to El Niño.

El Niño is one of the two major phases of a more complicated irregular cycle, typically lasting three to seven years, during which ocean temperatures within a few degrees of the equator between South America and the International Date Line become warmer than average. The other major phase, La Niña, is characterized by cooler than average ocean temperatures in the same region. Strictly speaking, the terms El Niño and La Niña refer to the oceanic temperatures.

Another signal is seen in the overlying atmosphere. When mid-ocean temperatures are high (El Niño), the surface atmospheric pressure near Easter Island and Tahiti is a bit lower than usual and near Indonesia and northern Australia is a bit higher than usual. At monthly time scales, the atmospheric pressure over large areas centered on these two regions varies in a strongly out-of-phase sense, a nearly global


Four River Index reconstructed
0
10
20
30
40
Year
500
700
900
1100
1300
1500
1700
1900

(a)

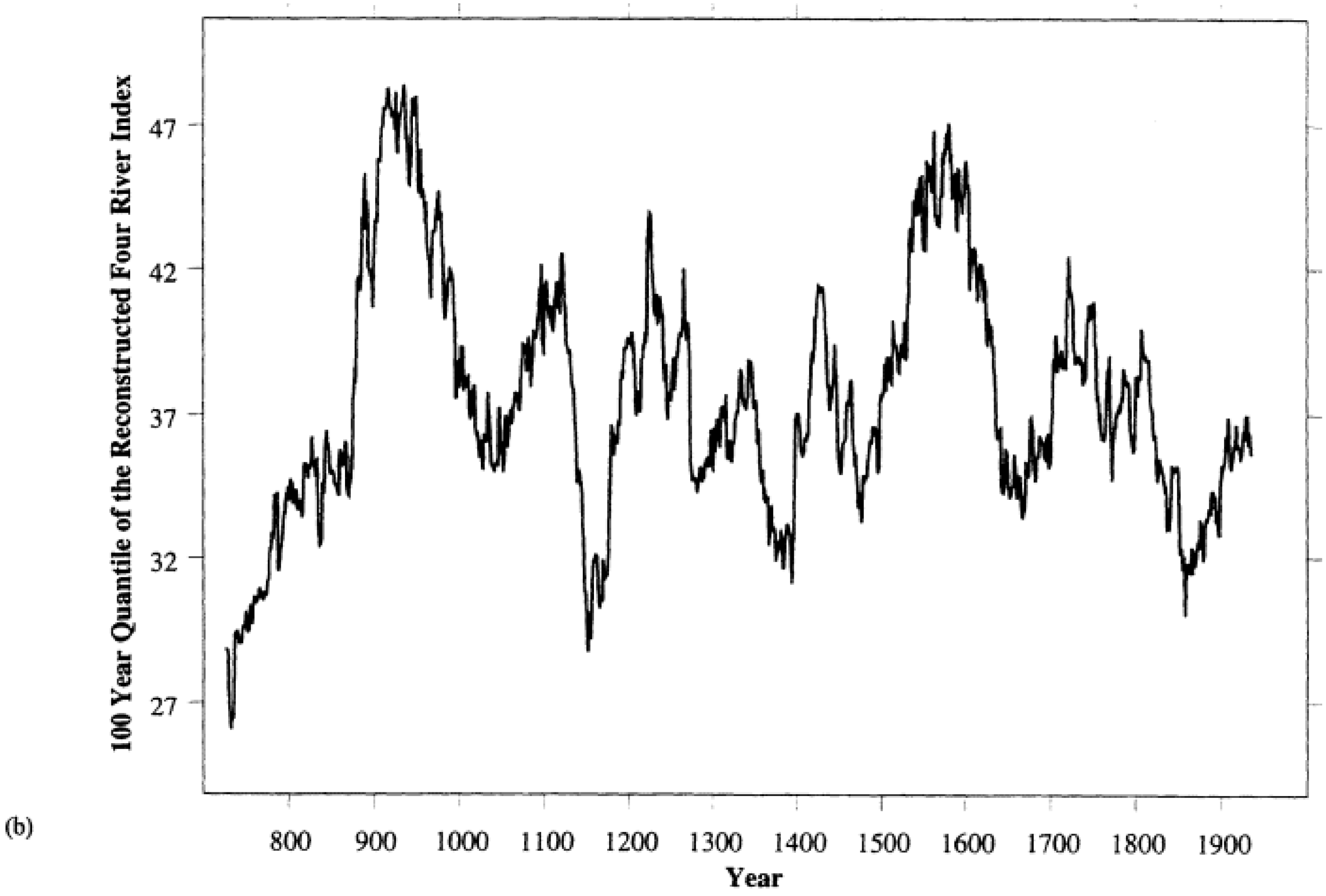


Figure 4.7
(a) Annual Four River Index (Sacramento Basin) reconstructed from tree rings for the period A.D. 700-1961, and smoothed using a 51-year window with linear locally weighted regression (Loess); (b) The estimated 0.99 quantile.

phenomenon known since the 1920s and earlier as the Southern Oscillation. Because this atmospheric oscillation is strongly linked to oscillations in the ocean temperatures in the El Niño region, the two terms are often merged together as El Niño/Southern Oscillation or ENSO.

Western US. and California Climate Relations to ENSO

Studies have shown significant connections between the state of ENSO and the winter climate of the western states (e.g., Schoner and Nicholson, 1989; Redmond and Koch, 1991; Kahya and Dracup, 1993; Dracup and Kahya, 1994; Cayan et al., forthcoming). Wetter winters are more likely during El Niño winters in the southern West, including southern California, but there are exceptions. Drier winters are more likely in the Pacific Northwest with El Niño. Generally opposite patterns are seen with La Niña. The nodal line dividing the two behaviors extends from about San Francisco to Cheyenne, Wyoming. Thus, there is little relation between central Sierra Nevada winter precipitation (Oct-Mar) and ENSO. There are roughly equal numbers of dry and wet El Niño and La Niña winters.

In terms of the asymmetries in the California climate response to El Niño and La Niña there appear to be two exceptions to the overall picture outlined above. The first is that during larger El Niños, the nodal dividing line is found more to the north than during normal El Niños, and the central Sierra region experiences wetter winters. However, these winters tend to be long, cool, and snowy, with few instances of elevated freezing levels. A second exception is associated with the direction of upper air movement and an associated east-west contrast (at the latitude of the American River basin) in precipitation response. In El Niño years the upper air flow extends from the central Pacific north of Hawaii directly to California. This trajectory can deposit abundant snow on the Sierra Nevada without causing large floods and typically brings heavy precipitation to the low-lying coastal mountains, in the form of rain, thus making flooding of coastal streams more likely.

In this regard, it is particularly notable that none of the major floods in the Sierra Nevada over the last century has occurred during El Niño winters. The largest flood in an El Niño year ranks 10th among all floods since 1933 (see Figure 4.8, scatterplot of SOI versus American River floods).

La Niña winters are characterized by a flow regime with greater alternation of north-south movement and more storm systems affecting the Pacific Northwest and northern California. There is strong asymmetry in the response of the overlying atmosphere to tropical sea surface temperatures, and thus in cloudiness, precipitation, and heating of the atmosphere, and thus in teleconnections to and influences upon the mid-latitude jet stream. The convection and moisture sources in the western tropical Pacific are unusually active, and the interaction with equatorial excursions of the jet stream provides a western Pacific connection to the flow that eventually impinges on California. On occasion, southwesterly flows associated with embedded storm systems will tap deep into tropical low latitudes and their abundant moisture. A persistent flow, such as this, of a few days duration is sufficient to bring very heavy precipitation, warm temperatures, and floods to the Sierra Nevada. These situations

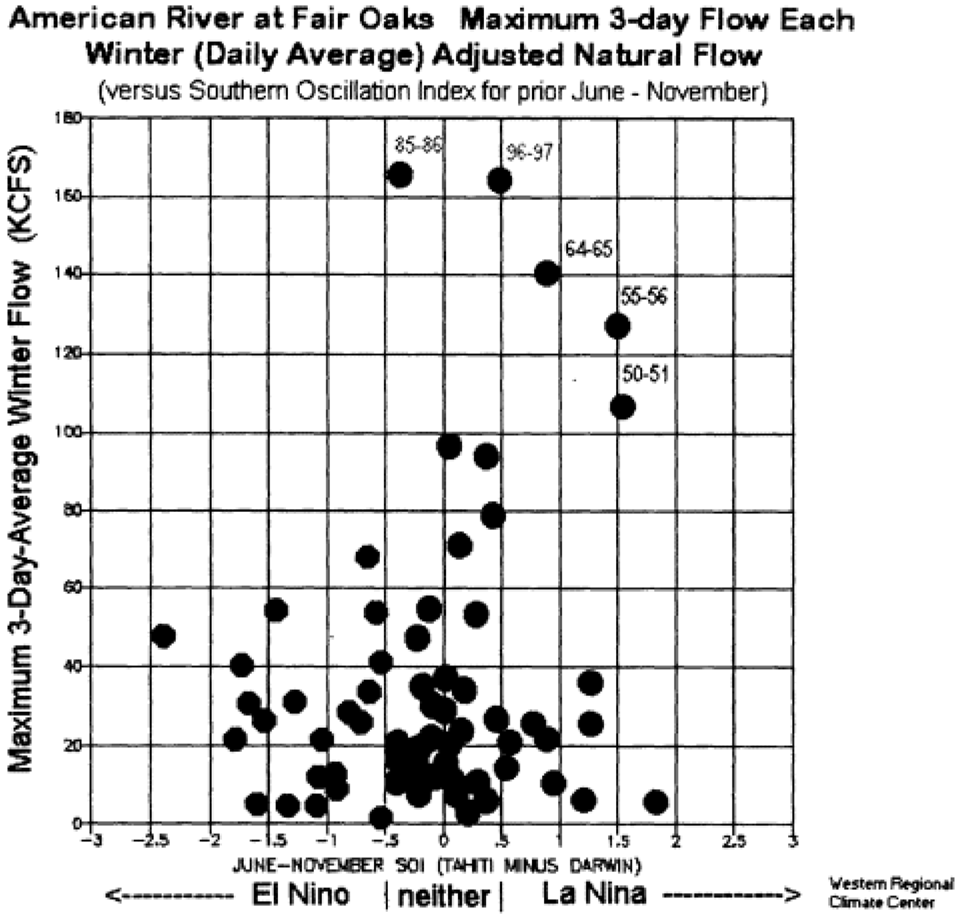


Figure 4.8
Relation between annual maximum three-day flow for the American River at Fair Oaks and the Southern Oscillation Index (SOI) for the preceding June-November. The SOI is a normalized pressure difference of Tahiti minus Darwin (Australia) and is strongly related to El Niño/La Niña.

are not common, and as a rule, flood peaks (highest three-day runoff) in La Niña winters tend to be lower than average on streams such as the American River. However, on the American four of the top five three-day flow events in the last 65 years have occurred during modest to strong La Niña winters (refer again to Figure 4.8). As mentioned before, aside from their flood periods, many of the big flood years are relatively lackluster, even dry; so their water year flows are large but not exceptional. La *Niña* winters appear to have the interesting property that peak flows are likely to be lower than average, but carry an increased risk of producing some of the highest flows in the record. Strong evidence is emerging that heavy West Coast precipitation episodes are related to the so-called Madden-Julian Oscillations ("MJO") seen in the vicinity of Indonesia (Mo, 1999; Mo and Higgins, 1998a, 1998b; Ye and Cho, 1999).

Regimes of El Niño/Southern Oscillation

To the extent there may be a relation between floods and any of the phases of ENSO, such as La Niña, periods of extended predominance of one or the other ENSO phase could affect the frequency of Sierra Nevada floods. The record of ENSO does indeed show such behavior, most notably the period since 1976, when a major shift occurred in the Pacific climate (see Ebbesmeyer et al., 1991; Trenberth and Hurrell, 1994). Since that time El Niño years (negative Southern Oscillation Index) have occurred at a much higher frequency than earlier this century, about nine times in 20 years or one year in 2.2, compared with a historical frequency of about 1 year in 3.7 years. La Niña has been notably scarce since this 1976 shift, with one appearance in 1988-1989, a weak episode in 1996-1997, and a significant episode in the winter of 1998-1999. These ENSO non-stationarities are also discussed by Trenberth and Hoar (1996, 1997), Harrison and Larkin (1997) and Rajagopalan et al. (1997). Trenberth and Hurrell (1994) argue that the duration of the 1991-1995 El Niño event and the increase in the frequency of El Niño events is likely to be an indicator of global climate change. Rajagopalan et al. (1997) use non-homogeneous Markov chains to argue that these changes can be explained as natural long-term variations of the ENSO cycle and may not be dissimilar to the nature of ENSO activity in the late 1800/early 1900s. Lall et al (1998) used a wavelet analysis of the NIÑO3 sea surface temperature index to show that there have been several systematic variations in the dominant return period of ENSO between 1856 and 1997. They also analyzed a 1,000-year sequence from the Cane-Zebiak ENSO model with stationary forcings and found that El Niño frequencies in this deterministic stationary model varied dramatically at century time scales. Several papers (Enfield, 1992; Diaz and Pulwarty, 1992; Lough, 1992; Thompson et al., 1992; and Michaelson and Thompson, 1992) in the volume edited by Diaz and Markgraf (1992) examine the history and statistics of ENSO, by a variety of means, which collectively show intermittency, regime-like behavior, and general non-stationarity on scales ranging from decades to centuries. Mann et al. (1998) has attempted to put the recent El Niños in context by reconstructing their occurrence using proxy records extending back over six centuries. The commentary in studies such as this has tended to focus more on El Niño than La Niña, but the data in some cases do portray both phases.

Pacific Decadal Oscillation

The Pacific Decadal Oscillation as a Potential Modulator of ENSO Effects

Mantua et al (1997) and Hare et al. (in press) have identified a pattern of variability in the Pacific basin and the overlying atmosphere having characteristic time scales of 20-30 years, which they called the Pacific Decadal Oscillation (PDO). The pattern resembles the interannual-to-ENSO time scale variability pattern, but clearly separates out using singular value decomposition of the time histories of a set of fields of oceanic and atmospheric variables. This pattern expresses itself most clearly in the North Pacific, and thus is also referred to by some as the North Pacific Oscillation. One prominent aspect of the PDO is an out-of-phase relationship between the Pacific Northwest of the U.S., and the northern Gulf of Alaska. Streamflow, temperatures, and salmon abundance are clearly linked to this mode of variability over this century (Hare et al, in press).

Mann and Park (1994; 1996) also identified a 16 to 20 year oscillation related to the North Pacific, which oscillation appears to correspond to one identified by Latif and Barnett (1994) using a coupled ocean-atmosphere model. Latif and Barnett's postulated mechanism is that self-sustained oscillations at interdecadal time scales can be set up through the influence of the subtropical ocean gyre on SST anomalies in the North Pacific and a subsequent delayed response of wind stress that spins down the gyre. This mechanism provides a potential for understanding and predicting interdecadal fluctuations in climate and flow in the western United States. Indeed, Lall and Mann (1995) and Mann et al (1995) show that a projection of this mode on to the Great Basin explains a significant fraction of the interannual variation in the Great Salt Lake and is tied to its major highs and lows. The connection of the interdecadal mode identified by these authors to the more diffuse decadal variability identified as the PDO is not clear.

The primary importance of the PDO and other extratropical interdecadal North Pacific climate patterns is that they may modulate the mean position of the jet stream and also of the tropical interaction with the jet stream. Potential ENSO effects could be enhanced or reduced depending on the phase of the longer period North Pacific oscillation. An understanding of these issues would help (a) by allowing proper adaptation to ENSO events at interannual time scales and (b) by providing an understanding of interdecadal tendencies for increased or decreased flood potential. If the PDO is also shown to be associated with the regimes of frequent and stronger or infrequent and weaker El Niño events, additional understanding of regimes of wet and dry periods will result. Finally, an understanding of internal dynamic modes of the climate system with interdecadal time scales and their impacts on floods is essential if the potential effects of secular global climate change are to be sorted out from the last century of record.

Regimes in ENSO Resulting from PDO Decadal Modulation

One of two ways that the PDO could be relevant to central Sierra floods could be its possible modulation of relationship between ENSO and the winter climate of the western United States. Gershunov and Barnett (1998) and Gershunov et al. (1998) have indicated that this may very well be the case. During one phase, lasting a few decades, the strength and robustness of the connection appears to be greater than during the opposite phase. That is, whether or how La Niña or El Niño affects the West Coast would, if these findings bear up, depend on which phase the PDO or the Mann and Park/Latif and Barnett interdecadal oscillation or more generally the state that the North Pacific seas surface temperatures is in. In a very interesting paper, McCabe and Dettinger (1998) have recently examined the temporal characteristics of the relationships reported by Redmond and Koch (1991). They find that the relationship between the Southern Oscillation Index (SOI) and western winter climate has varied considerably over the past 100 years. Currently the relationship is quite good, but earlier in the 20th Century it was much weaker. They also note that the relationship between Pacific equatorial atmospheric pressure behavior (expressed by the SOI) and Pacific equatorial ocean behavior (expressed by sea surface temperatures, SSTs) has similarly varied quite considerably this century. Of relevance to the American River and California, it is likely not a mere coincidence that the SOI-SST relationship was rather weak until about 1950, when it became the much stronger relationship to which we have grown accustomed. McCabe and Dettinger also find a strong modulation of the SOI-SST correlation and of the SOI western climate correlation by the Pacific Decadal Oscillation. This lends further support to the idea that large-scale changes in Pacific Basin climate behavior, and in its relation to Pacific Rim locations, took place about 1950. These findings are quite intriguing. Of particular note, if this is related to "regime" behavior rather than secular global change trends (below), then the possibility exists to return to a prior regime, i.e., the one that existed during the first part of this century.

Other Potential PDO Effects Not Involving ENSO

The second way that the PDO could be relevant to central Sierra floods could be by modulating other connections, not related to ENSO, between the North Pacific and the Sierra Nevada. By contrast with the tropics, the ocean and the atmosphere drive each other more equally in the higher latitudes, on scales of a few weeks, and it is nearly impossible to say anything specific about the implications for the Sierra Nevada. Because ENSO accounts for only a modest fraction of the year-to-year climate variability in the West, there must be other sources of variability, and the conditions in and over the Gulf of Alaska would be a strong candidate for an additional influence. Much more remains to be learned about potential connections there. It seems almost certain that any such connection would involve the deep ocean.

Other Potential Natural Influences on California

The earth's climate system is extremely complicated. In the fullest sense, climatic behavior at any given location and over any significant span of time (e.g., a few decades) is determined by processes involving the earth's biological organisms, its frozen water, volcanic activity, astronomical factors, solar output, radiatively active components in the atmosphere, ocean behavior from top to bottom, as well as a host of positive and negative feedbacks involving clouds, precipitation, adiabatic heating and cooling, flow dynamics, and more, with numerous thresholds at which subcomponent behavior changes radically (e.g., freezing, convection), all interacting in highly nonlinear ways. For an engaging popular discussion of this subject, see, for example, Bak (1996). In such a system it would not be surprising if internal feedbacks operating through a multiplicity of links could contribute to the variability observed at any one point of interest. In fact, the absence of variations resulting from internal dynamical processes would be a major surprise. A consideration of the variety of external forcings interacting with a variety of complicated internal interactions and feedbacks led Bryson (1997) to state unequivocally that "the history of climate is a non-stationary time series."

A frequently cited example of a "remote" and large-scale influence is the thermohaline circulation of the world's oceans. Temperature and salinity both affect the density of sea water, spatial and temporal variations of which produce horizontal and vertical accelerations and motion at all depths. These factors, in concert with fluxes of heat, moisture, and momentum across the water-atmosphere interface, affect the circulation of the atmosphere (e.g., Cayan and Peterson, 1989; Cayan, 1992). Because of the small speeds and large time constants involved, oceanic influences on climate can have time scales from days to about a millennium. Manabe and Stouffer (1996, 1997) have used the results of very long simulations to argue that General Circulation Model (GCM) runs of nearly a thousand years are needed to properly understand the role of natural variations and internal feedbacks affecting ocean circulation, and thus by implication effects on terrestrial climates. Broecker's notion (1987, 1991) of a global linkage among the world's oceans driven by temperature and salinity differences (an aspect of the thermohaline circulation dubbed the "conveyor belt") has attracted wide attention. Though the ocean is regarded as slow and ponderous, gradual processes could bring conditions to near thresholds, where behavior changes suddenly. Ice cores from Greenland (e.g., Mayewski et al. 1993a, 1993b) are showing that major circulation changes in, for example, Gulf Stream position may occur in less than a decade; perhaps in just a few years atmospheric adjustments would be seen over the entire hemisphere.

GLOBAL CHANGE ISSUES

To this point only the natural variations in climate have been addressed. During the last century the human population has increased to the point where its activities can significantly alter the flow of radiation in the atmosphere. Although much of the focus has been on temperature, the realization has been slowly growing that other significant climatic adjustments to the altered radiation regime may be expressed in the hydrologic cycle. A general conclusion is that global evaporation and precipitation will proceed more energetically and that water will cycle through the system faster. This implies that large precipitation rates will be more common. Climate change, whatever the cause, almost never affects all locations and seasons equally, and these details cannot be resolved at the current level of understanding.

Hydrologic modeling studies for California by Lettenmaier and Gan (1990), Lettenmaier and Sheer (1991), and Tsuang and Dracup (1991), all indicate that similar temperature increases (e.g., those predicted by GCMs under global change scenarios) would cause changes in streamflow timing and increased flooding, primarily due to increases in the rain-to-snow precipitation ratios. These conclusions are clearly of concern in light of the changes in seasonality and extreme floods noted earlier. A brief perspective on the global climate change debate is provided here.

All the various natural mechanisms that can potentially cause climate fluctuations on annual to century scales are considered to be capable of producing both positive and negative contributions to climate forcing at one time or another. With respect to human-induced changes in climate forcings, especially the radiative forcings associated with atmospheric composition changes, a widely held view is that such temporal trends are unidirectional and unlikely to change course in a century or two. Partly on the evidence of modeling experiments, it is likewise widely held that a steadily increasing forcing will also lead to a steadily increasing response. Of course, in finite physical systems, no component can increase forever without limit, but it can appear to do so within a limited range of forcing. Unfortunately, modeling experiments pertaining to global climate change do not have a realistic representation of known low-frequency ocean-atmosphere interactions and their treatment of the hydrologic cycle is also relatively primitive. Given the importance of water vapor as a greenhouse gas and also its role in the atmospheric energy balance, a better understanding of the radiative nature of clouds and the movement, organization, and precipitation of atmospheric water vapor is needed.

It is possible that the response will be stepped, as a series of plateaus; or will have different seasonal signs that are influenced by the background state; or sometimes will even be in this direction, sometimes in that, as planetary adjustments in the mass fields and flow of the two major fluids—water and air—take place. In light of the possibility that long term natural variations in climate occur, the global climate change response in this area may occur as a change in the frequency distribution, strength, and recurrence of these regimes. Such changes will of necessity be at longer time scales than the recent record. Thus, an unambiguous detection of global change and its impacts is unlikely unless the changes are altogether dramatic. Definitive answers to these questions are not expected anytime soon.

Essentially, the problem facing flood managers, engineers, and everyday citizens in this situation amounts to making *a forecast* for the next several decades of what the flood statistics will be and then acting on that forecast. Aside from recently introduced human-induced or human-enhanced factors, the remaining natural mechanisms for climate change have been operating all along, have been "seen" before, and have been either directly measured or otherwise recorded in the proxy evidence. The human factors are new, may have unidirectional effects, and may carry system behavior beyond bounds it has not exceeded for some time.

When humans look at time series, there is a universal tendency to extrapolate any type of trend discerned in the latest points linearly out into the future. In a natural system it is widely realized that eventually this expectation will prove incorrect. With global climate change there is a possibility that, within the useful lifetime of a prediction (say, a century or so, by which time the entire matter of how humans interact with rivers will almost certainly have been completely re-thought), this linear extrapolation might be correct. If this logic is correct, flood frequency curves may edge closer to or enter territory not seen during Sacramento's history. Moreover, there still remains the possibility that natural variations of larger amplitude, not observed during the few centuries of recorded settlement, could also occur (or recur). Of the various mechanisms for climate change facing us in the near term, the human-induced global changes appear to have the greatest likelihood of taking us to this point.

Just as a cautionary note, it is worth pointing out that like carbon dioxide, the optically active gas methane—which contributes about 15% of the enhanced greenhouse effect—was also expected to continue to rise steadily in concentration well into the next century; however, in a major surprise, the concentration began to increase less rapidly in the early 1990s, and by 1996 had essentially leveled off (Dlugokencky et al., 1998). This holds important lessons about how we should regard even our "safe" assumptions.

It is also worth noting that for short time periods—a few decades or centuries—naturally occurring fluctuations would masquerade as "trends," especially with the short records we possess. When we are sensitized to the prospect that our activities may lead to global or regional climatic changes, we are more likely to find such trends, and to interpret them as evidence of the hypothesized effect. The hard question, one very difficult to answer, is "what would the natural system have done otherwise?" We are a long way from answering this. In climate change research, this problem is known as the attribution problem, in contrast to the other two main pieces of the puzzle: the detection problem and the prediction problem.

In addition to greenhouse gas concerns, a body of literature is emerging (see, for example, Chase et al., 1996; Pielke, 1991, 1998, In press, and references therein) showing that land use changes—on local, regional, and global scales—are a significant factor in causing actual and potential climate change—again at local, regional, and global scales. Changes in land use modify flows of energy in substantial ways. The climate system adjusts to these energy flow changes by changing its circulation patterns. The atmospheric adjustments are both local and remote. This area of climate change research is beginning to receive a substantial amount of attention.

Recent climate modeling experiments by these investigators (e.g., Chase et al., 1996) show that the observed changes in land use around the earth during this century (with no change in greenhouse gasses) are sufficient by themselves to produce regional circulation and surface temperature responses of the same magnitude as the changes that have been projected for changes resulting from greenhouse gas increases. In such regions as western North America worldwide land use changes in these preliminary experiments lead to temperature increases on a par with those observed in the Sierra Nevada winter over the last several decades.

There is no simple pattern to global land use changes over the last 100 years, and the patterns of land use change are themselves changing. Although it is not clear whether the earth as a whole will warm or cool from such changes, the way the climate response (temperature, precipitation, and snowfall) is distributed in space and by season and altitude could be very complex. Because of the highly nonlinear nature of this system, climate changes that result from land use changes will not necessarily have to exhibit monotonic trends. Model performance will need to improve still further before specific results can be accepted without question. For now, the conclusion that land use effects can rival other sources of variability is sufficient.

Unfortunately, these long-term trends in land use are taking place while greenhouse gases and atmospheric sulfate aerosol emissions are also changing. There is as yet no way to separate out their effects, and it is not clear if additive (linear) approaches are even appropriate (see, for example, Hanson et al., 1997; Hanson et al., 1998). These instructive and sobering studies have increasingly led to a reluctant acceptance of the possibility that our ability to provide useful climate change predictions may stay barely ahead of the actual progress of time, if at all.

SUMMARY

Non-stationarity in the flood process can come from naturally structured, low-frequency climate variability; from human changes to the watershed (e.g., hydraulic mining, subsidence, urbanization, land use, and vegetative cover); or from watershed influences on the large-scale climate system (likely minimal in this case). There is evidence of significant changes in land use and surface attributes of the American River basin over the last two centuries. Trends are evident in basin land use and surface attributes, as well as precipitation and other climatic elements, particularly the incidence of extremes. A context for understanding these trends in terms of climatic mechanisms has been provided above. Global climate change concerns related to greenhouse gas emissions over the last century may also be considered as a plausible factor in changing flood frequencies. The contribution of structured, oscillatory, interannual- to millennial-scale climate variability to changing flood potential in the region is also of considerable interest. The latter may represent the behavior of a nonlinear dynamical system that exhibits unstable oscillations or close returns of a trajectory that appears periodic. Such a system would have stationary dynamics, but a finite period of record may exhibit apparent non-stationarity in terms of the statistics.

Key implications of these observations are:

(1) Given trends, persistence or memory in the system, the true variability of the flood process could be substantially higher than that estimated from a finite period of record. In other words, the uncertainty in the estimate of the T-year flood is higher than that indicated by a method that considers the n years of record to

represent a stationary, independent identically distributed stochastic process. The latter is the standard assumption for flood frequency analysis.

(2) Record high and low floods are likely to be clustered over extended periods of years, if the underlying climate system is slowly oscillating. Thus, the pre-and post-1950 segments of the American River flood record are plausible members of trajectories of the same stationary dynamical system. As the underlying climate state changes slowly, the flood potential, as well as the timing and causative mechanisms undergo systematic structural changes. This leads to the question of whether a single probability distribution is an appropriate descriptor of the flood process, and whether the frequency curve should be bent at one end, or whether low and high floods should be modeled by the same distribution. Censoring, mixed distribution models and non-parametric flood frequency estimators are commonly offered as solutions to this problem. However, all these methods assume that the underlying process is independent identically distributed. Consequently, the resulting flood frequency estimates will be reasonable only if our flood record extends over an adequate number of the underlying cycles and if our planning horizon is infinite in the future.

(3) Unless the quasi-oscillatory climate behavior is predictable over the next 5 to 30 years, and unless that information is used for modifying the underlying flood frequency curve, the independent identically distributed procedures used may lead to an apparent bias in the flood frequency curve, as seen in the pre- and post-1950 period for the American River. Unfortunately, neither the understanding of the complexity of the underlying dynamical system nor the technology for such interannual to century scale predictions (see, however, Rajagopalan et al., [1998] and Lall et al. [1996]) is currently available. Consequently, the risk of being wrong about the estimate of the flood frequency curve remains higher than anticipated by the standard analyses.

(4) The use of paleodata spanning centuries or millennia is often offered as a tool for improving flood frequency estimates in conjunction with a probable maximum flood analysis. Such information, if untainted by anthropogenic effects and derived accurately, is potentially very useful for refining the flood frequency estimate for "steady state" future conditions. This may or may not be reasonable, as our understanding of cyclic climate variations at century to millennia time scales is still very much in its infancy. In a Bulletin 17-B setting, where a guideline for steady state flood prediction is of interest, the recent few centuries of reconstructed data is likely to be useful at least for providing a context for interpreting the flood record of the American River over this century.

The committee's summary recommendation is that its understanding of climate variability suggests that (a) the uncertainty of the flood frequency estimates is higher than indicated by the usual statistical criteria, (b) climatic regime shifts may—slowly or abruptly—significantly affect the local flood frequency curve for protracted periods, and (c) at this time, given the limited understanding of the low frequency climate-flood connection, the traditional independent identically distributed approach to flood frequency estimation is recommended with the strong caution that the application of such a curve is likely to lead to significant biases or variability over any period of time. A more conservative design criterion as well as adaptive flood control measures in addition to structural flood control may therefore be appropriate.

Recognition of the non-stationary nature of climate dynamics should motivate society to replace the existing static flood risk framework with a dynamic one. The existing static flood risk paradigm considers the estimation of a single flood frequency distribution from all available historical, regional, and paleoflood data and the application of the estimated distribution for an indefinite future period. A dynamic risk paradigm would call for the evaluation of potential flood risk over the duration of project operation, and/or a regular flood frequency updating procedure. Adaptive flood control and design strategies would be favored under this paradigm. Given the usual paucity of flood data, the interest in extreme (1% annual risk) floods, the limited ability to forecast climate statistics into future planning periods, and the weak understanding of the connection between slowly-varying climate factors and the at-site or regional flood process, it is beyond our ability at the present time to implement practical dynamic flood risk models. However, research in various areas is needed to address these important issues. New diagnostic, prognostic and decision frameworks need to be developed.

First, investigations of the nature of flood risk variations in the historical record and their connections to low frequency climate variability are needed to establish the nature and sensitivity of the at-site or regional flood process to key climate indicators or factors, to provide a context for understanding the apparent changes in flood risk as seen in the American River, and to assess the need to consider climate induced flood non-stationarity in the decision process. Given the potential for anthropogenic climate change, and ongoing research on its prognostication, it is important to assess the specific ocean-atmosphere. state variables that are useful predictors of flood risk, and their spatial signature in the regional flood process. A causal, hypothesis-testing framework may be useful for such analyses. Identification of the sensitivity of flood risk to identifiable, changing (and predictable) climate indicators will be useful for decisions on whether a dynamic risk framework is useful. Such analyses also have implications for changing regional flood frequency estimation methods. At-site flood records used for regional frequency curve estimation can often have widely varying periods of record. Recognition of quasi-periodic and monotonic trends in climate factors influencing floods behooves stratification of these records by "climate epoch" prior to the estimation of regional frequency curves. An examination of the spatial structure of the regional flood risk relative to the climate state may also be useful. For small basins where flood risk is determined by local thunderstorms, regional information for several decades could be quite useful. For large basins (such as the American River basin) where flood risk is determined by very large regional storms, regional information extracted using traditional methods may be of limited value. These large regional storms have preferred tracks that can be related to seasonality and to identifiable slowly varying ocean temperature (and associated atmospheric) conditions. There may hence be prospects for relating low-frequency climate variability to regional storm frequency and severity and hence to floods. Conditioning basin and regional flood process on ocean-atmosphere teleconnections using the century long records available may be more fruitful in this context than "pooling" available regional flood data. A statistical characterization of the connections between ocean-atmosphere variability at interannual to decadal time scales and the frequency of the annual maximum flood in the region is needed. This relationship, coupled with "beliefs" as to scenarios for future climate derived from an analysis of the historical and paleoflood record and coupled general circulation models of the climate system, may be useful for assessing scenarios for future flood risk. A framework for formally conducting such analyses to better estimate potentially changing flood frequency distributions and their uncertainty is needed.

Second, a framework is needed for decision analysis on flood management that explicitly considers the dynamic risk and its estimation uncertainty. Clearly, such a framework needs to consider both the length of the planning period over which the projected flood risk will be used and the reliability with which the risk can be estimated from available information. Such a framework may be developed considering a "bias-variance" tradeoff or considering related explicit economic consequences. Consider first a monotonic trend in the annual maximum flood. In this case, one may be tempted to use the last 10 years of record to estimate the 100 year flood for the next 10 years (the planning period). One would reduce bias, but there would be tremendous uncertainty in risk estimates because the record is so short. If instead one had employed a 200-year period of record to project the flood risk over the next 10 years, then the bias in flood risk is likely to be larger, while the variance of flood risk estimators should be reduced. The magnitude of the expected shift (i.e. the projected bias) in the estimated 100 year flood over the next 10 years, and its economic consequences, relative to the increased uncertainty of estimate of this flood, would determine whether the shorter record is used. This answer may well be different if a 50-year planning period were considered. The bias would be larger, as would the uncertainty associated with projecting the monotonic trend into the future. This situation is complicated if quasi-periodic climate variations are considered. For instance, if a 20 year periodic climate variation were considered, using the last 10 years of record to project flood risk for the next 10 will increase both bias (as one goes from the high to the low phase of the oscillation) and variance of estimated flood risk. Explicitly conditioning the flood risk estimate on climate state has an effect similar to the selection of a subset of years of the record as discussed above. The use of such a conditional probability statement would attach higher weights to floods in years with climate state similar to the one projected and lower weights to other floods. This reduces the effective sample size used for flood risk estimation. Thus, the "conditional risk estimation" framework needed needs to consider length of record, length of planning period, the nature of the climatic non-stationarity and causal relations between the climatic factors and the floods. The utility of paleoflood and proxy climate data could be evaluated in the same framework.

5

Summary and Recommendations

RECOMMENDED FLOOD FREQUENCY DISTRIBUTION

Based on consideration of the available data and consistent with Bulletin 17-B guidelines, the committee recommends the use of the flood frequency distribution given in Table 5.1 for estimation of quantiles and exceedance probabilities of three-day rain flood flows on the American River. Note, however, that this recommendation is made for annual exceedance probabilities greater than 1 in 200. For smaller exceedance probabilities, the committee believes there is compelling evidence that the true probability distribution flattens. If it is necessary to extrapolate the distribution for smaller exceedance probabilities, the recommended distribution provides a basis that is consistent with Bulletin 17-B. However, in view of the possibility that the true distribution flattens, other estimation approaches should be investigated.

Our recommended distribution is based on the systematic record of three-day rain flood flows estimated by the USACE from the USGS flow record for Fair Oaks, and upon the historical record for 1848-1904 which included an estimated large three-day flow associated with the 1862 historic flood. Based on several independent analyses conducted by the committee and the USACE, the committee conclude that the three-day rain flood record is an accurate representation of the magnitude of the flood flows over the period of record and that the observed increase in frequency in large floods since 1950 is not an artifact of the method by which flood peaks were computed. The estimate of the three-day flow associated with the 1862 flood is based on the use of an instantaneous peak flow estimated by Bossen (1941) and a regression model developed by the committee. In its frequency analysis the committee assumes that this flow was the largest three-day flow in the historic period from 1848 to 1905.

The committee used the Expected Moments Algorithm (Cohn et al., 1997) to fit a log-Pearson type III distribution to the systematic and historical data, assuming a fixed skew of -0.1. The skew is based on a weighted average of a regional skew (-0.1) and the sample skew (-0.06). The committee estimated the regional skew by averaging the sample skew of the log three-day flow series from seven rivers on the west slope of the central Sierra Nevada. The Expected Moments Algorithm matches log space sample and population moments, and hence is consistent with Bulletin 17B. However, it makes more effective use of historical and paleoflood information than does the weighted moments method recommended by Bulletin 17-B. Approximate confidence intervals were estimated by Monte Carlo simulation.

TABLE 5.1 Summary of Three-Day Flood Quantile Estimates for the American River at Fair Oaks Using the Expected Moments Algorithm (EMA)[a]

Data and Assumptions:	
Systematic Observations:	1905 - 1997
Historical Period:	1848 - 1904
Historical Flood	1862; 147,000[b]
Upper Bound for Remainder of Historical Period	147,000[b]
Paleoflood Observations:	not included
Estimated Distribution Moments:	
Log(10) Mean:	4.3329
Log(10) Std. Deviation:	0.4149
Log(10) Skewness Coefficient:	-0.1000
Estimated Three-Day Mean Flood Quantiles and 90% Confidence Intervals[c]:	
Q_{10} ($P_{exceed} = 0.10$)	72,500 cfs (60,000 cfs; 88,000 cfs)
Q_{20} ($P_{exceed} = 0.05$)	101,000 cfs (81,000 cfs; 126,000 cfs)
Q_{50}($P_{exceed} = 0.02$)	145,000 cfs (109,000 cfs; 192,000 cfs)
Q_{100}($P_{exceed} = 0.01$)	185,000 cfs (131,000 cfs; 257,000 cfs)
Q_{200}($P_{exceed} = 0.005$)	230,000 cfs (154,000 cfs; 338,000 cfs)

[a] Flood quantile estimates are based on rain floods only.

[b] Corresponds to estimated 1862 three-day mean Q.

[c] Based on the LPIII fitted using a log skew of -0.1 to the systematic record and the historical record from 1848 that included the historical 1862 flood.

Sensitivity analysis using the recommended approach indicates that censoring below various flows with exceedance probabilities ranging from about 0.94 to 0.31 does not significantly affect the estimated distribution.

The committee chose not to apply the expected probability adjustment to the distribution obtained by application of the expected moments algorithm.

In developing the recommended flood frequency distribution, it was decided not to use paleoflood information recently obtained by the U.S. Bureau of Reclamation. Use of the paleoflood data implies that the log skew is much more negative, and as a result when the paleoflood data is used with the systematic and historical data, the resulting fitted log-Pearson type III distribution does not provide an adequate description of the flood flow frequency relationships for floods with exceedance probabilities from 0.5 up to and beyond 0.002.

BEYOND BULLETIN 17-B

While its preferred estimate of the frequency distribution of three-day rain flood flows on the American River is consistent with the systematic and historical data, the committee is uncomfortable with extrapolating it much beyond the flow with an exceedance probability of 0.005. Use of the recommended distribution to estimate the exceedance probabilities of two recent PMF estimates yields values that are relatively high, suggesting that for very large flows the upper tail of the "true" distribution flattens relative to the upper tail of our preferred estimated distribution (The term "flattens" refers to the flood distribution as plotted in Figure 3-3.). The paleoflood information supports this conclusion; however it was decided not to use the USBR paleoflood information to extrapolate the frequency distribution of three-day volumes beyond an exceedance probability of 0.005 because the committee was uneasy about climate variability during the 1,350- to 3,500-year period for which there is a paleoflood record given the present understanding of likely global climate variations over that period.

To further explore the extrapolation issue, the committee developed a partial duration series of basin average precipitation. An exponential fit to this series crossed the recommended fit to the three-day flow series, clearly an impossibility. While it is possible that the fitted precipitation series is the source of the problem, it seems more likely that the upper tail of the flow distribution flattens. Using the estimated distribution of average basin precipitation and a simple regression model of the rainfall-runoff relationship, the committee estimated a three-day flow distribution that flattens in response to the constraint imposed by precipitation. While this estimated distribution is based on incomplete data and simplifying assumptions, the general approach should be explored as a potential method of extrapolating the flood frequency distribution.

The committee did not have time to develop a recommendation regarding extrapolation of the frequency distribution beyond the flow with an exceedance probability of 1 in 200. This is clearly an area in need of research. One complicating factor is the observed post-1950 increase in large floods.

POST-1950 INCREASE IN FREQUENCY OF LARGE FLOODS

There is little doubt that the observed frequency of large floods on the American River is much greater in the period from 1950 to the present than it was in the period from 1905 to 1950. Based on the present understanding of climate dynamics, it is not possible to assess the relative contribution of natural and anthropogenic factors to this observed increase. More importantly, it is not possible to predict its likely persistence in time. The committee is very uncomfortable with this situation, but it has little choice given the absence of information. However, even if the post-1950 increase in large floods is due to natural climate variations, Sacramento and the surrounding areas face a severe flood risk. If the increase is due to anthropogenic factors, the already high risk increases.

IMPLICATIONS FOR FLOODPLAIN CERTIFICATION

Based on the USACE 1998 100-year flood estimate, the Federal Emergency Management Agency (FEMA) issued new floodplain maps for Sacramento. As a result of these new maps, most of the floodprone areas of Sacramento were classified as being in the so-called AR zone. Generally, this designation would have resulted in building restrictions and higher flood insurance rates. In this case, FEMA waived the increases in flood insurance rates, but enforced the building restrictions.

If adopted, the 100-year flood estimate recommended by this committee may result in removal of the floodprone areas of Sacramento from the AR zone. This would result in suspension of the building restrictions.[1] It would also likely reduce the political pressure to achieve a solution to the acute flooding threat facing Sacramento.

If the 100-year flood estimate does indeed imply that floodprone areas of Sacramento along the American River levees are not in the 100-year floodplain, it will be by the thinnest of margins. Because the uncertainties in this estimate are so large, the evidence that these areas are not in the 100-year floodplain is far from compelling. In fact, there is about equal evidence that these areas belong or do not belong in the 100-year regulatory floodplain. The worst consequence of falsely designating such floodprone areas to be in the regulatory floodplain would be the requirement for building restrictions that in the future may prove unnecessary. The worst consequence of falsely designating such floodprone areas to be out of the regulatory floodplain would be a prolonged delay in solving acute flood problems, a delay that could have catastrophic results. Given the gross inequality of these two consequences, the committee strongly recommends that authorities consider the situation carefully and the large uncertainties in the estimated 100-year floods, and attempt to develop a flood risk management strategy that addresses the significant risk of flooding in Sacramento.

RESEARCH NEEDS

Flood frequency analysis has been practiced for nearly a century and has seen significant developments in both technological and sociopolitical contexts. Despite progress, much remains to be learned. This improved understanding will be problematic when new knowledge and methods are proposed to be incorporated into nationwide guidelines, such as Bulletin 17-B. In particular, it will raise questions as to whether previously completed flood frequency analyses need to be revised and whether such revisions would significantly change the boundaries of regulatory floodways and floodplains. In this context, one needs to be careful to distinguish between changes in flood frequency curves occasioned by the collection of additional data and those caused by changes in methods of data analysis and prediction. From a scientific point of view, both types of changes should be expected as data bases grow and knowledge advances, but the latter type of change is much more difficult to deal with from a sociopolitical point of view. In effect, to what extent should sociopolitical issues resisting change overshadow advances in scientific methodology and vice versa? How can a compromise be reached and how can it be implemented

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[1] The 100-year flood estimate recommended in this report is for unregulated maximum average three-day rain flood discharges at Fair Oaks. Floodplain designation in Sacramento is based on the 100-year regulated annual maximum instantaneous discharge in Sacramento. Determination of the latter requires modeling of the hydrology and hydraulics of the river and associated flood-mitigation systems.

without thwarting the goal of national consistency underlying the genesis of Bulletin 17-B?

Answers to such questions will require both scientific study and informed public debate. As was pointed out by the NRC Committee on Flood Risk Management in the American River Basin, the need for future research and issue resolution should not be used as an excuse for inaction now. While that committee's comment was directed specifically to the American River situation, this committee believes that the ongoing needs and opportunities being experienced by Sacramento suggest that the time is ripe to begin to seriously reassess policy and strategies for flood risk assessment and management not only for the Sacramento case but for the nation as a whole. For example, a similar issue has arisen in Tucson regarding temporal changes during this century in both the frequency of floods, and changes in the relative contributions by different members of the population of generating mechanisms (Webb and Betancourt, 1992).

The committee recommends the establishment of a new interagency research effort focused on flood risk assessment and management. The impetus for such action is clear: rising property damages and loss of life; 30 years of experience with the National Flood Insurance Program; aging federal policy and technical guidance; improvements in scientific methods of computing and modeling; emergence of understanding of paleohydrologic and climate variability issues; and a growing data base and availability of information. Virtually all of these issues have arisen in the Sacramento case, and can be expected to arise in others as well.

It is envisioned that this recommended interagency effort will emphasize research programs oriented towards coordinated flood risk reduction, including meteorologic, hydrologic and hydraulic, and policy and socio-economic aspects of flood management. Participating agencies should include such entities as the U.S. Geological Survey, the National Weather Service, the Federal Emergency Management Agency, the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the Tennessee Valley Authority, the Federal Energy Regulatory Commission, the National Science Foundation, and appropriate state, regional, and local agencies. Participation, in perhaps an ex-officio role, might also be considered for the academic community through a periodic rotation system.

In their deliberations, committee members identified a number of specific issues that should be addressed by the recommended interagency effort. These issues are summarized below:

(1) Enormous progress has been made in the analysis of flood data since the last major revisions were made to Bulletin 17-B. This progress has largely involved regionalization and the collection and use of historical and paleoflood data. In addition, a number of methods have been developed to handle mixed distributions, including aggressive censoring. These and other innovations in flood frequency analysis should be considered in a revision of Bulletin 17-B.

(2) A very strong research need is to better understand interannual to century scale climate variability as it relates to the potential for winter/spring floods in the American River basin and surrounding areas. This of course is a major undertaking by the earth science community. As indicated in Chapter 4, a framework for

formally conducting such analyses to better estimate potentially changing flood frequency distributions and their uncertainty is needed. Historical and paleoclimate and hydrologic data as well as future model projections would need to be integrated in this framework. Efforts should be continued to develop more detailed, comprehensive and systematic documentation of all major and significant floods, as part of a national database on floods. These efforts need to tie in information on ocean and atmosphere circulation conditions to the information on floods.

(3) A decision analytic framework that uses information as to the uncertainty of the flood frequency estimates explicitly in the analysis of the design level of flood protection is also needed. Dynamic and static risk analyses as discussed in Chapter 4 may be needed. Such a framework would consider the length of the record, climatic factors, the length of the planning period, an implicit long range climate forecast associated with this period, considerations of risk and estimate uncertainty, and a prescription of how the decisions could be periodically re-evaluated.

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Appendix

Biographical Sketches of Committee Members

KENNETH W. POTTER, *Chair,* is a professor of civil and environmental engineering at the University of Wisconsin, Madison. His teaching and research interests are in hydrology and water resources, including hydrologic modeling, estimation of hydrologic risk, estimation of hydrologic budgets, watershed monitoring and assessment, and hydrologic restoration. Dr. Potter has served on many NRC committees and was vice chair of NRC's Committee on Flood Control Alternatives in the American River Basin. He received his B.S. in geology from Louisiana State University and his Ph.D. in geography and environmental engineering from Johns Hopkins University.

SANDRA O. ARCHIBALD is an associate dean and associate professor of public affairs and planning at the Hubert H. Humphrey Institute of Public Affairs, University of Minnesota. Her primary research interests are in productivity analysis and measurement with a focus on the social costs of technology and the design of effective environmental policies. She has served on several NRC committees, including most recently: the Committee on Valuing Ground Water and the Committee on Research Opportunities and Priorities for the Environmental Protection Agency. Dr. Archibald received B.A. and M.S. degrees in public policy from the University of California, Berkeley, and M.S. and Ph.D. degrees in agricultural economics from the University of California, Davis.

DUANE C. BOES is a professor of statistics at Colorado State University. His principal research interests include stochastic modeling and time series analysis of geophysical phenomena, statistical inference, and reservoir and storage theory. Dr. Boes received a B.A. at St. Ambrose University, and his M.S. and Ph.D. degrees from Purdue University.

TIMOTHY A. COHN is a Hazards Theme Coordinator in the director's office, U.S. Geological Survey, Reston, Virginia. Formerly, he was a hydrologist in the USGS Office of Surface Water in Reston, Virginia. He has extensive experience and expertise in statistical hydrology and modeling transport and loading of fluvial constituents. Dr. Cohn received his B.A. in mathematics from Swarthmore College and his M.S. and Ph.D. degrees in water resources systems engineering from Cornell University.

S. ROCKY DURRANS is an associate professor of civil and environmental engineering at the University of Alabama. His research focuses on water resources engineering and probabilistic and stochastic modeling of water quantity and quality variables, especially as related to heavy precipitation of large floods and droughts.

He received his B.S. and M.S. degrees in civil engineering from the University of Colorado at Denver. Dr. Durrans received his Ph.D. in civil engineering from the University of Colorado at Boulder.

C. THOMAS HAAN is the Regents and Sarkeys Distinguished Professor in the Department of Biosystems and Agricultural Engineering at Oklahoma State University. His research and teaching interests include hydrology, hydrologic and water quality monitoring, risk assessment, and geographic information systems. A member of the National Academy of Engineering, Dr. Haan received his B.S. and M.S. degrees from Purdue University and his Ph.D. in agricultural engineering from Iowa State University.

ROBERT D. JARRETT is chief of the U.S. Geological Survey's National Research Program on Paleohydrology and Climate Change in Lakewood, Colorado. The primary goal of this ongoing project is to conduct interdisciplinary research on critical water issues, particularly hydrologic hazards, facing water resource agencies. His general research interests include flooding, debris flow, dam-failure processes, river system processes, and assessing hydrologic effects of climate change. Recent research has focused on conducting hydrometeorologic and paleohydrologic research on extreme floods for use in risk-based assessments of dam safety. He received his B.S. in hydrology from the University of New Hampshire. Dr. Jarrett received his M.S. and Ph.D. in civil engineering from Colorado Sate University.

UPMANU LALL is a professor in the Department of Civil and Environmental Engineering and associate director of the Utah Water Research Laboratory at Utah State University. His current research focuses on several areas of hydrology and hydroclimatology, including hydroclimate seasonal to decadal climate variability, global change, hydroclimate modeling, spatial data analysis and visualization, time-series analysis and forecasting, floods and droughts, water quantity and quality management and subsurface characterization. He received a B.Tech. degree in civil engineering from the I.I.T. in Kanpur, India. Dr. Lall received his M.S. and Ph.D. in civil engineering from the University of Texas, Austin.

KELLY T. REDMOND is regional climatologist and the deputy director of the Western Region Climate Center, Atmospheric Sciences Center, at the Desert Research Institute, a nonprofit, statewide division of the University and Community College System of Nevada. His research interests and expertise encompass all facets of climate and climate behavior, including heavy precipitation episodes and spatial patterns of western U.S. climate variability. He received a B.S. degree in physics from the Massachusetts Institute of Technology and M.S. and Ph.D. degrees in meteorology from the University of Wisconsin, Madison.

JERY R. STEDINGER is a professor of civil and environmental engineering at Cornell University. His research focuses on the efficient design and operation of reservoir systems, development of alternative models for improving system operations, efficient use of hydrologic data, and many topics in stochastic hydrology. Dr. Stedinger has served on several NRC committees, including the Committee on Flood Control Alternatives in the American River Basin. He earned his B.A. in applied mathematics from the University of California, Berkeley. Dr. Stedinger received his M.A. in applied mathematics and Ph.D. in engineering from Harvard University.